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(54) PROCESS FOR TREATING HEAVY OIL

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Publication Classification

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C10G 69/02 (2006.01)

(52) **U.S. Cl.** **208/60**; 208/66

(57) **ABSTRACT**

This invention relates to a process for hydroprocessing heavy oil under process intensification conditions to form an upgraded hydrocarbon product.

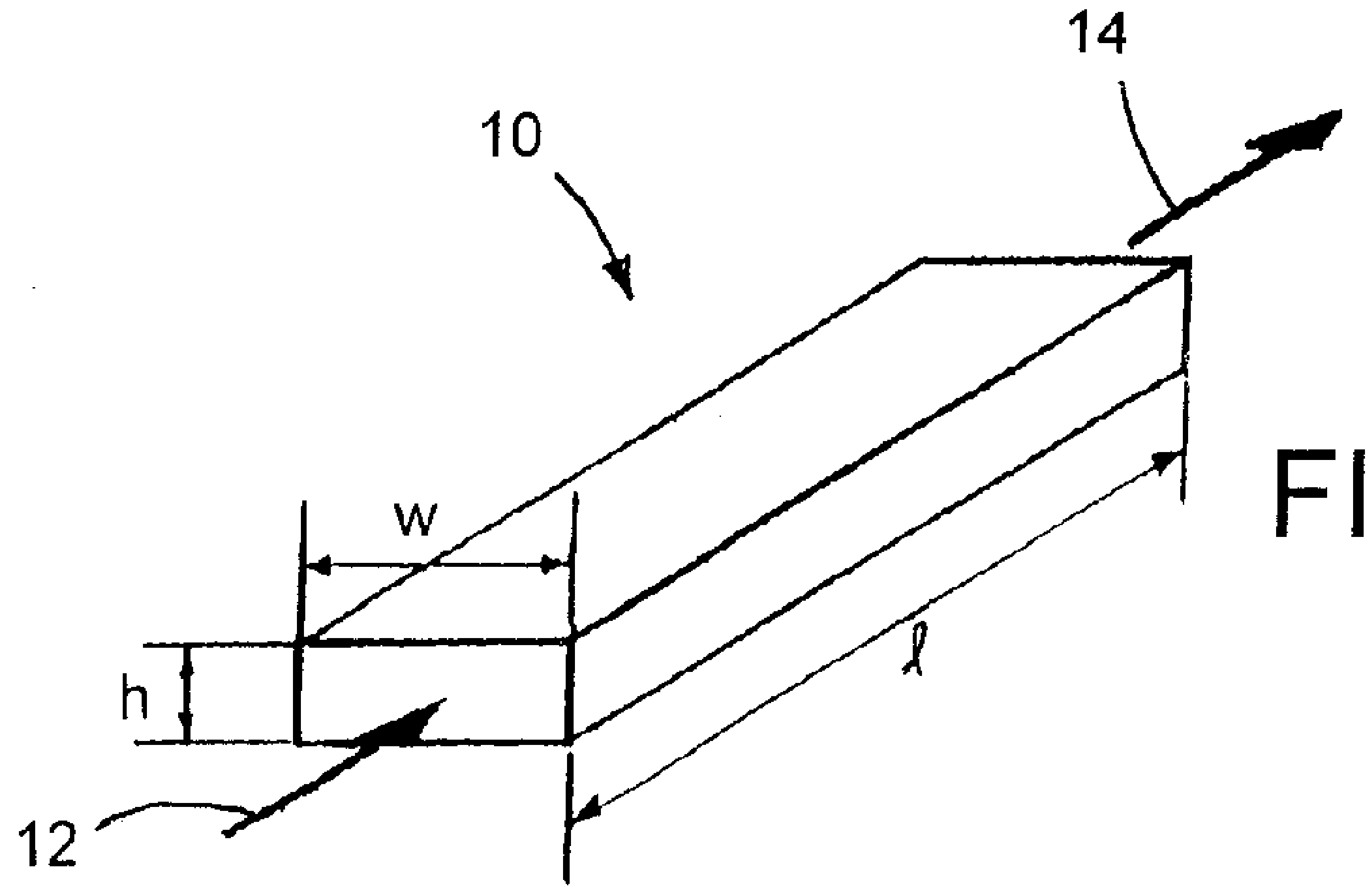


FIG. 1

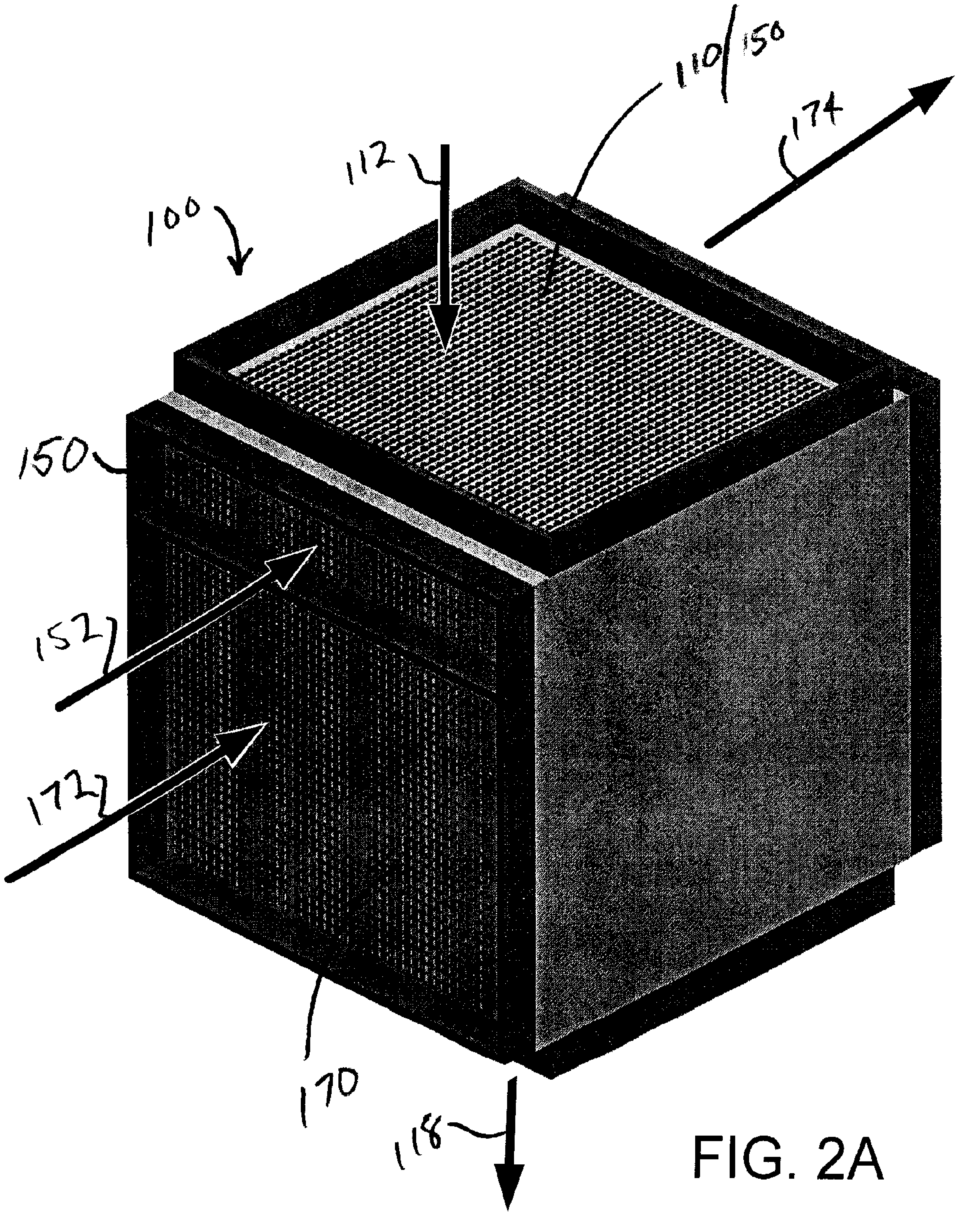


FIG. 2A

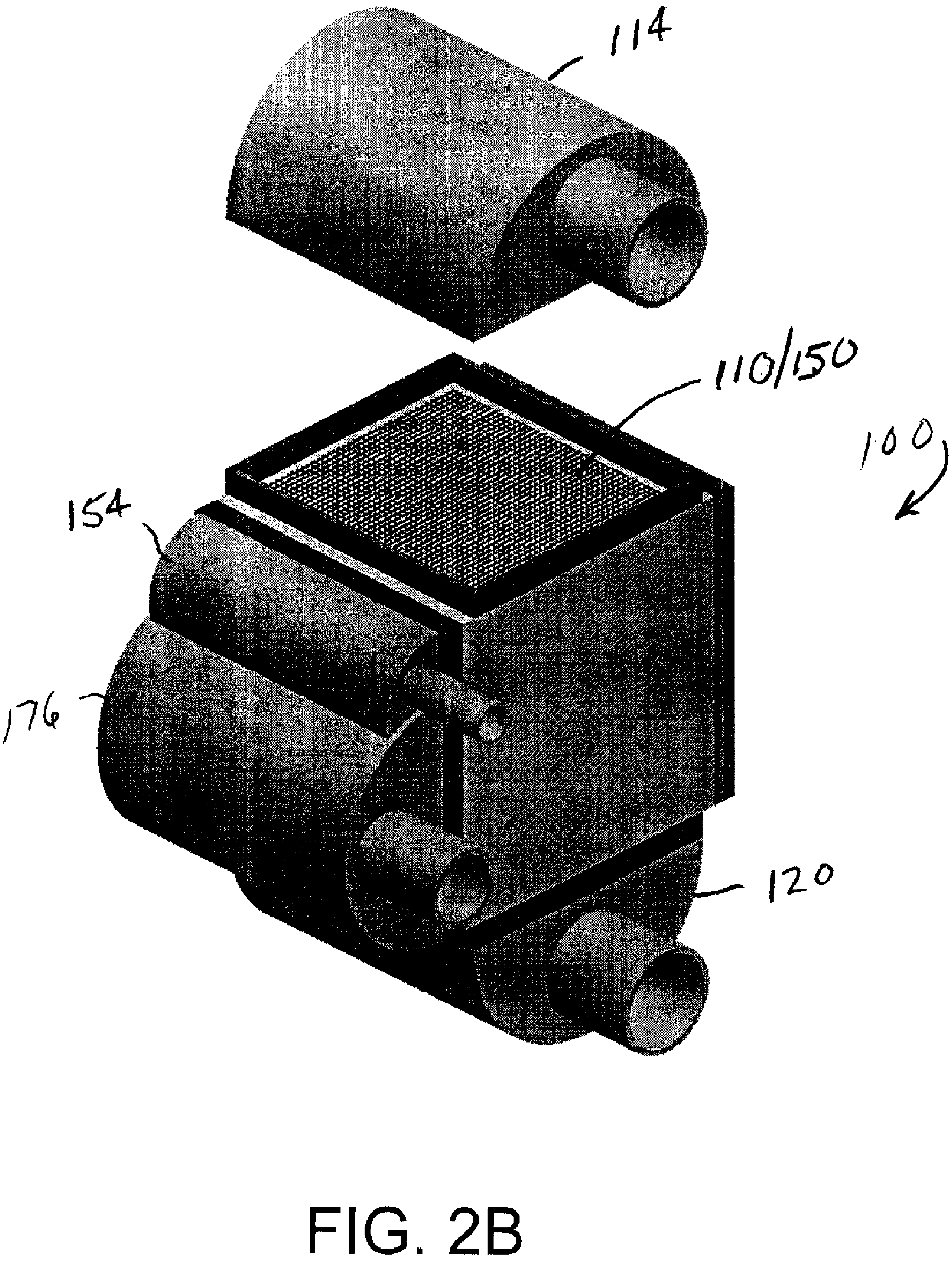


FIG. 2B

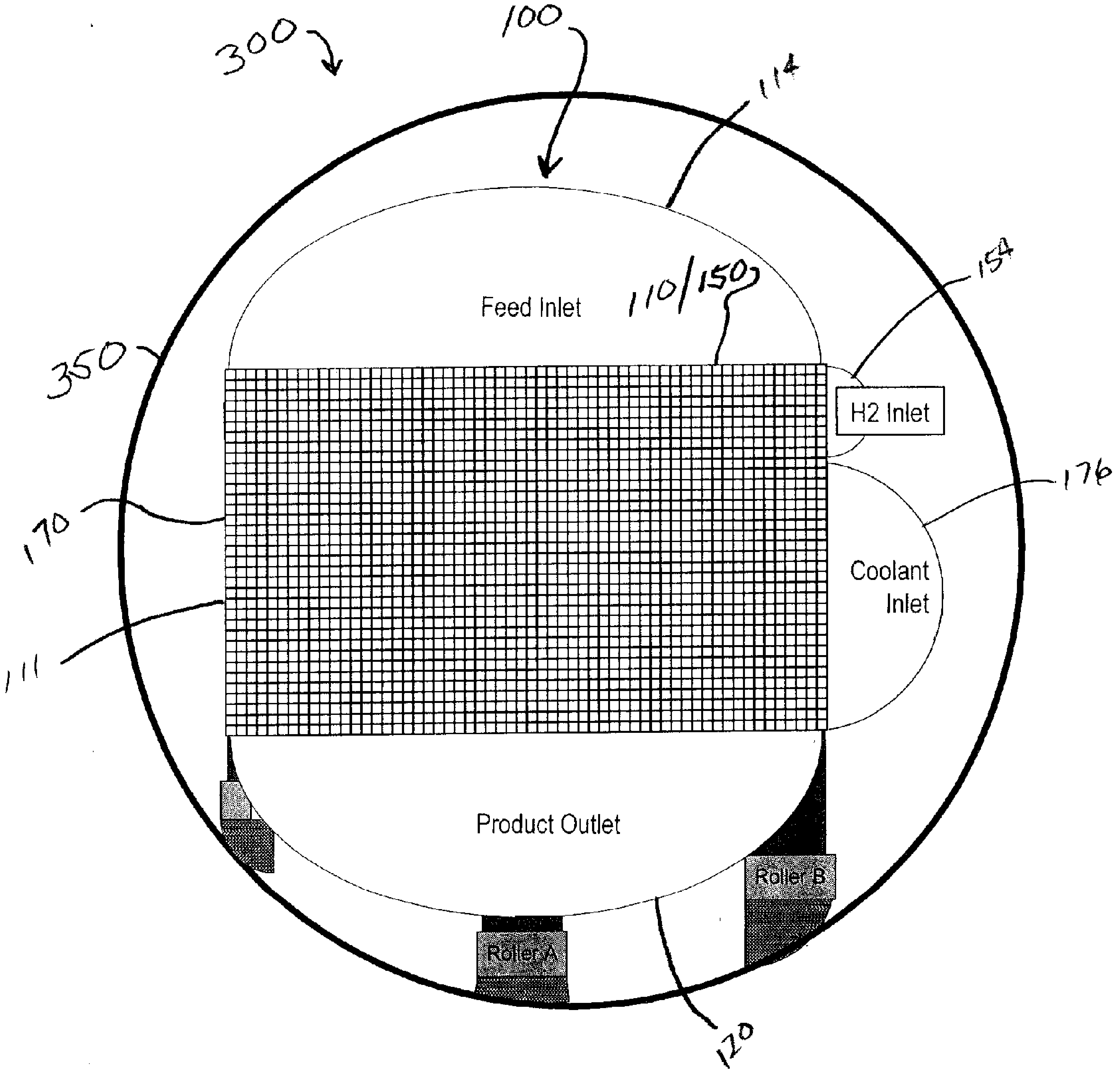

300
100
114
Feed Inlet
110/150
154
H2 Inlet
350
170
176
Coolant Inlet
111
Product Outlet
Roller B
Roller A
120

FIG. 2C

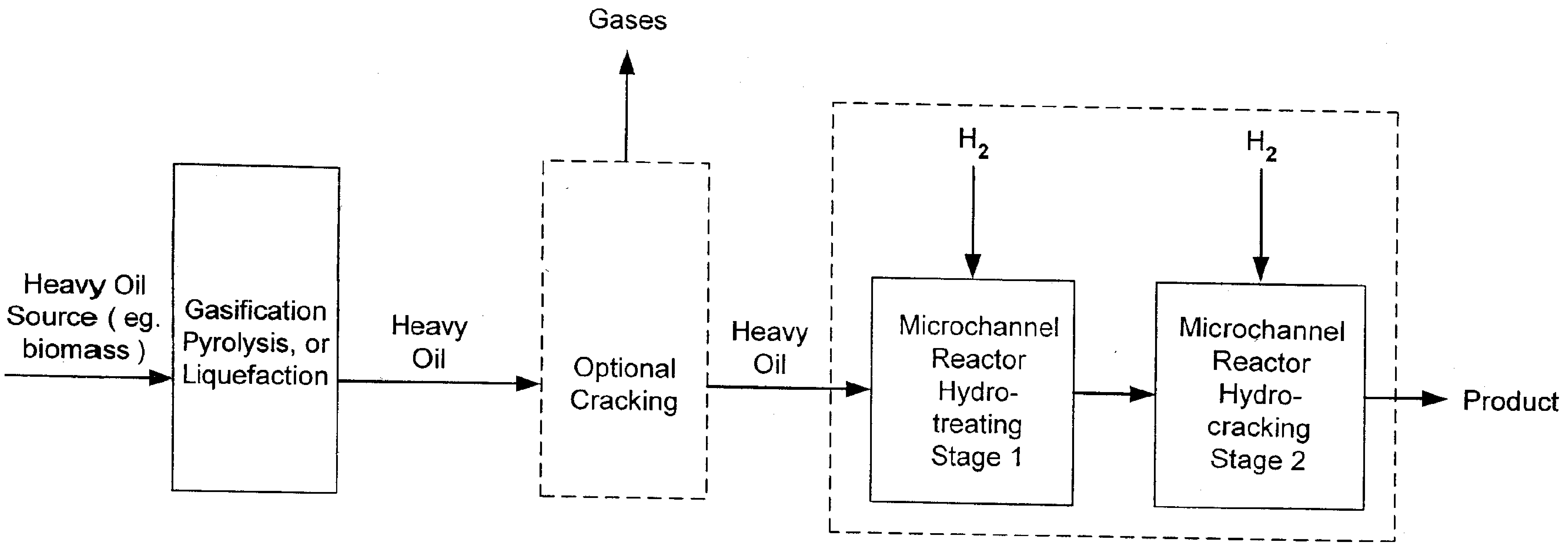

Heavy Oil Source (eg. biomass)
Gasification Pyrolysis, or Liquefaction
Heavy Oil
Gases
Optional Cracking
Heavy Oil
H_2
H_2
Microchannel Reactor Hydro-treating Stage 1
Microchannel Reactor Hydro-cracking Stage 2
Product

FIG. 3

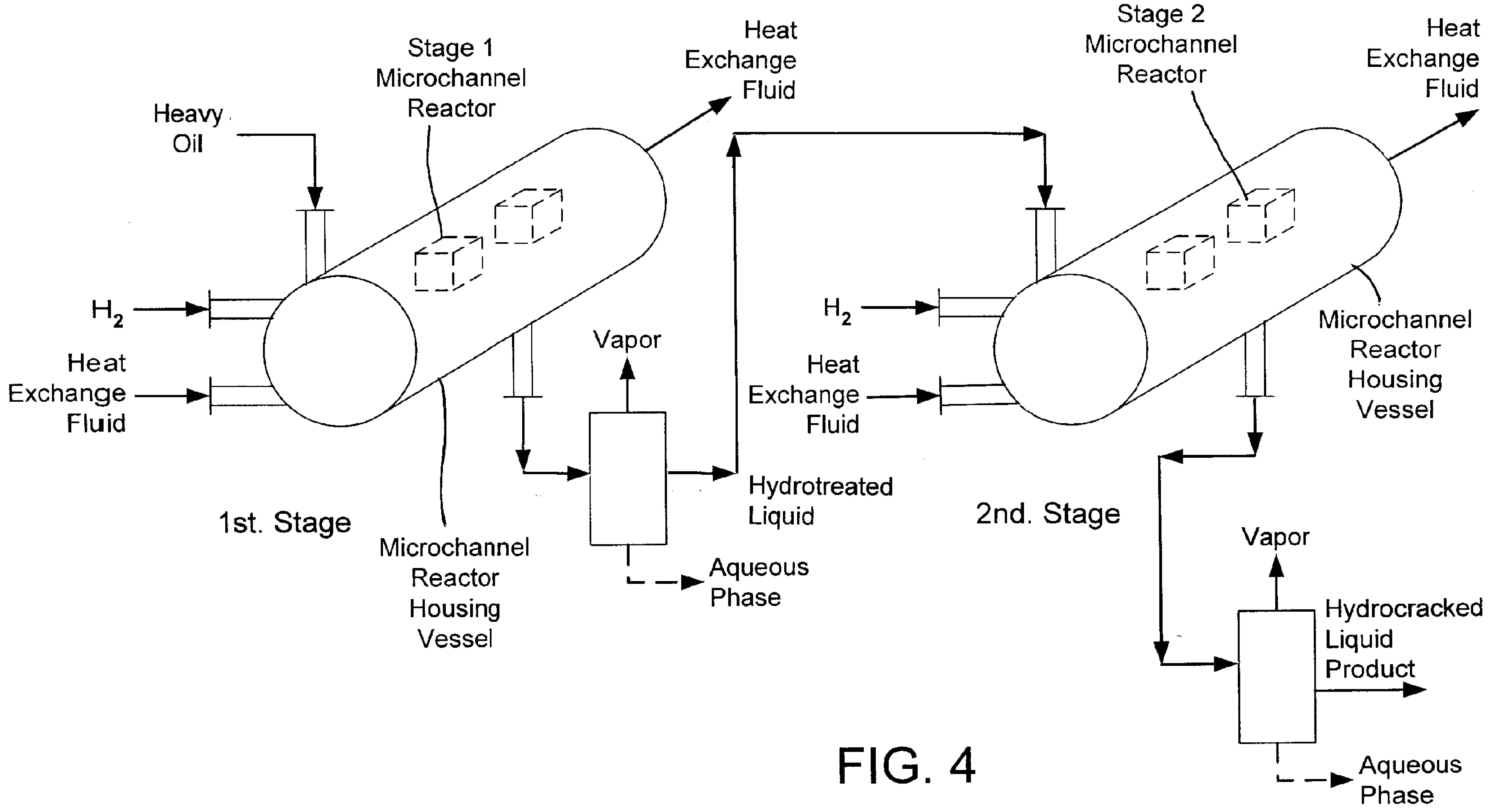

Heavy Oil
Stage 1 Microchannel Reactor
Heat Exchange Fluid
H_2
Heat Exchange Fluid
Vapor
Hydrotreated Liquid
1st. Stage
Microchannel Reactor Housing Vessel
Aqueous Phase
Stage 2 Microchannel Reactor
Heat Exchange Fluid
H_2
Heat Exchange Fluid
Microchannel Reactor Housing Vessel
2nd. Stage
Vapor
Hydrocracked Liquid Product
Aqueous Phase

FIG. 4

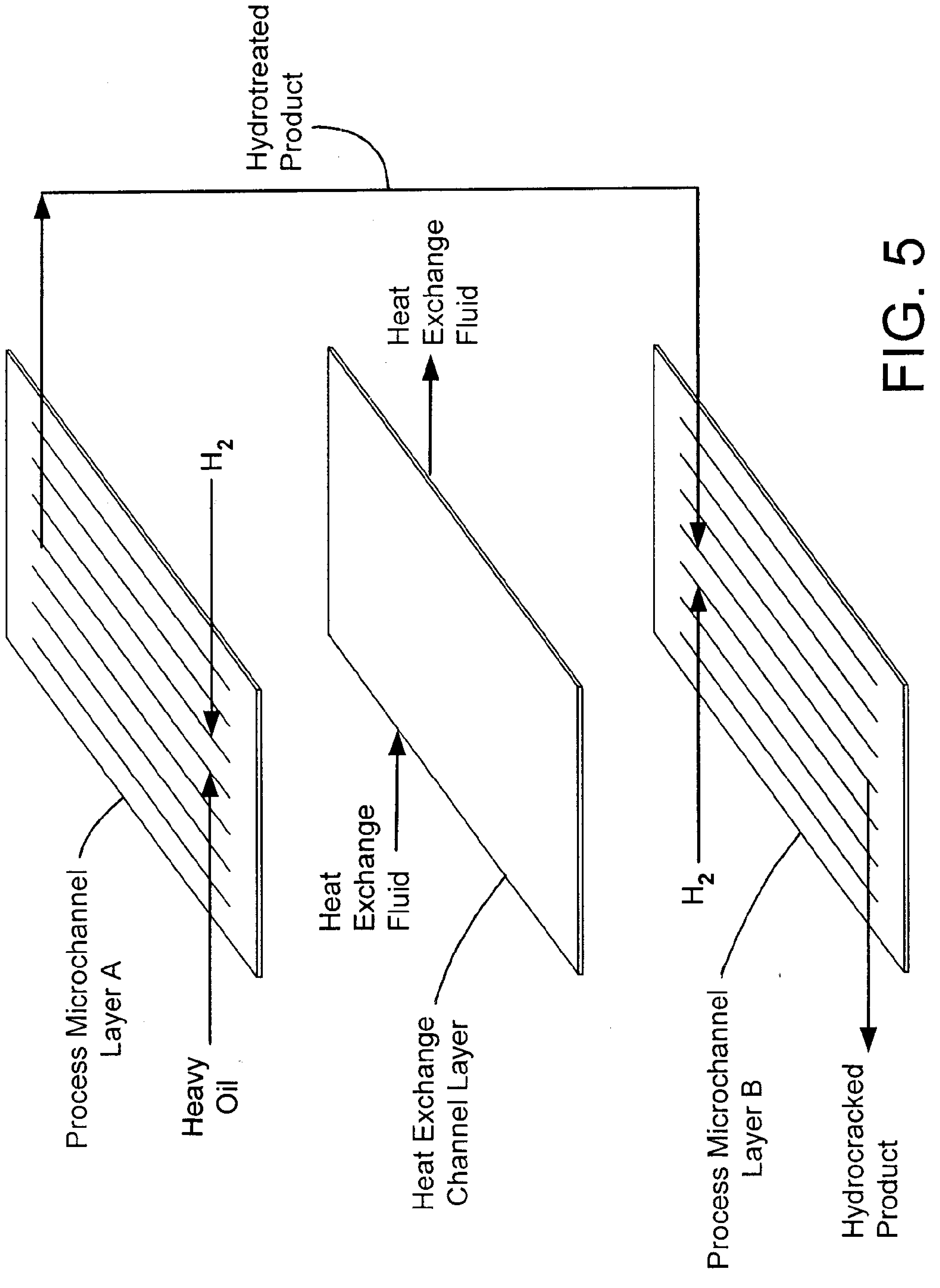

Process Microchannel Layer A
Heavy Oil
H_2
Hydrotreated Product
Heat Exchange Fluid
Heat Exchange Channel Layer
Heat Exchange Fluid
H_2
Process Microchannel Layer B
Hydrocracked Product

FIG. 5

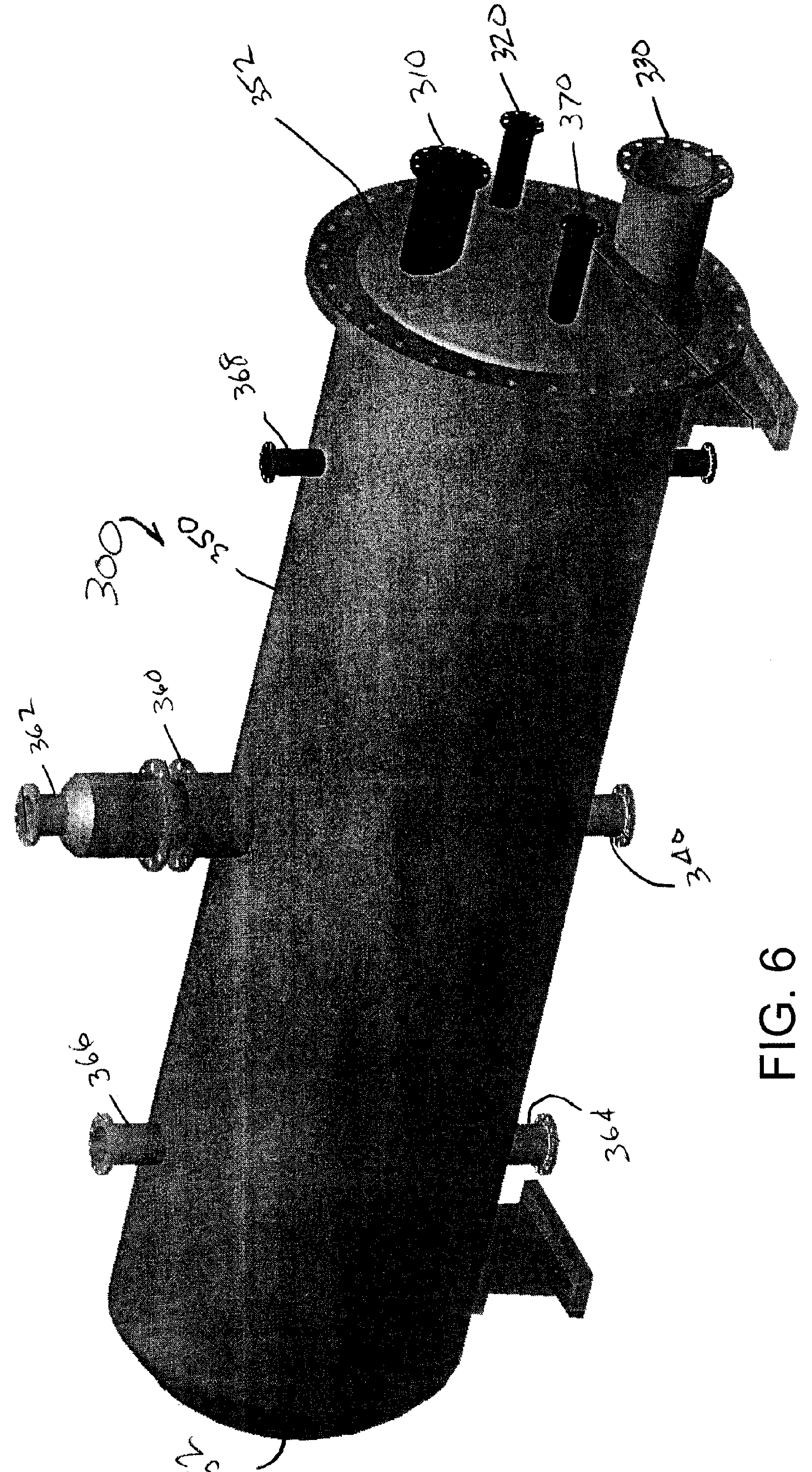
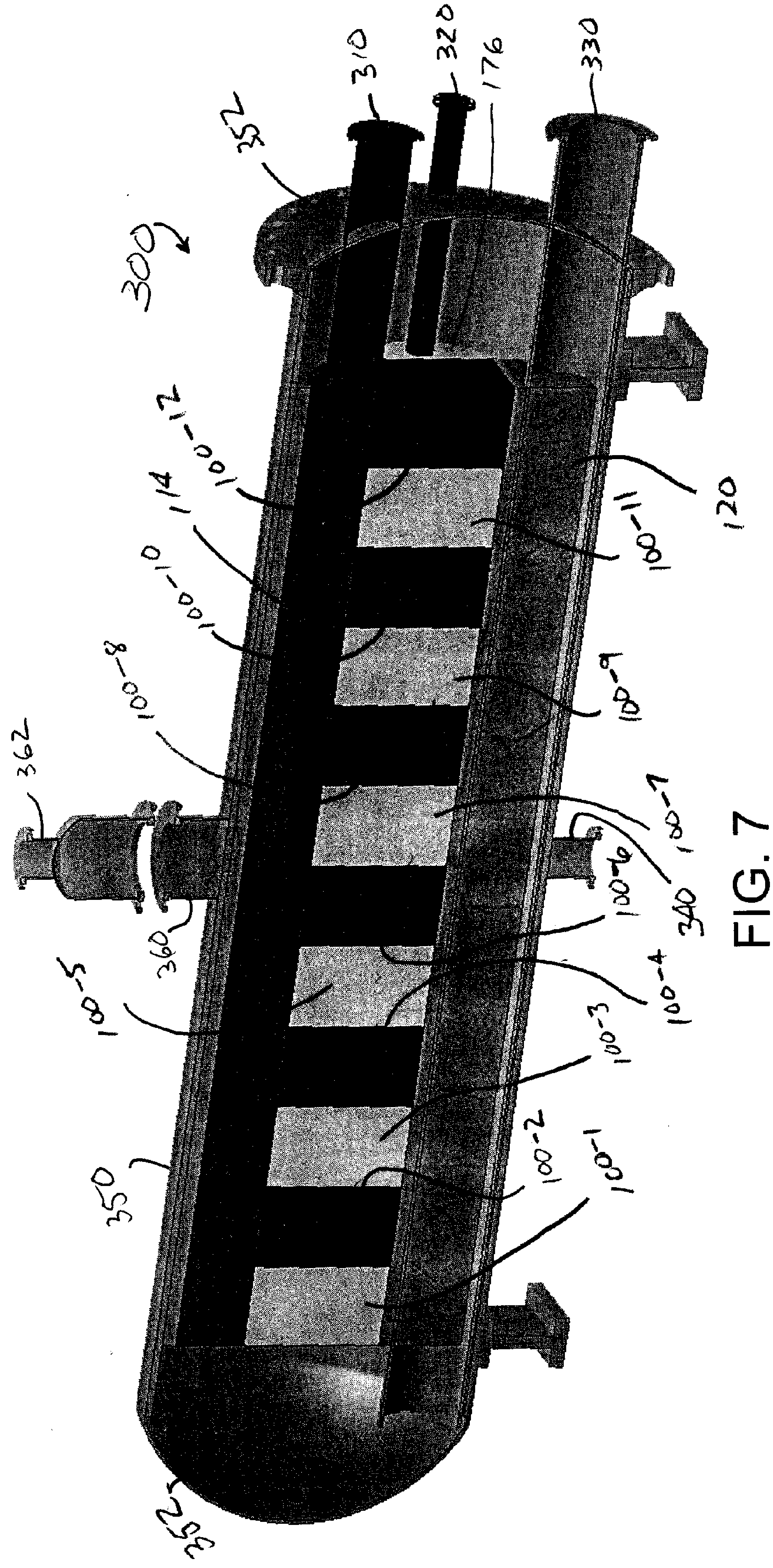


FIG. 6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310
320
176
330
352
100-12
114
100-10
100-8
362
360
100-5
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100-1
100-2
100-3
100-4
100-6
340
100-7
100-9
100-11
120
352

FIG. 7

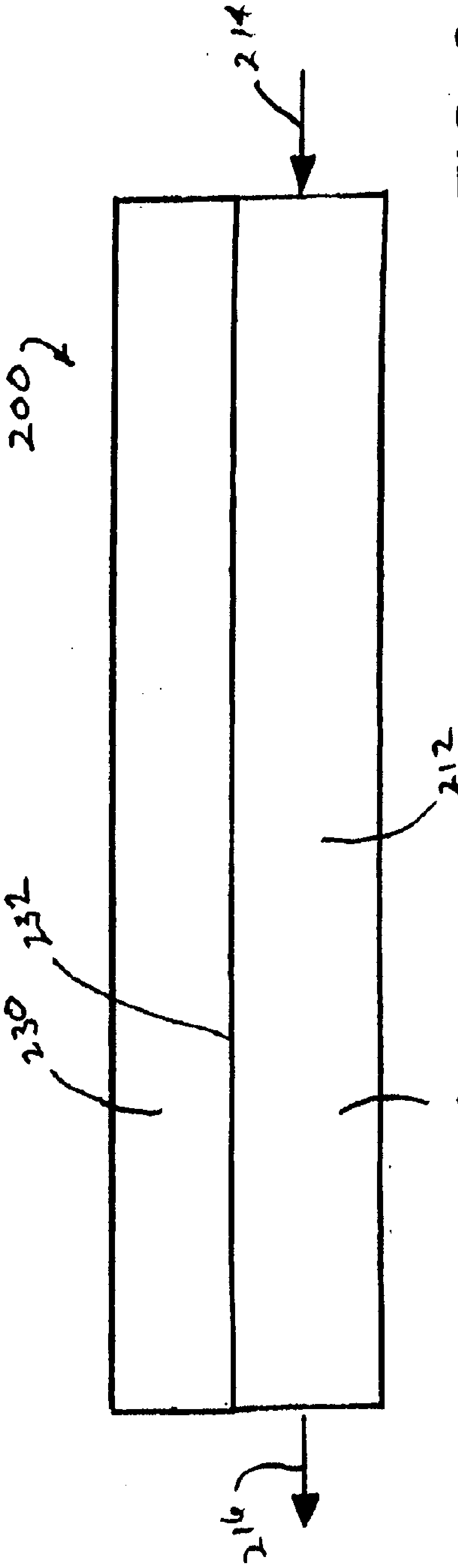

200
214
212
232
230
210
216

FIG. 8

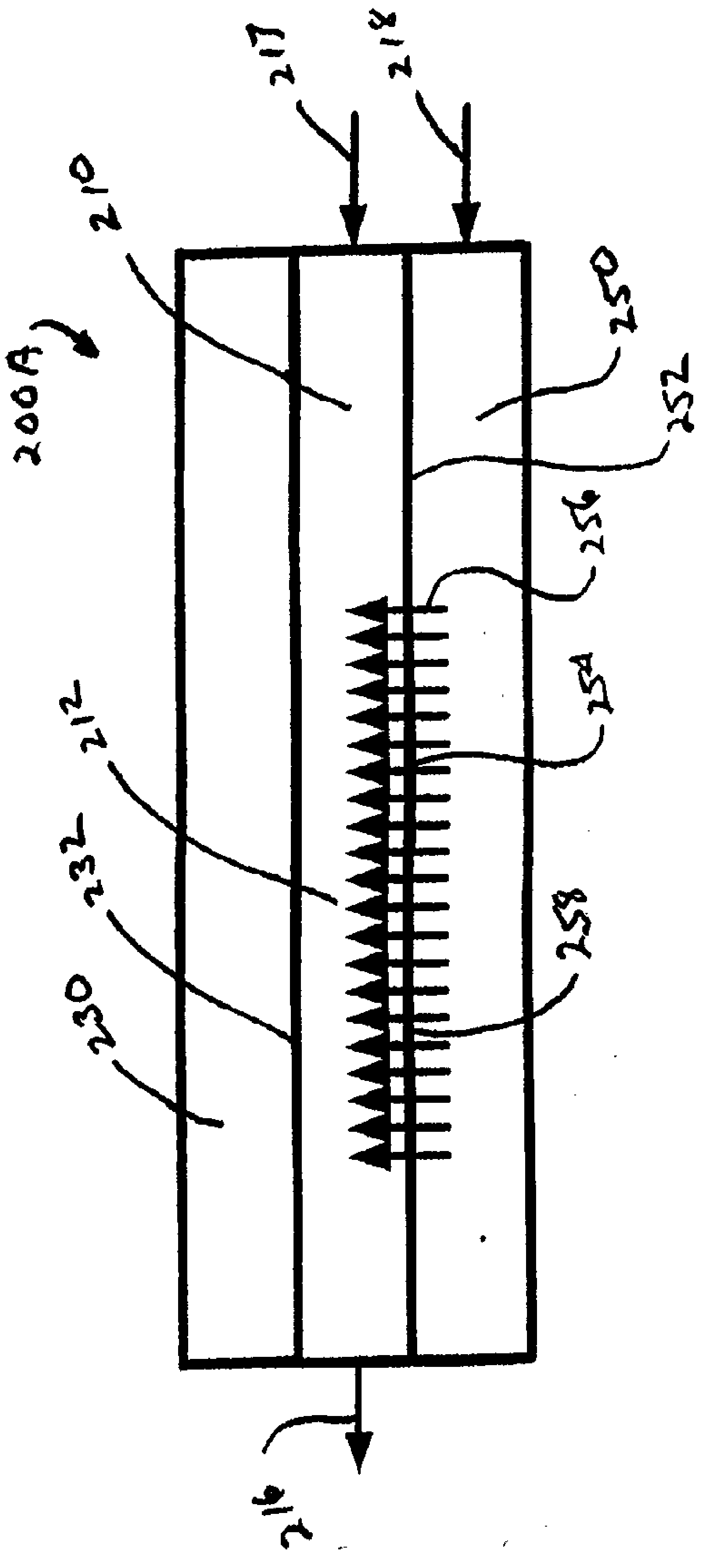
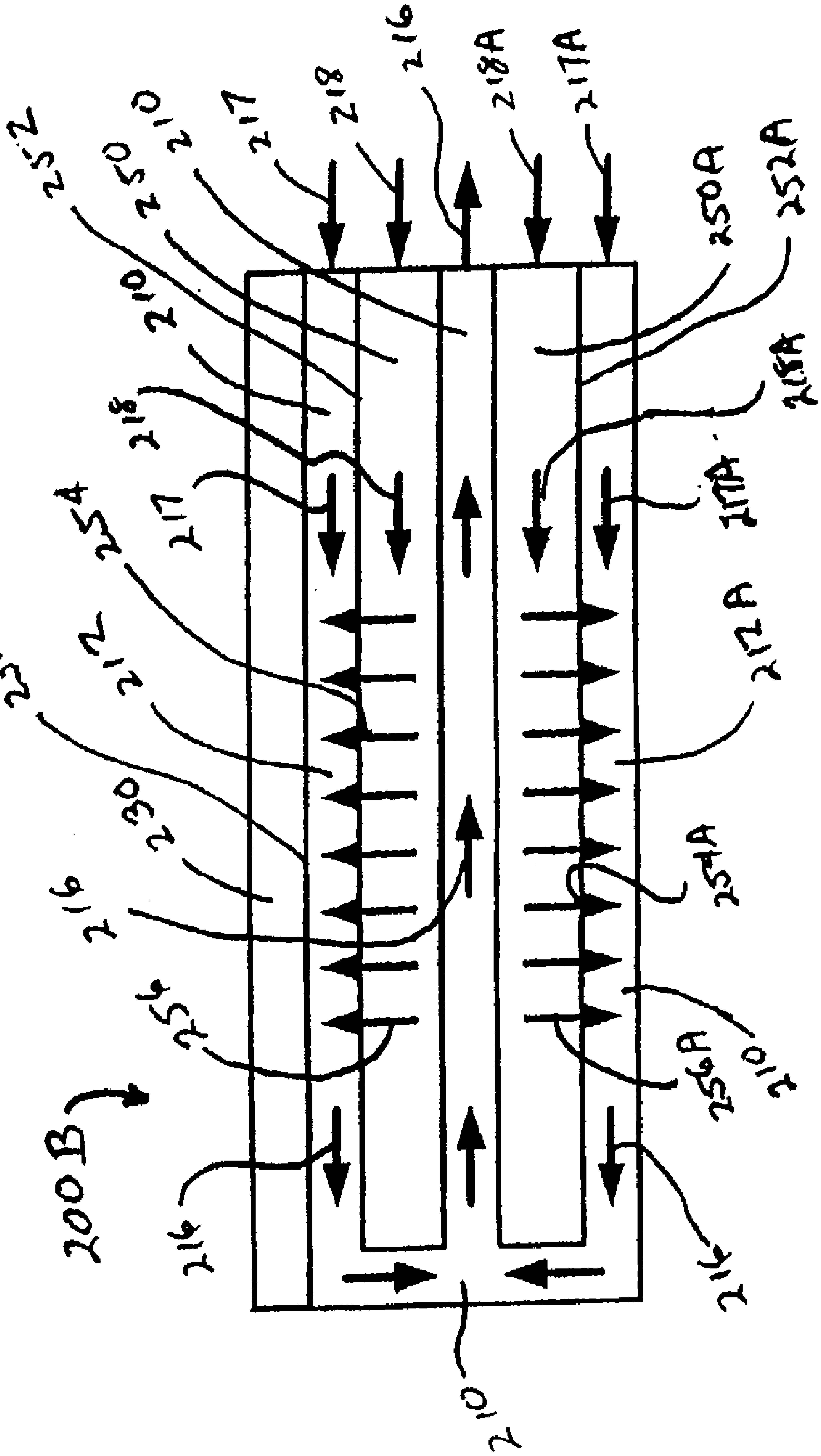

200A
210
217
218
250
252
256
254
212
232
258
230
216

FIG. 9


252
250
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218A
217A
250A
252A
210
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218A
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217A
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212A
232
230
254A
216
256
256A
210
200B
216
216
210

FIG. 10

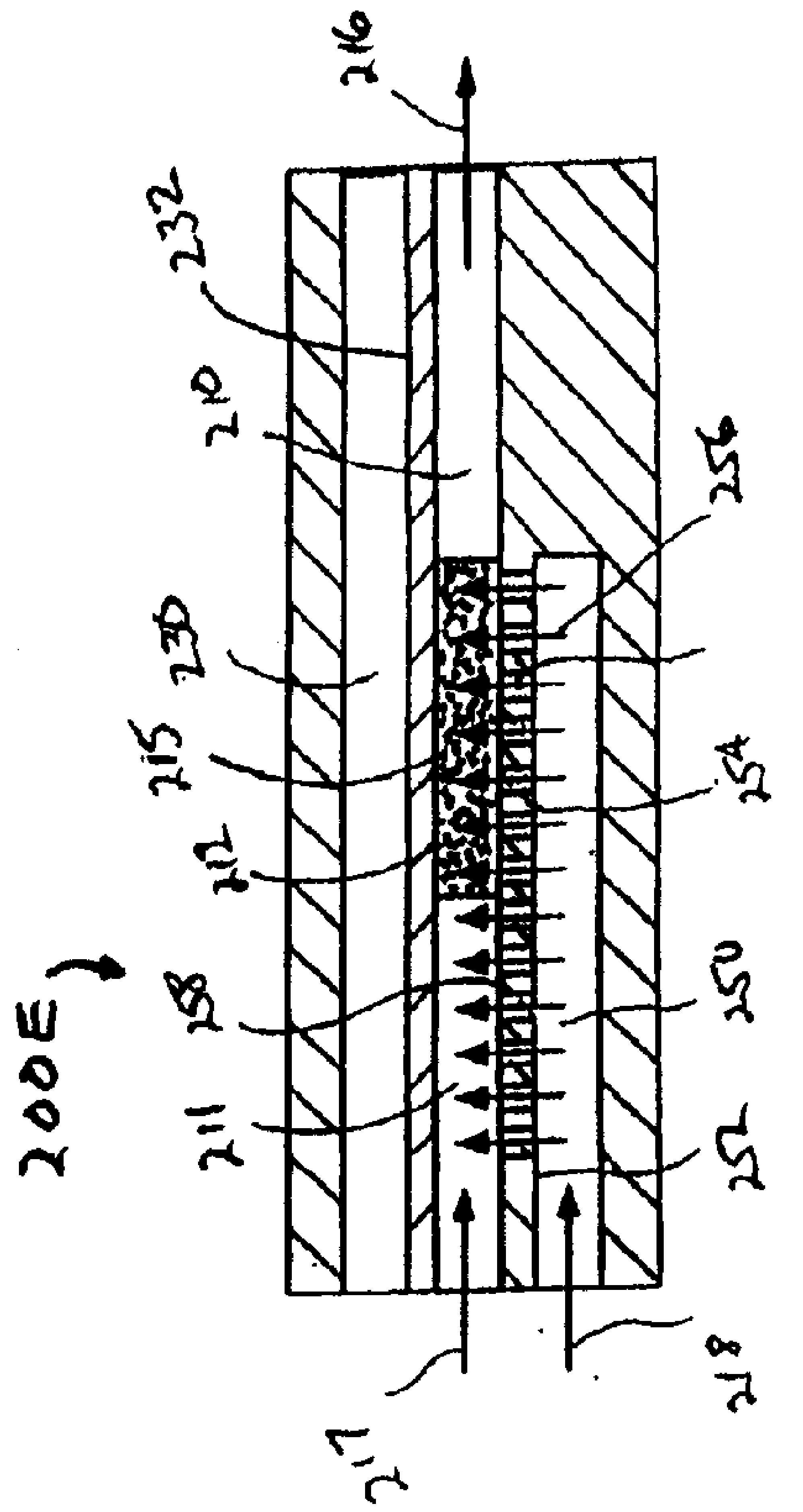


FIG. 13

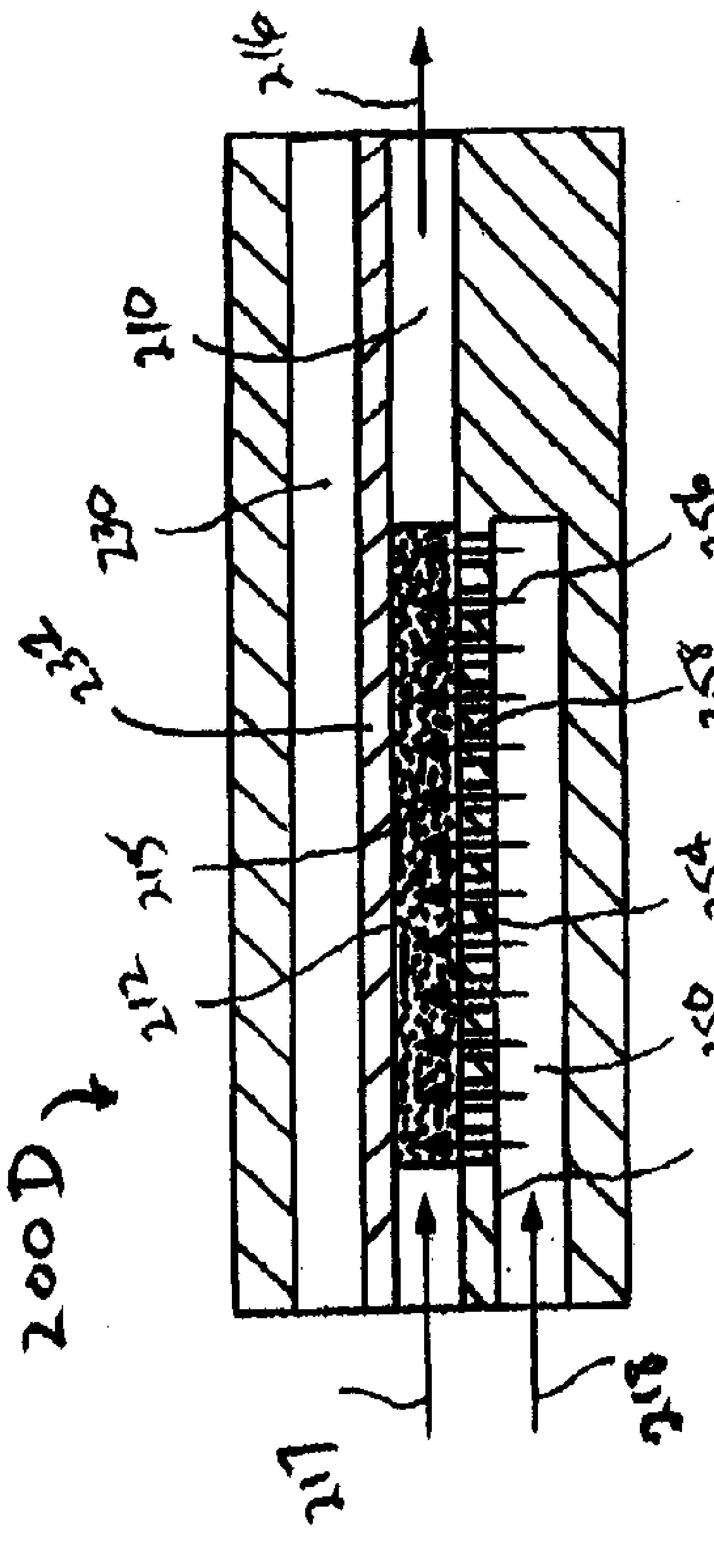


FIG. 12

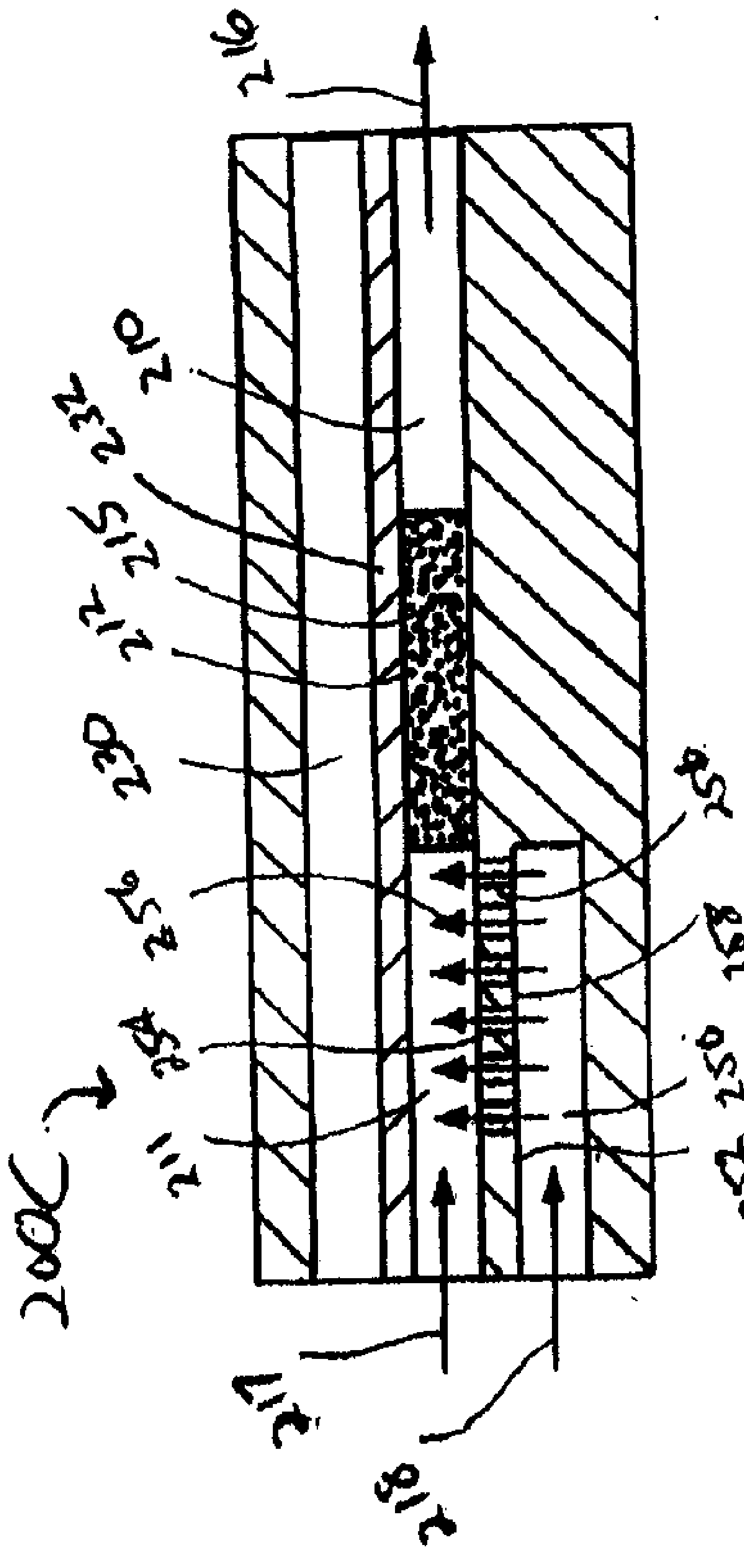


FIG. 11

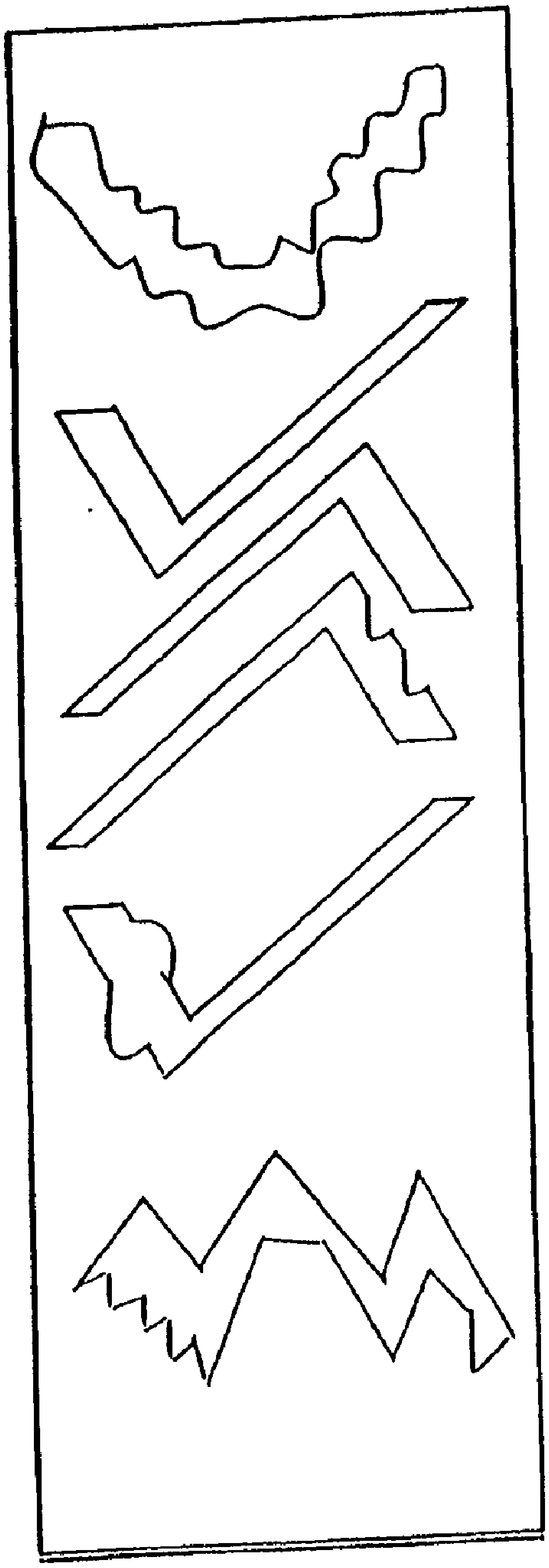


FIG. 14

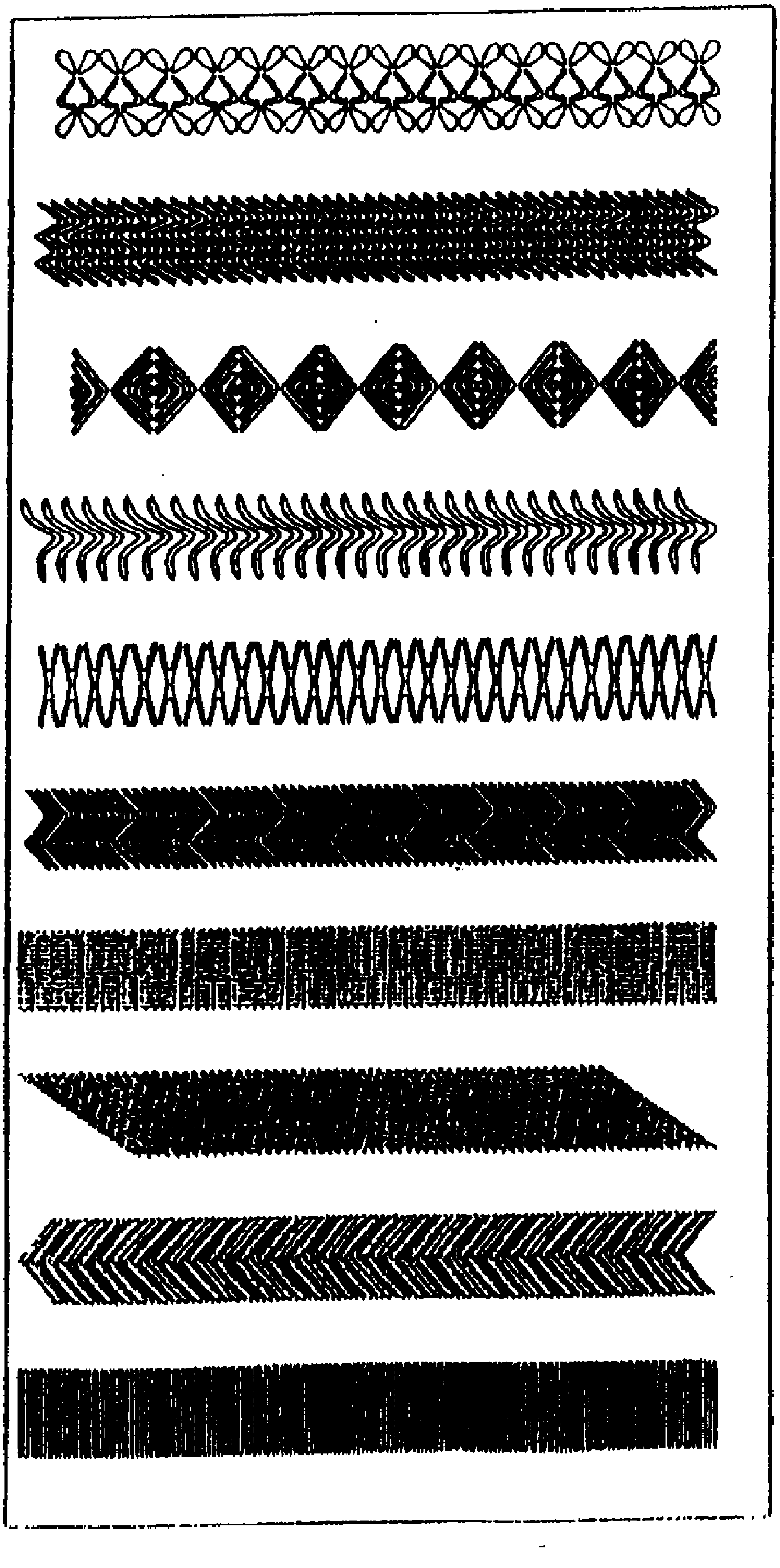


FIG. 15

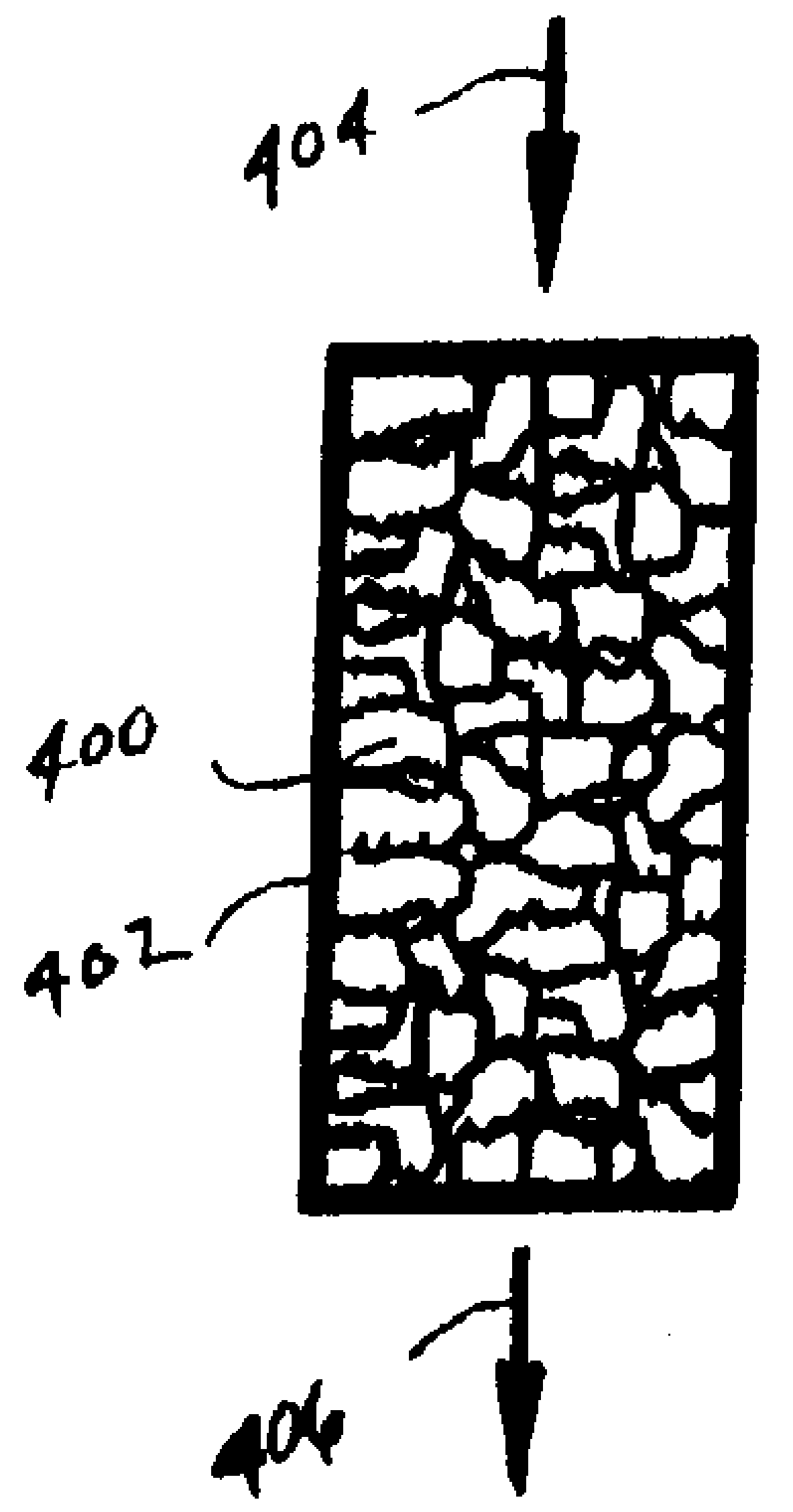


FIG. 16

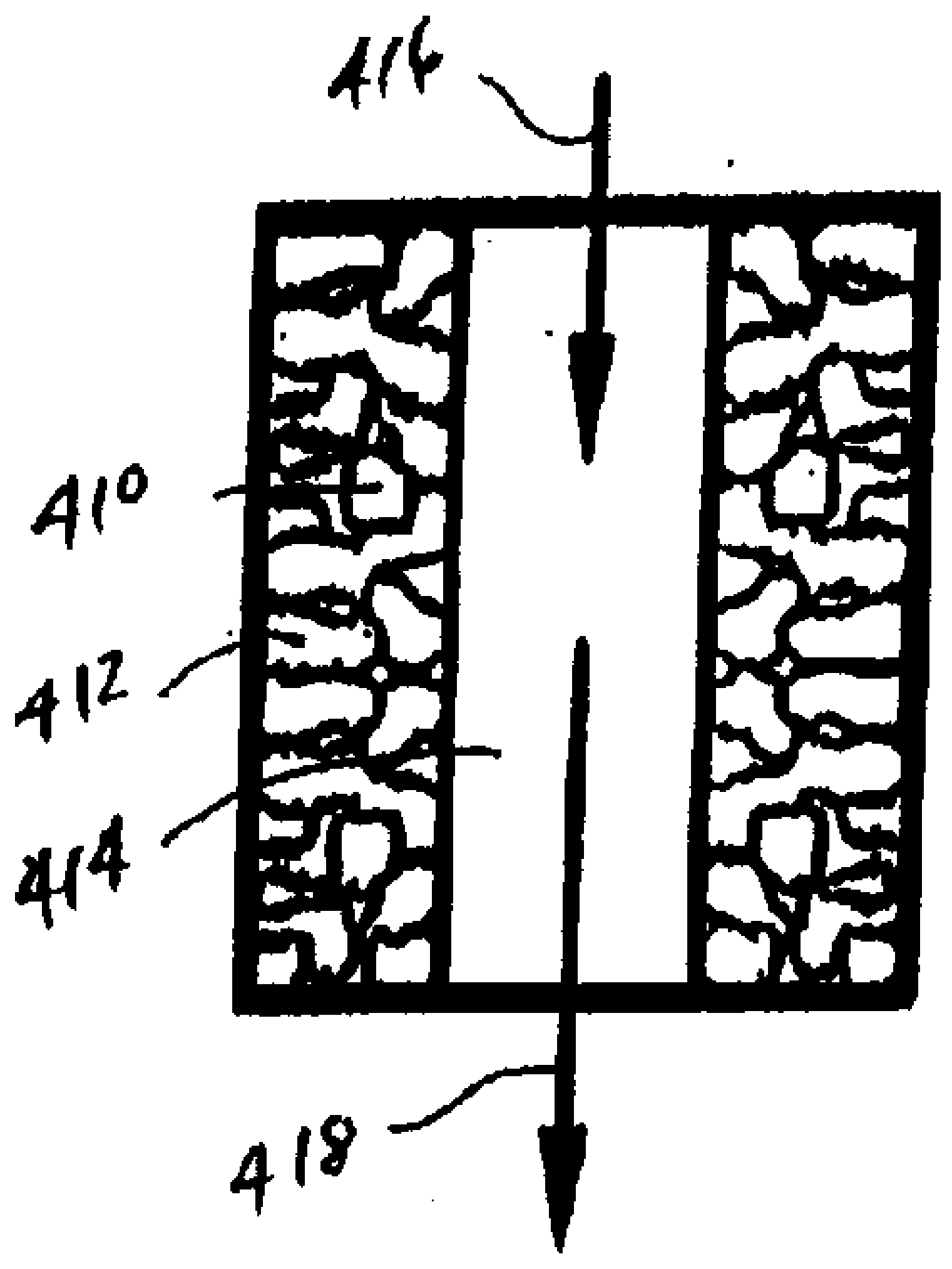


FIG. 17

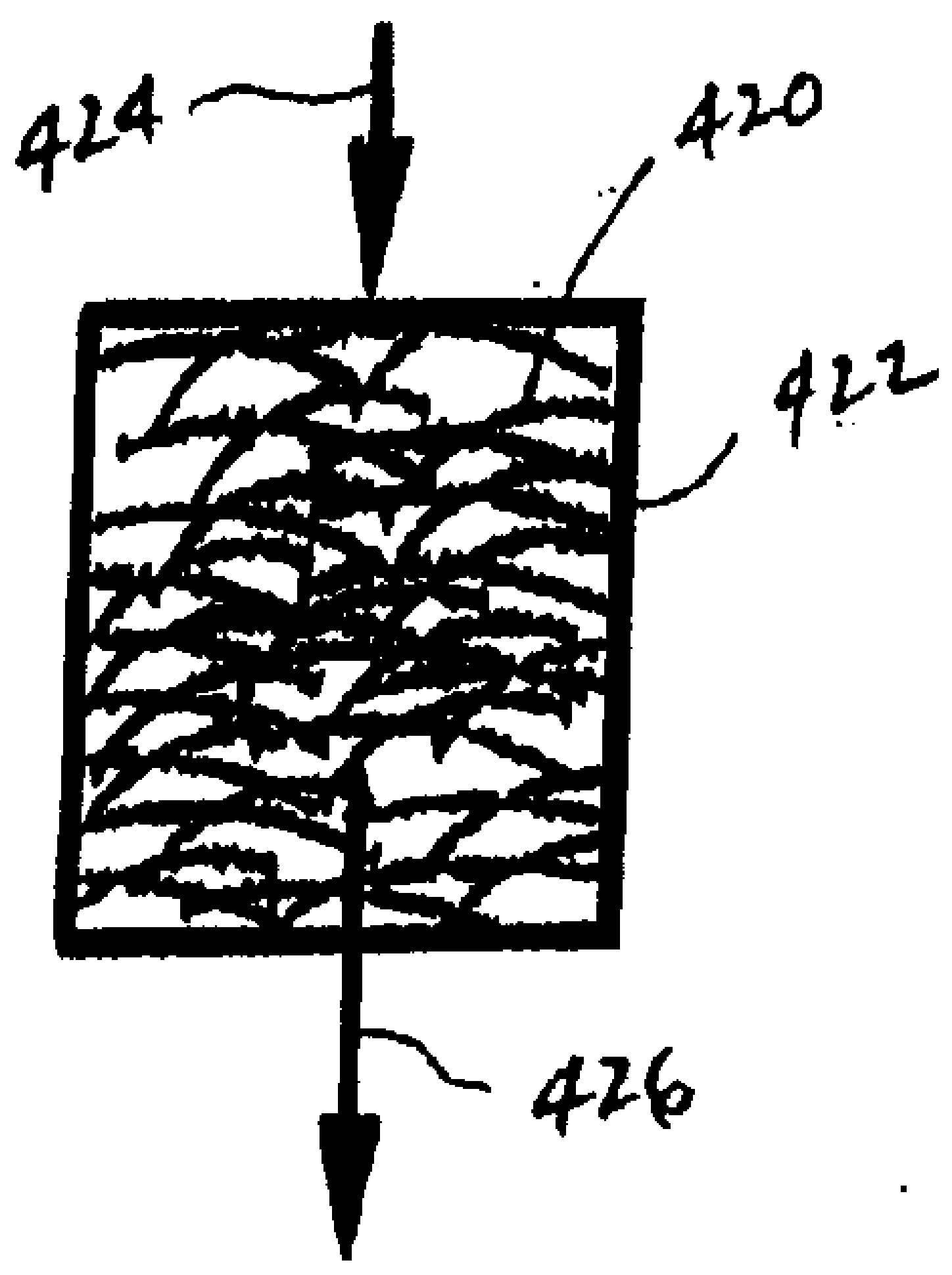


FIG. 18

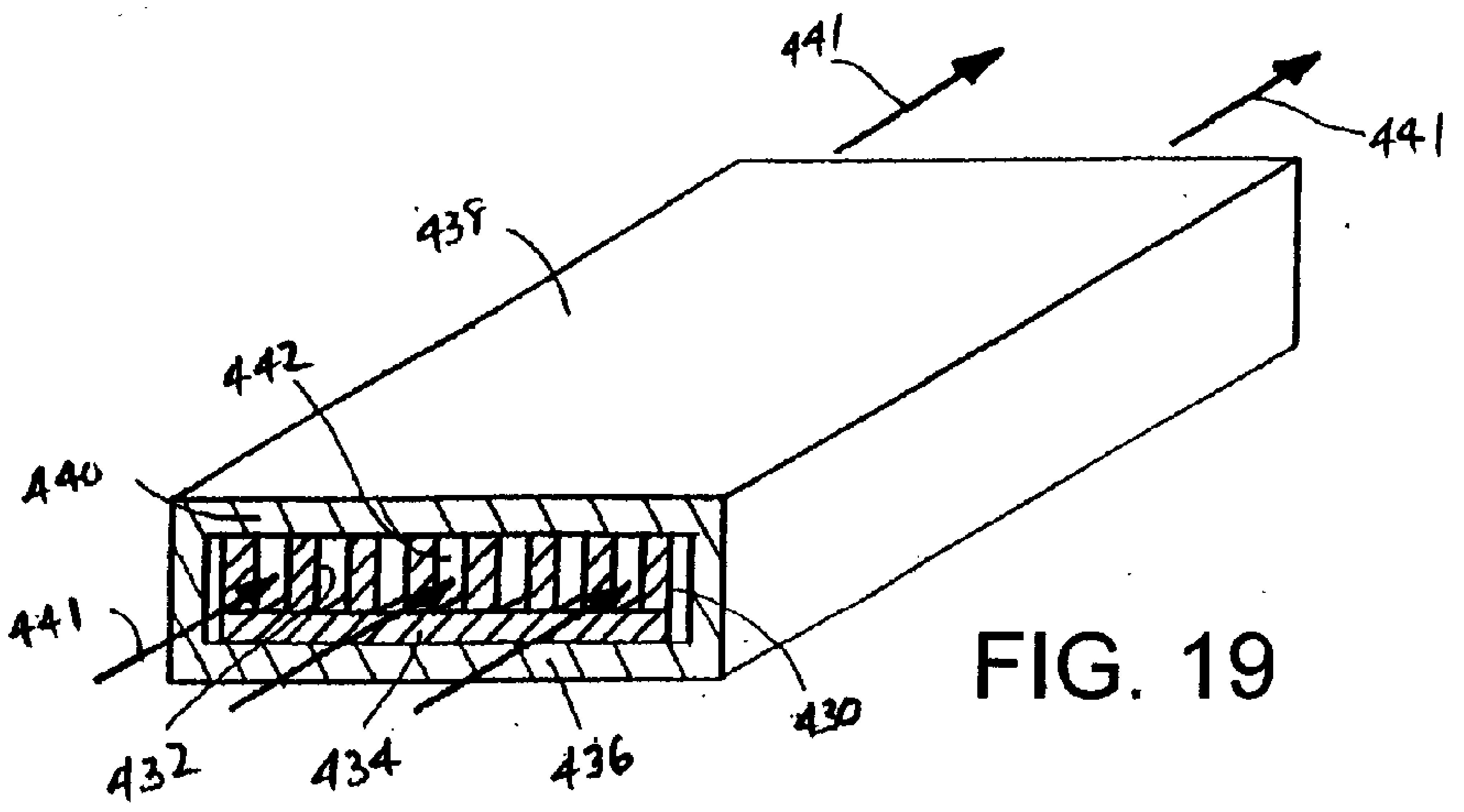


FIG. 19

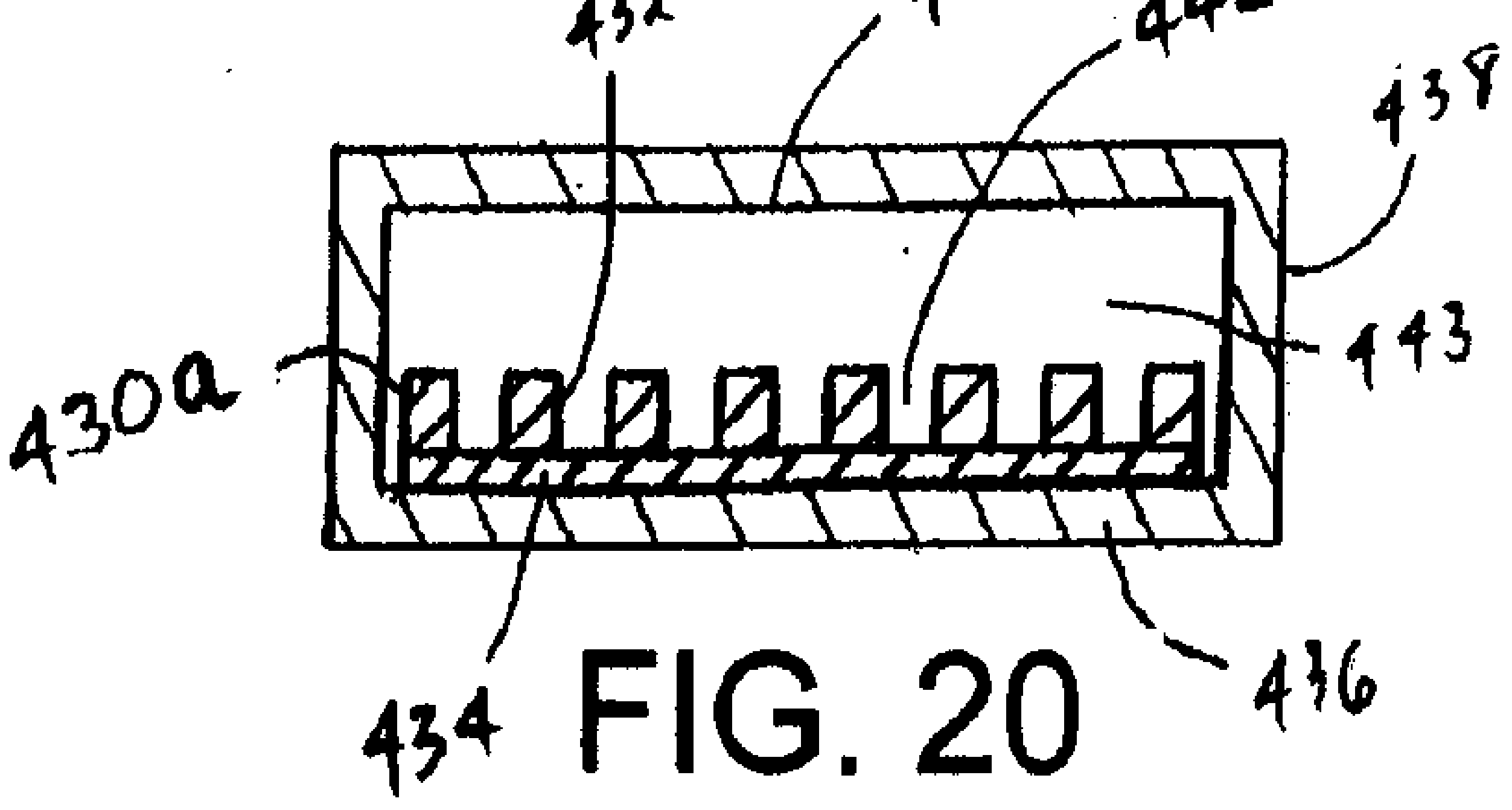


FIG. 20

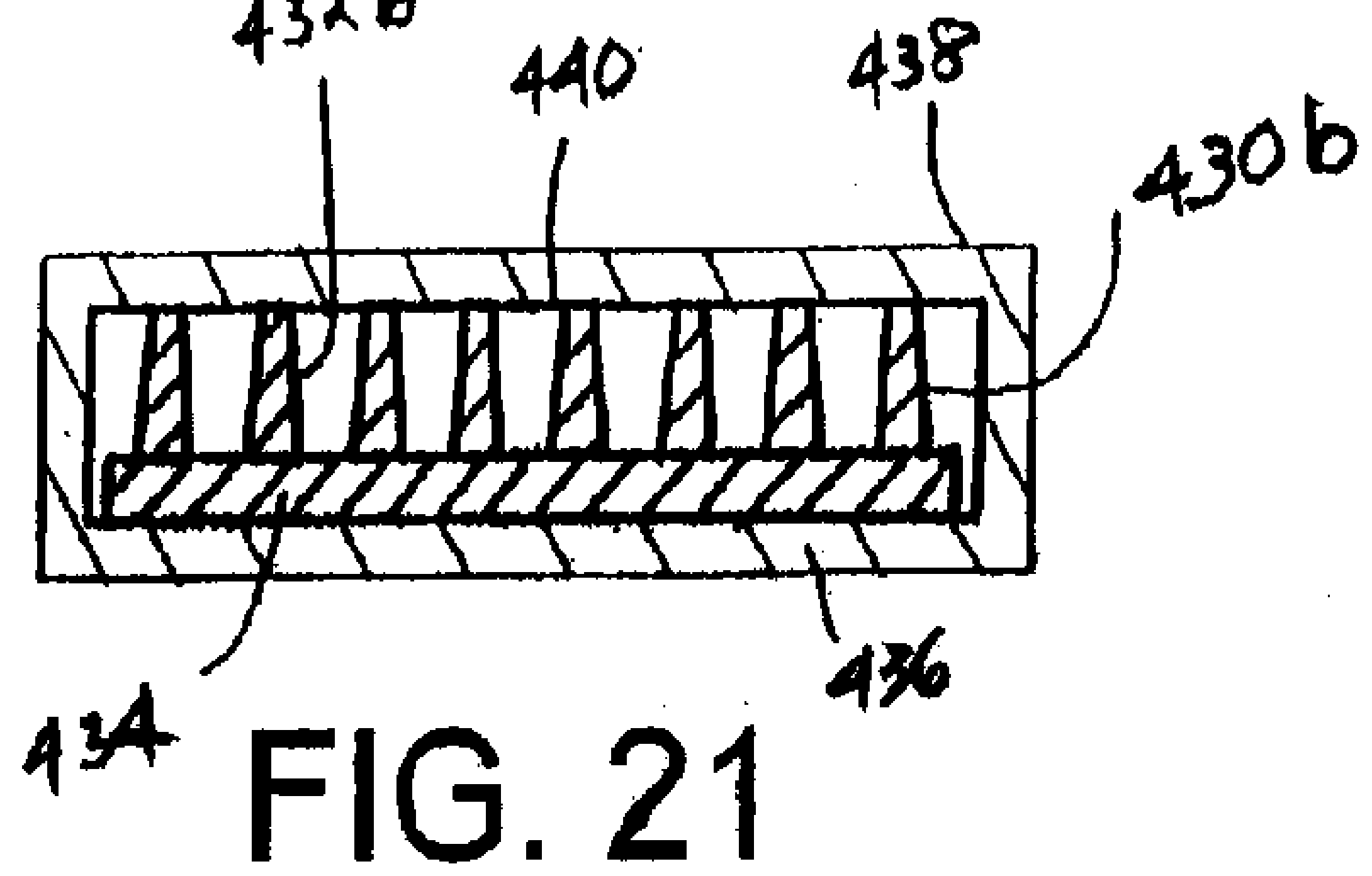
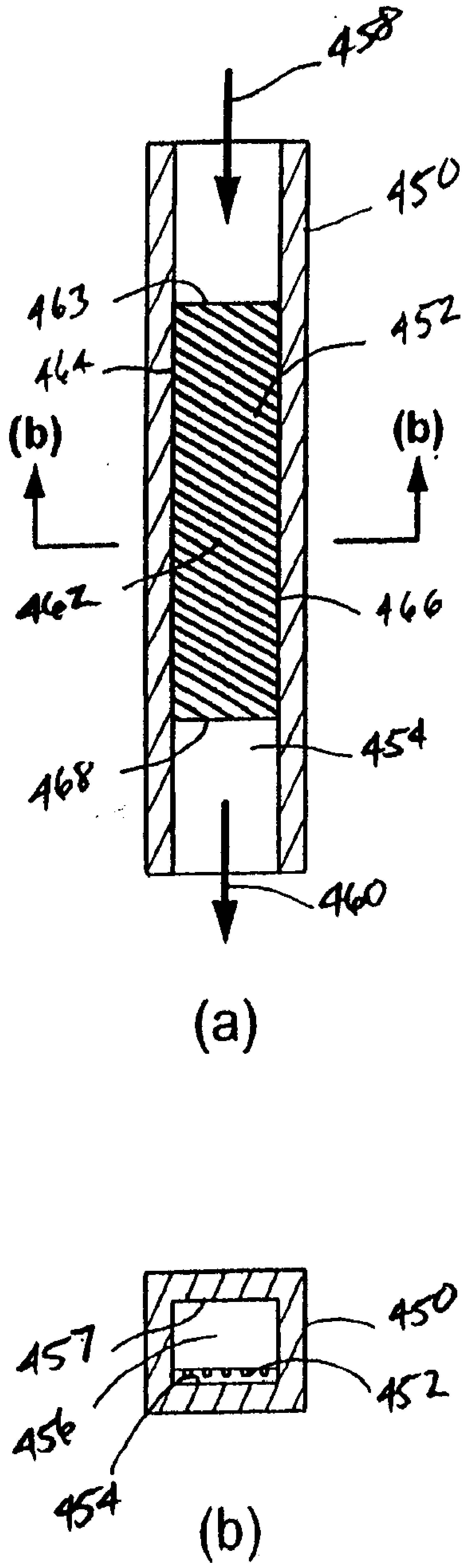


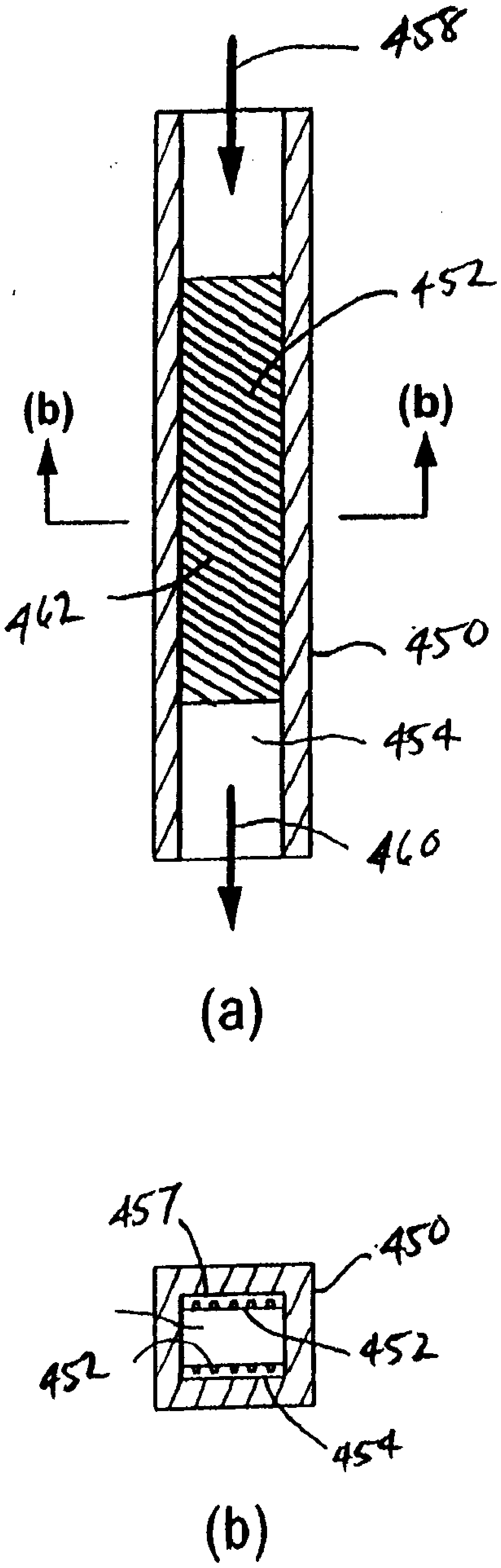
FIG. 21



(a)

(b)

FIG. 22



(a)

(b)

FIG. 23

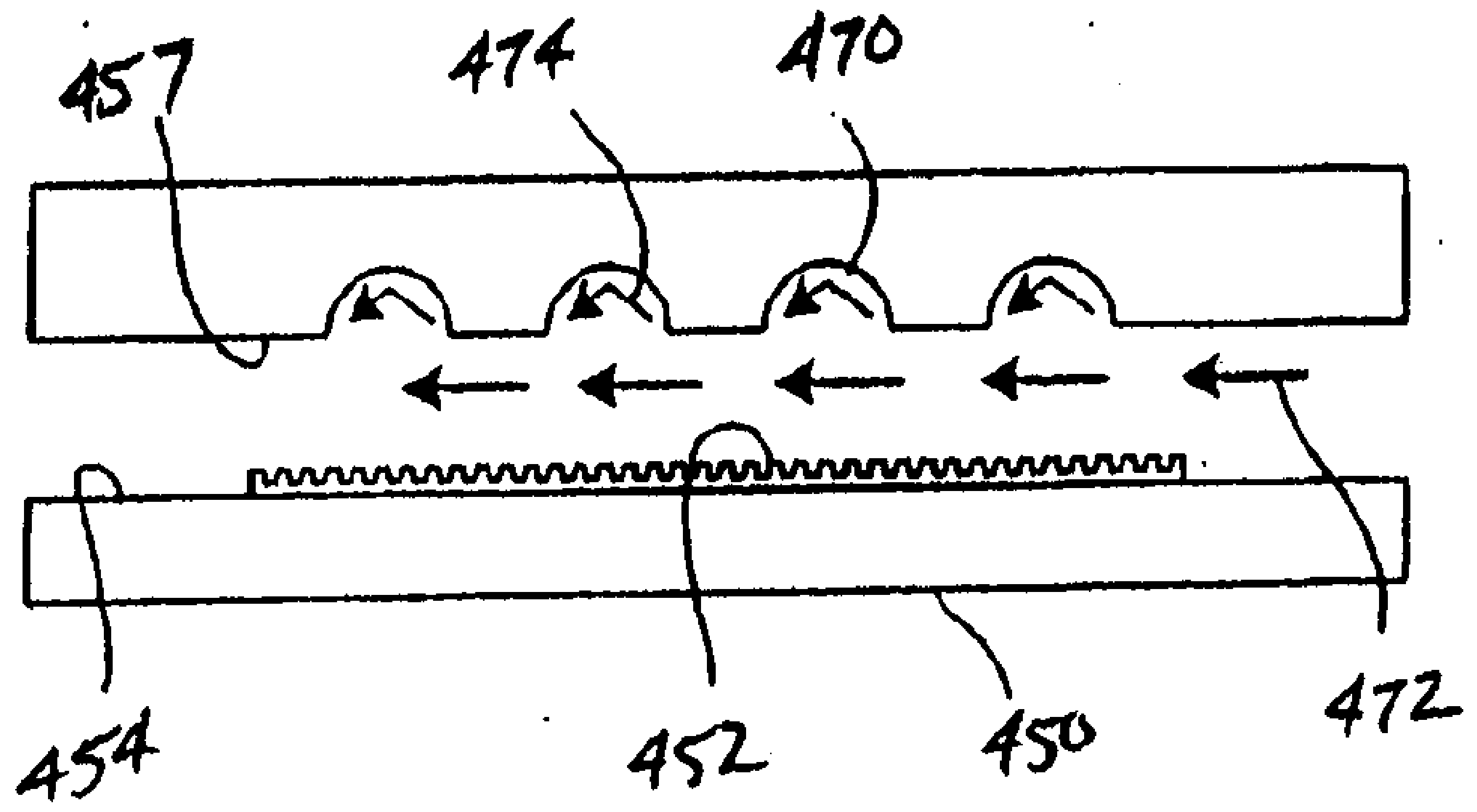


FIG. 24

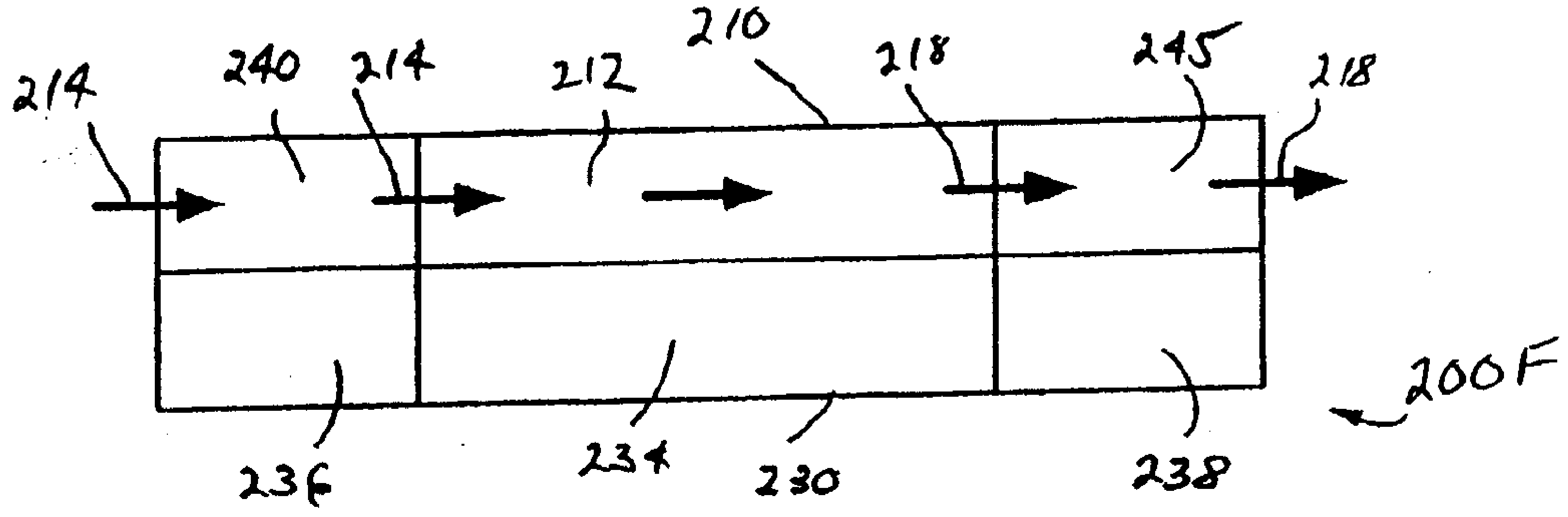


FIG. 25

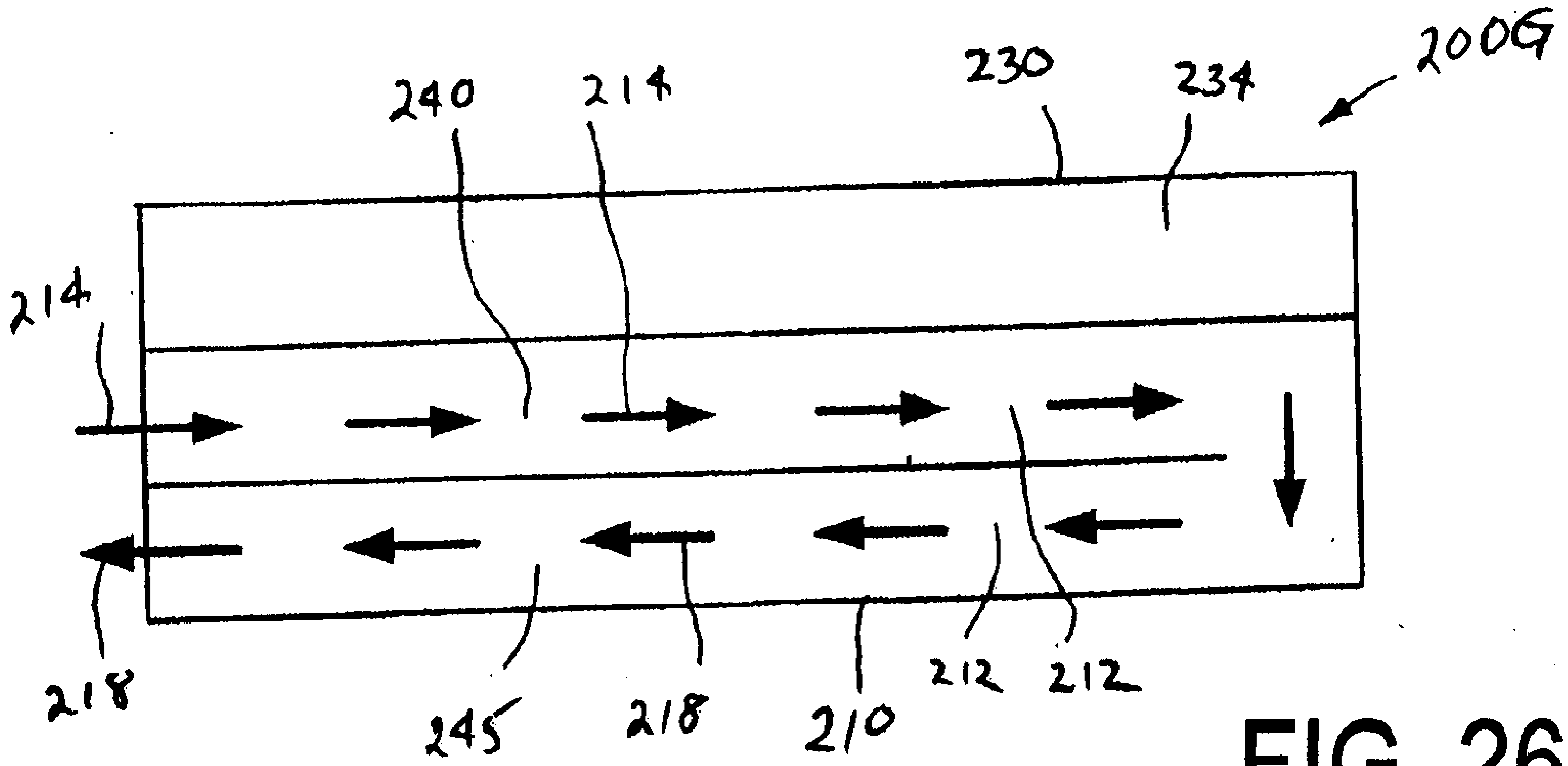


FIG. 26

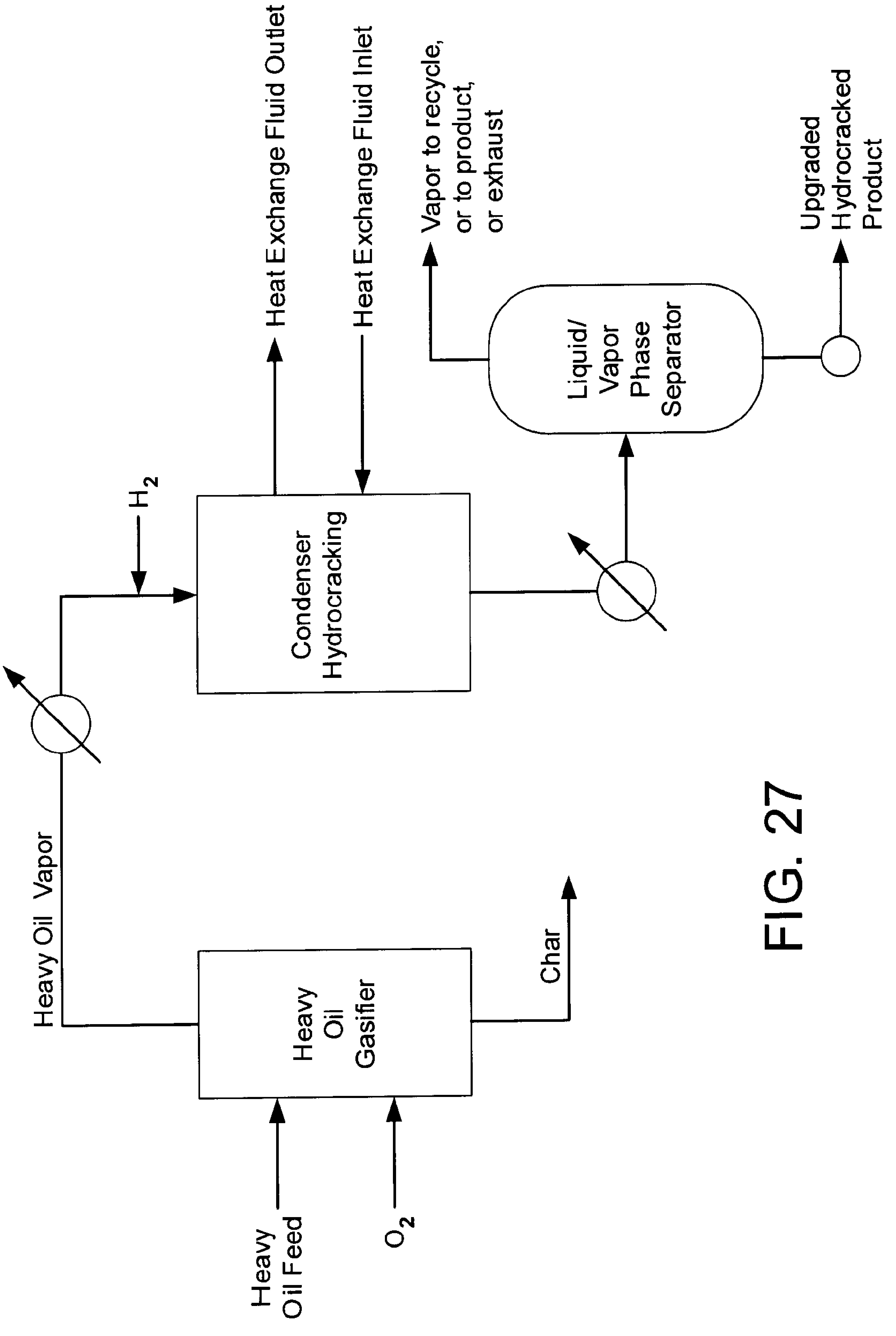

Heavy Oil Feed
O_2
Heavy Oil Gasifier
Char
Heavy Oil Vapor
H_2
Condenser Hydrocracking
Heat Exchange Fluid Outlet
Heat Exchange Fluid Inlet
Liquid/ Vapor Phase Separator
Vapor to recycle, or to product, or exhaust
Upgraded Hydrocracked Product

FIG. 27

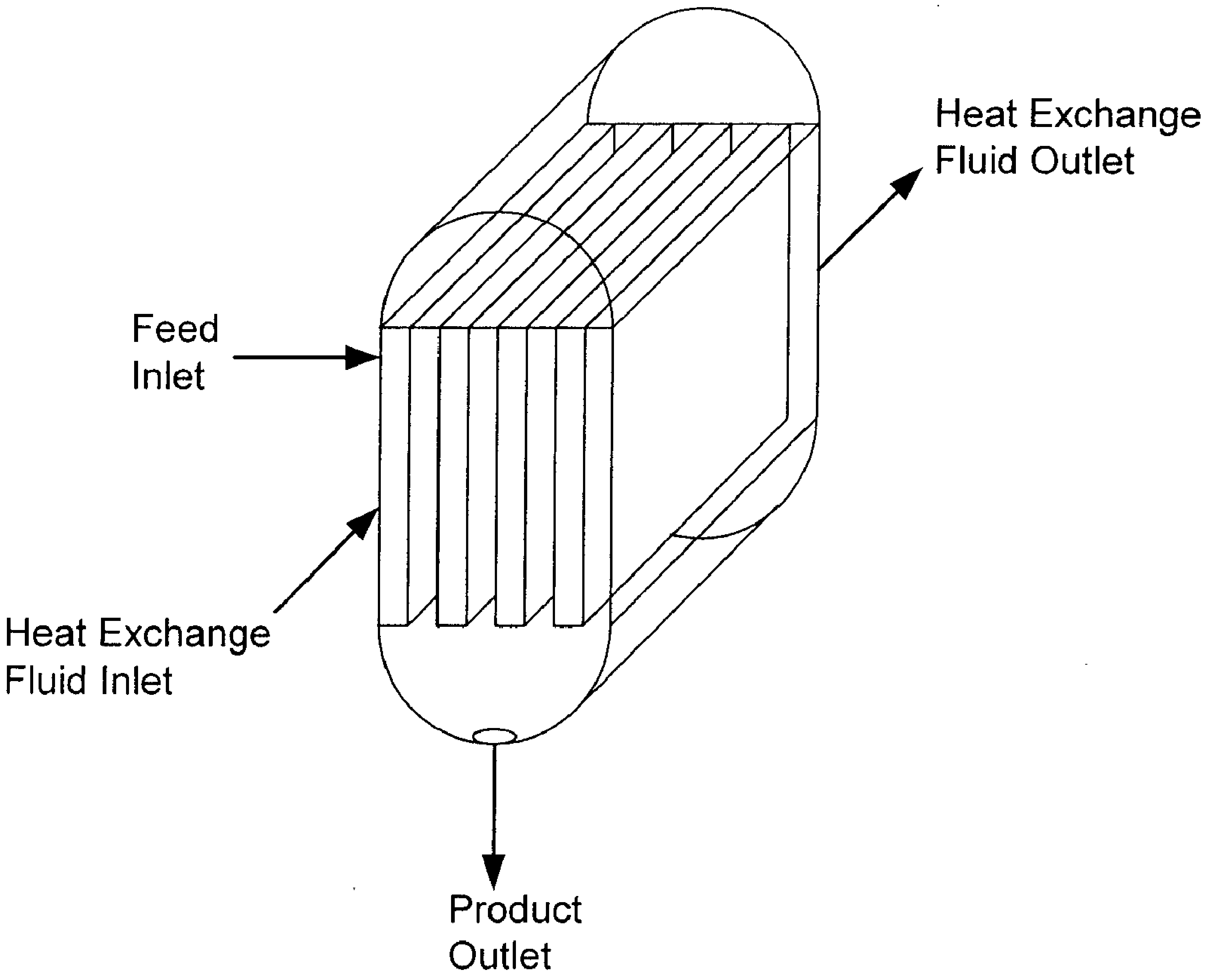

Heat Exchange
Fluid Outlet
Feed
Inlet
Heat Exchange
Fluid Inlet
Product
Outlet

FIG. 28

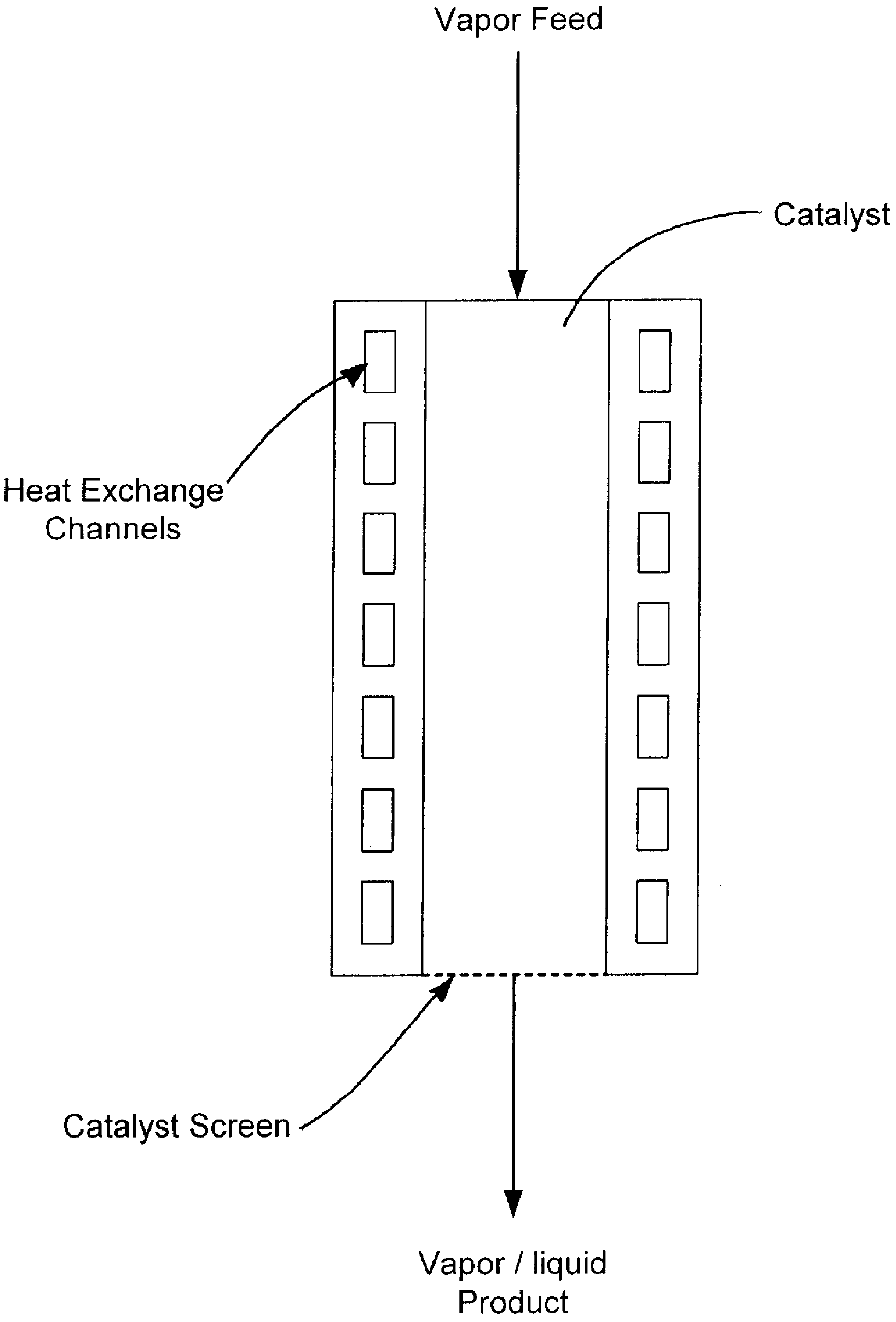

Vapor Feed
Catalyst
Heat Exchange Channels
Catalyst Screen
Vapor / liquid Product

FIG. 29

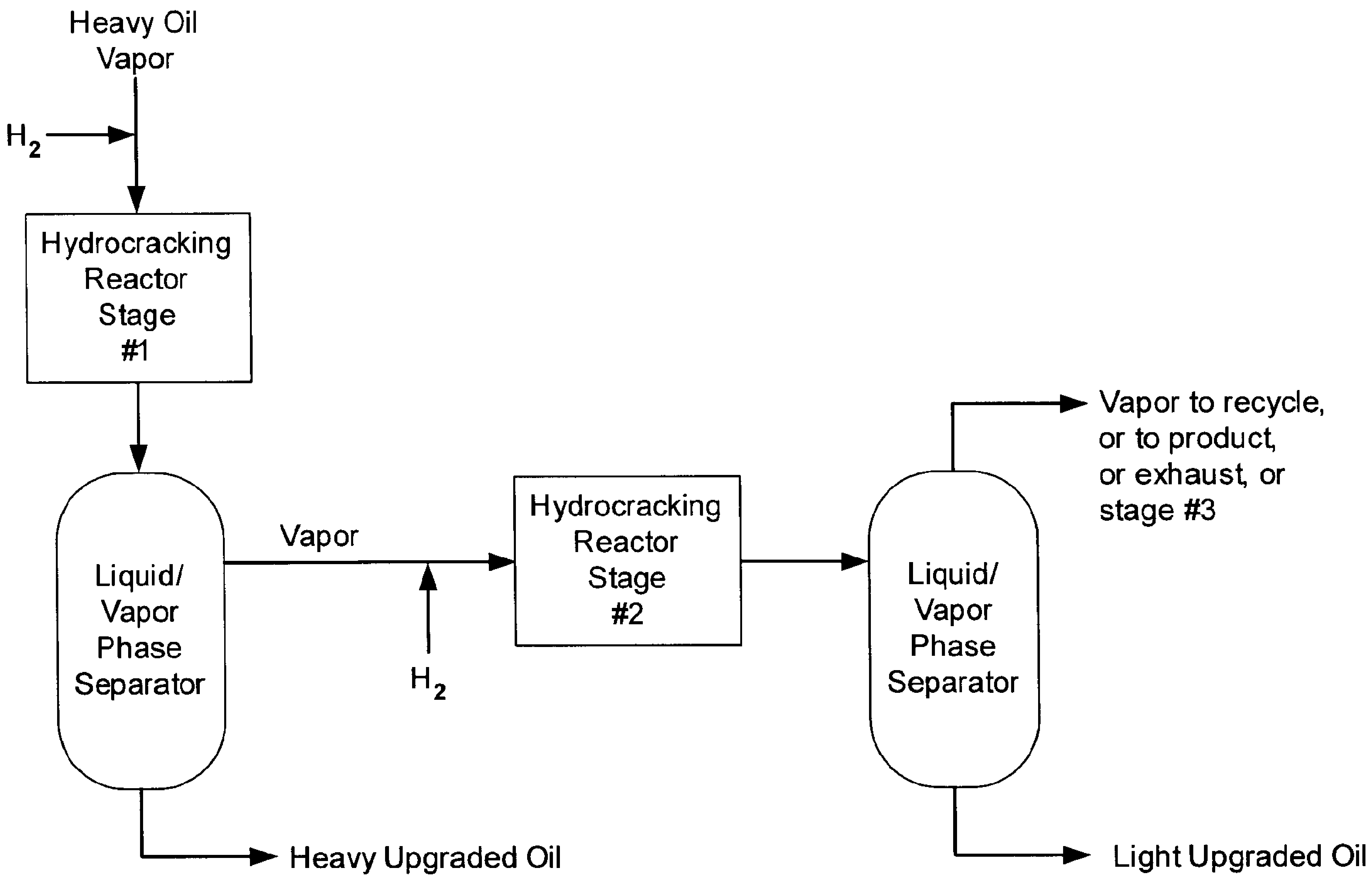

Heavy Oil
Vapor
H_2
Hydrocracking
Reactor
Stage
#1
Liquid/
Vapor
Phase
Separator
Vapor
H_2
Heavy Upgraded Oil
Hydrocracking
Reactor
Stage
#2
Liquid/
Vapor
Phase
Separator
Vapor to recycle,
or to product,
or exhaust, or
stage #3
Light Upgraded Oil

FIG. 30

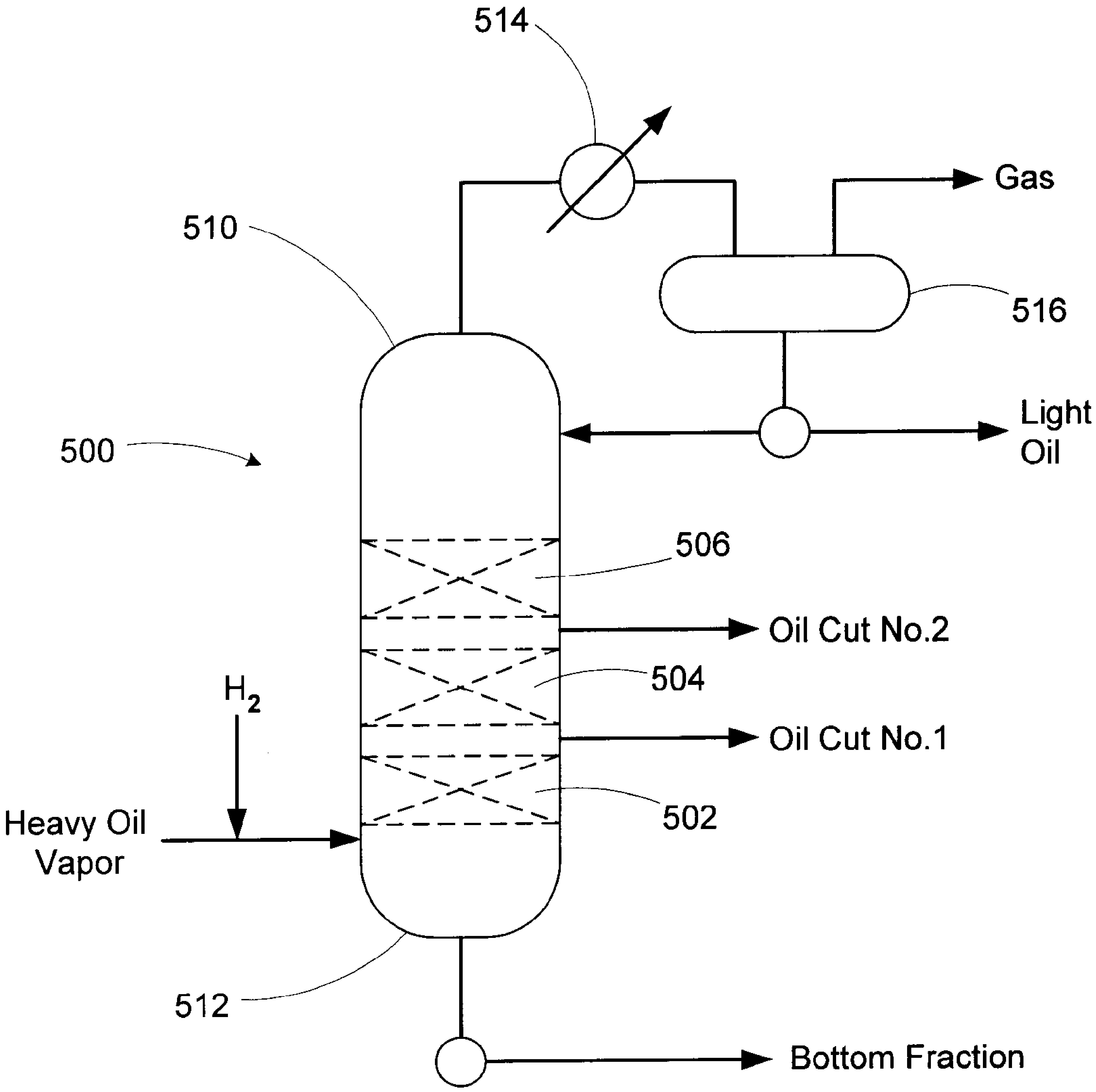

514
510
Gas
516
500
Light Oil
506
Oil Cut No.2
504
H_2
Oil Cut No.1
502
Heavy Oil Vapor
512
Bottom Fraction

FIG. 31

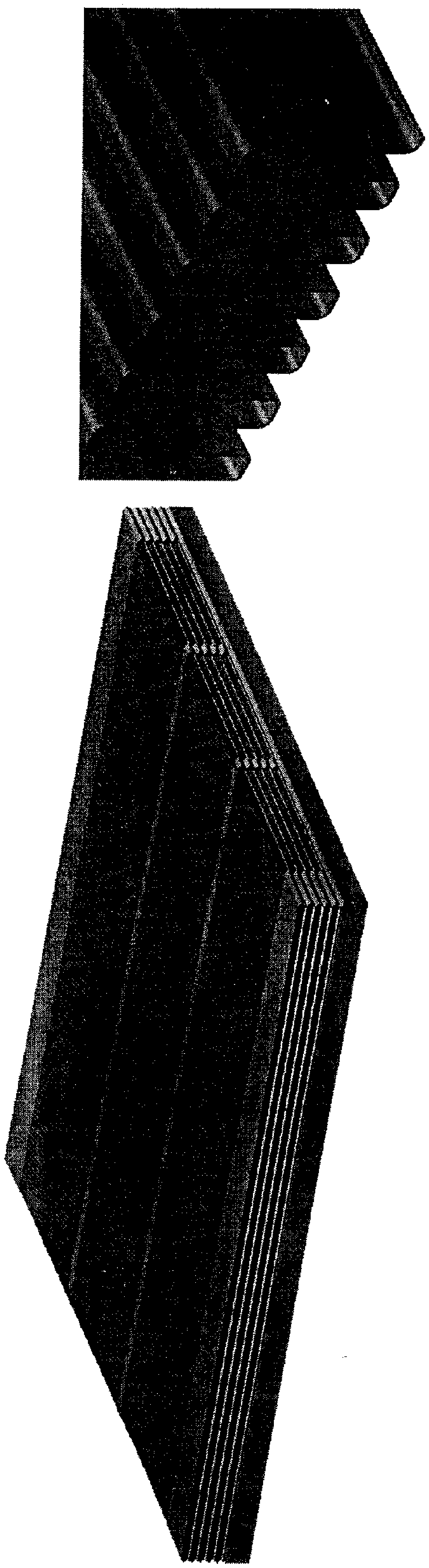


FIG. 32

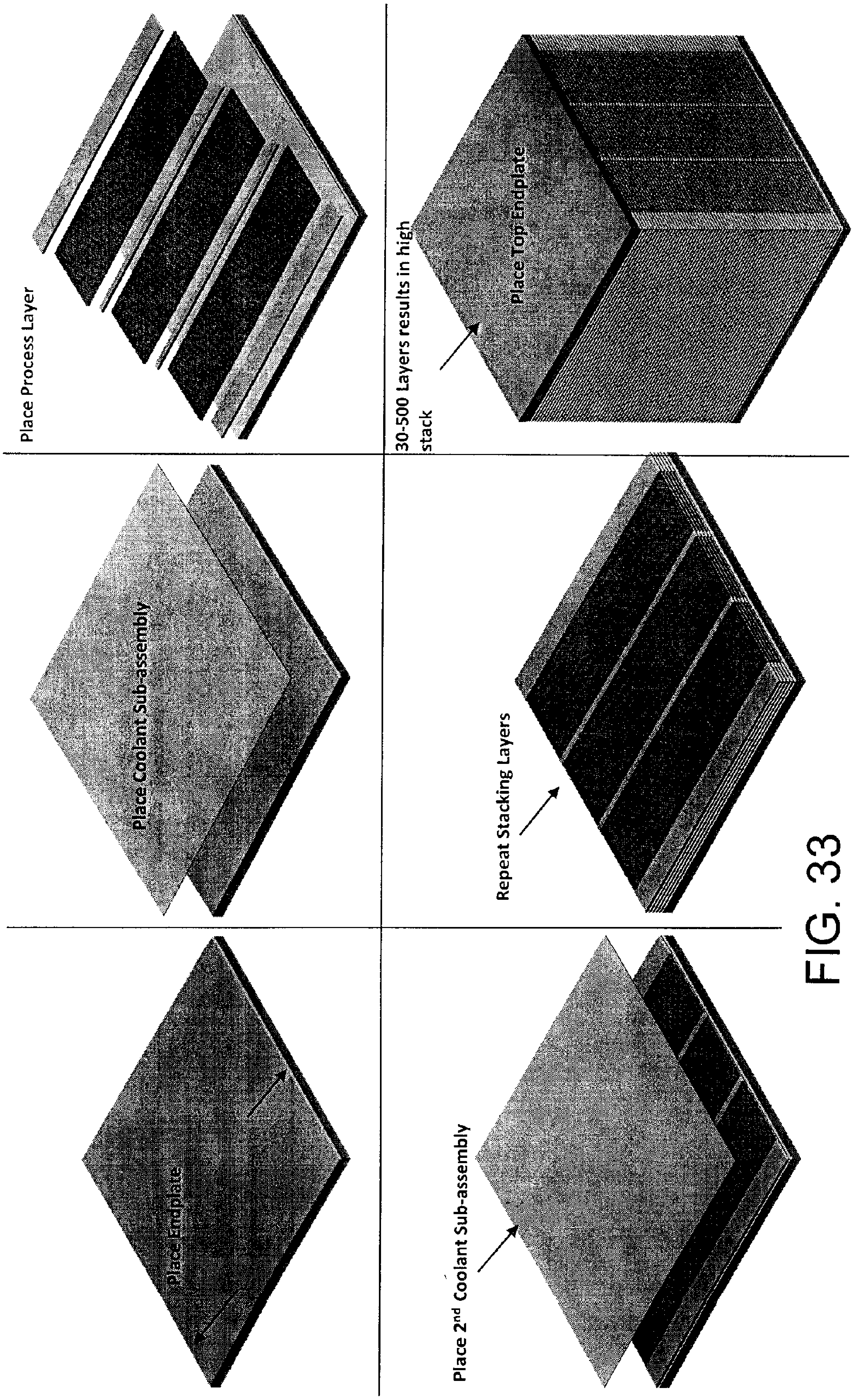

Place Endplate
Place Coolant Sub-assembly
Place Process Layer
Place 2nd Coolant Sub-assembly
Repeat Stacking Layers
30-500 Layers results in high stack
Place Top Endplate

FIG. 33

PROCESS FOR TREATING HEAVY OIL

[0001] This application claims priority under 35 U.S.C. §119(e) to U.S. Provisional Application Ser. No. 61/250,282, filed Oct. 9, 2009, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] This invention relates to a process for treating heavy oil. More particularly, this invention relates to a process for upgrading heavy oil by hydroprocessing the oil using process intensification techniques.

BACKGROUND OF THE INVENTION

[0003] Untreated heavy oils are typically in the form of a dark brown, free-flowing liquids. Unconventional sources of these heavy oils include those made from the gasification, pyrolysis or liquefaction of carbonaceous materials such as coal, shale, tar sand, bitumen, biomass, and the like. These unconventional heavy oil sources are often distributed in locations far from large central processing facilities that are required to upgrade these oils to useful products such as middle distillate fuels, and the like. Additionally many of these oils are unstable in long-term storage and not miscible with conventional hydrocarbon-based fuels, making transportation to central processing facilities difficult or uneconomical.

SUMMARY OF THE INVENTION

[0004] The problem relates to providing a viable process for upgrading heavy oil to produce useful hydrocarbon products such as middle distillate fuels and the like, using equipment that is modular or relatively small in size so that the process can be conducted economically at locations closer to the source of the heavy oil and thus avoid the problems of storage and transportation incurred when using large central processing facilities. It would be advantageous if the equipment could be readily adapted to process the heavy oil at any desired production volume. This invention provides a solution to this problem. With the present invention, heavy oil is upgraded to form useful hydrocarbon products by hydroprocessing the oil using process intensification techniques. Heavy oil in the form of a liquid, vapor or combination thereof may be treated using the inventive process.

[0005] This invention relates to a process, comprising: flowing heavy oil (that is, heavy oil in the form of a liquid, vapor, or combination thereof) and hydrogen (i.e., H_2 or reactant streams containing H_2) in a reactor in contact with a hydroprocessing catalyst under process intensification conditions, the heavy oil comprising heteroatoms (e.g., sulfur, nitrogen, oxygen and/or metals such as Ni, V, and the like); reacting at least some of the heteroatoms with the hydrogen to form one or more heteroatom containing compounds; and hydrocracking the heavy oil to form an upgraded hydrocarbon product. The hydroprocessing catalyst may be a hydrotreating catalyst or a hydrocracking catalyst. The heteroatom containing compounds may be separated from the upgraded hydrocarbon product. In one embodiment of the invention, the reactor comprises a process microchannel, and the heavy oil and hydrogen flow in the process microchannel in contact with the hydroprocessing catalyst and undergo reaction. The process may be conducted in one or more process microchannels or one or more microchannel reactors.

[0006] In one embodiment, the heavy oil comprises water, the process further comprising removing water from the upgraded hydrocarbon product.

[0007] In one embodiment, the heavy oil is reacted in the presence of a hydrotreating catalyst to form an intermediate hydrocarbon product, and then the intermediate hydrocarbon product is reacted in the presence of a hydrocracking catalyst to form the upgraded hydrocarbon product. In one embodiment, the reaction with the hydrotreating catalyst is conducted in a process microchannel and the reaction with the hydrocracking catalyst is conducted in a process microchannel, the hydrotreating catalyst and the hydrocracking catalyst being in the same process microchannel. In one embodiment, the reaction with the hydrotreating catalyst is conducted in a first process microchannel and the reaction with the hydrocracking catalyst is conducted in a second process microchannel. In one embodiment, the reaction with the hydrotreating catalyst is conducted in a first microchannel reactor and the reaction with the hydrocracking catalyst is conducted in a second microchannel reactor.

[0008] In one embodiment, the pressure in the reactor is in the range from about 0.5 to about 25 MPa.

[0009] In one embodiment, the temperature in the reactor is in the range from about 100° C. to about 500° C.

[0010] In one embodiment, ratio of hydrogen to heavy oil in the reactor is in the range from about 10 to about 6000 standard cubic centimeters of hydrogen per cubic centimeter of heavy oil.

[0011] In one embodiment, the heavy oil entering the reactor is in the form of a liquid, a vapor, or a combination of liquid and vapor.

[0012] In one embodiment, the reactor comprises one or more process microchannels, the heavy oil and hydrogen being mixed with each other in the one or more process microchannels.

[0013] In one embodiment, the reactor comprises a process microchannel and the process microchannel is in a microchannel reactor, the microchannel reactor comprising a reactant stream channel adjacent to the process microchannel, the process microchannel and the reactant stream channel having a common wall, and a plurality of openings in the common wall, the process further comprising flowing the pyrolysis oil in the process microchannel and flowing the hydrogen from the reactant stream channel through the openings in the common wall into the process microchannel in contact with the pyrolysis oil.

[0014] In one embodiment, the heavy oil and hydrogen are mixed prior to entering the reactor.

[0015] In one embodiment, the reactor comprises a microchannel reactor comprising a plurality of process microchannels, the microchannel reactor comprising a manifold providing a flow passageway for the heavy oil and hydrogen to flow into the process microchannels.

[0016] In one embodiment, the reactor comprises a microchannel reactor comprising a plurality of the process microchannels, the microchannel reactor comprising a first manifold providing a flow passageway for the heavy oil to flow into the process microchannels, and a second manifold providing a flow passageway for the hydrogen to flow into the process microchannels.

[0017] In one embodiment, heat is transferred from the reactor to a heat exchanger.

[0018] In one embodiment, the reactor comprises a microchannel reactor comprising a plurality of process microchannels, the microchannel reactor further comprising at least one heat exchange channel in thermal contact with the process microchannels, a heat exchange fluid being in the heat exchange channel, and heat is transferred from the process microchannels to the heat exchange fluid in the heat exchange channel. The heat exchange fluid may undergo a phase change in the heat exchange channel. The reactants may flow in the process microchannel in a first direction, and the heat exchange fluid may flow in the heat exchange channel in a second direction, the second direction being cross current relative to the first direction.

[0019] In one embodiment, the reactor comprises a process microchannel and a tailored heat exchange is provided along the length of the process microchannel to maintain a substantially isothermal temperature profile along the length of the process microchannel.

[0020] In one embodiment, the heavy oil entering the reactor comprises heavy oil vapor, the heavy oil vapor being at least partially condensed in the reactor. In this embodiment, the catalyst may be positioned in a distillation column, the distillation column comprising a single stage catalytic distillation hydrocracker. Hydrogen may be mixed with the heavy oil vapor prior to entering the reactor, or the hydrogen and heavy oil may be separately manifolded into the reactor. Further, hydrogen and/or another reactive feed or a non-reactive gas or liquid (i.e., a third fluid) may be fed downstream of the first manifold region. In one embodiment, a second fluid may be used to tailor the reactions or to inhibit unwanted side reactions. The third fluid may be added to reduce coking or the formation of longer chain hydrocarbons. The third fluid, in one embodiment may be steam or an oxygen containing stream. In one embodiment, the third fluid may comprise hydrogen or a hydrogen-containing stream, containing, for example, other carbonaceous matter.

[0021] In one embodiment, the reactor comprises a first stage reactor, the hydroprocessing catalyst comprising a first hydrocracking catalyst, the process also employing a second stage reactor containing a second hydrocracking catalyst, the heavy oil comprising heavy oil vapor, the process comprising: flowing the heavy oil vapor and hydrogen in the first stage reactor in contact with the first hydrocracking catalyst, condensing and hydrocracking the heavy oil vapor to form a first hydrocracked hydrocarbon product comprising a first liquid hydrocarbon product and a first hydrocarbon vapor, and optionally a first aqueous phase product; separating the first hydrocarbon liquid product from the first hydrocarbon vapor, and optionally separating the first gaseous phase product from the first hydrocarbon liquid; flowing the first hydrocarbon vapor and hydrogen in the second stage reactor in contact with the second hydrocracking catalyst, condensing and hydrocracking the first hydrocarbon vapor to form a second hydrocracked hydrocarbon product comprising a second hydrocarbon liquid product and a second hydrocarbon vapor, and optionally a second aqueous phase product; and separating the second hydrocarbon liquid product from the second hydrocarbon vapor, and optionally separating the second aqueous phase product from the second hydrocarbon liquid product. Additional hydroprocessing and/or separation stages may be added.

[0022] In one embodiment, the hydroprocessing is conducted in a catalytic distillation unit (CDU) which contains a hydroprocessing catalyst. The heavy oil and the hydrogen are fed to the CDU. A portion of the light overhead product is condensed and recycled to the CDU. At least two product streams exit the CDU, including at least one product stream which has been converted to an upgraded hyrocarbon product. Optionally, the heavy oil feed to the CDU may comprise heavy oil vapor. Further, the hydrogen for the CDU may be premixed with the heavy oil vapor feed prior to being fed to the CDU. The heavy oil vapor feed may be fed to the CDU below the catalyst, so that the refluxing liquid may be used to wash down entrained solids into the bottom of the CDU to prevent the solids from entering the catalyst and causing fouling or plugging. In this embodiment, the hydroprocessing is integrated in the heavy oil production flowsheet. As the heavy oil is being reacted, it is being upgraded to a more stable, useable product. Further, the heavy oil may be upgraded as it is being condensed, a further integration, so that unstable liquids are not formed.

[0023] In one embodiment, the process comprises a first stage reaction section containing a first hydroprocessing catalyst, the process also employing a second stage reaction section containing a second hydroprocessing catalyst, the first stage reaction section and the second stage reaction section being positioned in a distillation column, the second stage reaction section being positioned above the first stage reaction section, the distillation column having a distillate end and a bottoms end and being equipped with a distillate condenser; the heavy oil comprising heavy oil vapor, the process comprising: flowing the heavy oil vapor and hydrogen in the first stage reaction section toward the distillate end in contact with the first hydroprocessing catalyst, condensing and hydrocracking the pyrolysis oil vapor to form a first hydroprocessed hydrocarbon product comprising a first hydrocarbon liquid product and a first hydrocarbon vapor; separating the first hydrocarbon liquid product from the first hydrocarbon vapor, and flowing the first hydrocarbon liquid product out of the distillation column; flowing the first hydrocarbon vapor and hydrogen, with optional addition of hydrogen, in the second stage reaction section toward the distillate end in contact with the second hydroprocessing catalyst, condensing and hydroprocessing the first hydrocarbon vapor to form a second hydroprocessed hydrocarbon product comprising a second hydrocarbon liquid product and a second hydrocarbon vapor; separating the second hydrocarbon liquid product from the second hydrocarbon vapor, and flowing the second hydrocarbon liquid product out of the distillation column; and condensing at least part of the second hydrocarbon vapor in the distillate condenser to form another hydrocarbon liquid product, a portion of the another hydrocarbon liquid product being refluxed to the distillation column. One or more of the liquid products may subsequently be sent to a phase separation step for removal of immiscible water, if present.

[0024] In one embodiment, the reactor comprises a first stage reactor, the hydroprocessing catalyst comprising a first hydrocracking catalyst, the process also employing a second stage reactor containing a second hydrocracking catalyst, the first stage reactor and the second stage reactor being positioned in a distillation column, the second stage reactor being positioned above and/or downstream of the first stage reactor, the distillation column having a distillate end and a bottoms end and being equipped with a distillate condenser; the heavy oil comprising heavy oil vapor, the process comprising: flowing the heavy oil vapor and hydrogen in the first stage reactor toward the distillate end in contact with the first hydrocracking catalyst, condensing and hydrocracking at least part of the heavy oil vapor to form a first hydrocracked hydrocarbon product comprising a first liquid hydrocarbon oil product and a first hydrocarbon vapor; separating the first liquid hydrocarbon oil product from the first hydrocarbon vapor, and flowing the first liquid hydrocarbon oil product out of the distillation column; flowing the first hydrocarbon vapor and hydrogen in the second stage reactor toward the distillate end in contact with the second hydrocracking catalyst, condensing and hydrocracking at least part of the first hydrocarbon vapor to form a second hydrocracked hydrocarbon product comprising a second liquid hydrocarbon oil product and a second hydrocarbon vapor; separating the second liquid hydrocarbon oil product from the second hydrocarbon vapor, and flowing the second liquid hydrocarbon oil product out of the distillation column; and condensing at least part of the second hydrocarbon vapor in the distillate condenser to provide a liquid reflux back to the distillation column.

[0025] In one embodiment, the hydroprocessing catalyst is positioned in a process microchannel, the hydroprocessing catalyst being in the form of particulate solids.

[0026] In one embodiment, the hydroprocessing catalyst is supported on a structure which comprises a foam, felt, wad, honeycomb, monolith, fin, structured packing, or a combination of two or more thereof.

[0027] In one embodiment, the hydroprocessing catalyst is in the form of a bed of particulate solids positioned in a process microchannel, and additional catalyst is washcoated and/or grown on one or more interior walls of the process microchannel.

[0028] In one embodiment, the hydroprocessing catalyst is a hydrotreating catalyst which comprises Ni, Mo, Co, W, or a combination of two or more thereof.

[0029] In one embodiment, the hydroprocessing catalyst is a hydrocracking catalyst which comprises Pt, Pd, Ni, Co, Mo, W, or a combination of two or more thereof.

[0030] In one embodiment, the upgraded hydrocarbon product comprises a middle distillate oil, a light oil, or a mixture thereof.

[0031] In one embodiment, the reactor comprises a process microchannel, the channel Bond number for the process microchannel being less than about 1.

[0032] In one embodiment, the hydroprocessing catalyst is in a process microchannel, the hydroprocessing catalyst being regenerated in-situ in the process microchannel.

[0033] In one embodiment, the heat exchange fluid is hydrogen or a hydrogen-containing fluid that is preheated from the heat of reaction or internal thermal recuperation before adding to the hydrocarbon reactant. The hydrogen-containing fluid may be combined with the hydrocarbon reactant before the reaction or distributed along the length of the reactor in two or more discrete locations.

[0034] In one embodiment, the inventive process is conducted in a plant facility, the plant facility comprising an integrated process for producing a heavy oil vapor product, the process comprising condensing the heavy oil vapor product, and hydroprocessing the heavy oil vapor product.

[0035] In one embodiment, the process is conducted in a plant facility, the plant facility comprising a plurality of process microchannels, or one or more microchannel reactors containing a plurality of process microchannels, or one or more reactor housing vessels containing one or more microchannel reactors, the hydroprocessing catalyst in one or more process microchannels, microchannel reactors or reactor housing vessels being regenerated while the process is carried out in other process microchannels, microchannel reactors or reactor housing vessels in the plant facility.

[0036] In one embodiment, the heavy oil is derived from the gasification, pyrolysis or liquefaction of coal, shale, tar sand, bitumen, biomass, or a combination of two or more thereof.

[0037] In one embodiment, the heavy oil comprises pyrolysis oil, pyrolysis oil vapor, or a mixture thereof.

[0038] In one embodiment, the heavy oil is formed in a plant, and the reactor is in the plant, the process comprising forming the heavy oil and transporting the heavy oil to the reactor.

[0039] With the inventive process, increased process efficiency may be achieved as a result of relatively high mass and energy transfer rates that can be achieved as a result of conducting the process under process intensification conditions. This may provide for the following advantages when compared to conventional processing:

[0040] significant increases in productivity,

[0041] significant reductions in process footprint for the same throughput,

[0042] increased processing windows and operational flexibility (opportunities to operate at lower pressures and temperatures),

[0043] increased process control (reduced problems with hot spots),

[0044] reduced operating costs,

[0045] reduced energy consumption,

[0046] easy variation in process throughput (by numbering-up scaling approach),

[0047] integration of multiple unit operations in single and movable device systems,

[0048] optimization of catalyst functionality,

[0049] easy implementation of catalyst regeneration schemes.

[0050] These benefits can eliminate cost and distribution issues that often constrain operation, allowing energy to be produced on site, adopting readily available, local and renewable feedstocks that may include agricultural resources, waste and/or other biological materials, as well as coal, shale, tar sand, bitumen, biomass, and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

[0051] In the annexed drawings, like parts and features have like designations.

[0052] FIG. **1** is a schematic illustration of a microchannel that may be used with the inventive process.

[0053] FIGS. **2**A, **2**B and **2**C are illustrations of a microchannel reactor that may be used to conduct the inventive process. This microchannel reactor comprises a plurality of process microchannels, reactant stream channels and heat exchange channels positioned side-by-side. Hydrocarbon reactants (i.e., heavy oil or intermediate hydrocarbon product) as well as the desired upgraded hydrocarbon product flow in the process microchannels. Hydrogen flows into the reactant stream channels and then from the reactant stream channels into the process microchannels where it mixes with the hydrocarbon reactants and undergoes a hydroprocessing reaction. Heat exchange fluid flows in the heat exchange channels. The reactants and product flow in a direction that is cross-current to the flow of the heat exchange fluid. FIG. **2**A shows the microchannel reactor without headers providing for the flow of fluids into and out of the microchannel reactor. FIG. **2**B shows the headers for providing for the flow of fluid into and out of the process microchannels, reactant stream channels and heat exchange channels. FIG. **2**C is an orthographic projection of the reactor shown in FIG. **2**B, with the reactor being positioned in reactor housing vessel.

[0054] FIG. **3** is a flow sheet illustrating the inventive process for hydrotreating and hydrocracking heavy oil to form one or more upgraded hydrocarbon products.

[0055] FIG. **4** is a schematic illustration of two reactor housing vessels which are used in sequence, one being identified as a first stage vessel, the other being identified as a second stage vessel. Each microchannel reactor housing vessel contains a plurality of microchannel reactors. In the first stage vessel, heavy oil is hydrotreated to form an intermediate hydrocarbon product. In the second stage vessel, the intermediate hydrocarbon product from the first stage is hydrocracked to form an upgraded hydrocarbon product.

[0056] FIG. **5** is a schematic illustration of two layers of process microchannels that are positioned in the same microchannel reactor. A layer of heat exchange channels is positioned between the process microchannel layers. In the first layer of process microchannels heavy oil is hydrotreated to form a intermediate hydrocarbon product or hydrotreated product. In the second layer of process microchannels the hydrotreated product from the first layer is hydrocracked to form an upgraded hydrocarbon product or hydrocracked product.

[0057] FIGS. **6** and **7** are schematic illustrations of a microchannel reactor housing vessel which may be used for housing a plurality of the microchannel reactors used with the inventive process. FIG. **7** is a cutaway image of the vessel illustrated in FIG. **6**.

[0058] FIGS. **8-13** are schematic illustrations of repeating units that may be used in the microchannel reactors used with the inventive process.

[0059] FIGS. **14** and **15** are schematic illustrations of surface features that may be used in the microchannels used with the inventive process.

[0060] FIGS. **16-24** are schematic illustrations of catalysts or catalyst support structures that may be used in the microchannels used with the inventive process. FIG. **22**(*b*) is a cross sectional view of FIG. **22**(*a*) taken along line (b)-(b) in FIG. **22**(*a*). FIG. **23**(*b*) is a cross sectional view of FIG. **23**(*a*) taken along line (b)-(b) in FIG. **23**(*a*).

[0061] FIGS. **25** and **26** are schematic illustrations of repeating units that may be used in the microchannel reactors used with the inventive process. Each of these repeating units includes a section for preheating the reactants and a section for quenching the product.

[0062] FIG. **27** is a flow sheet illustrating a process for gasifying heavy oil to form a heavy oil vapor and then hydrocracking the heavy oil vapor using a condenser hydrocracker.

[0063] FIGS. **28** and **29** are schematic illustrations of the condenser hydrocracker shown in FIG. **27**.

[0064] FIG. **30** is a flow sheet illustrating a two-stage process for hydrocracking heavy oil vapor.

[0065] FIG. **31** is a flow sheet illustrating a process for hydrocracking heavy oil vapor utilizing a distillation column.

[0066] FIGS. **32** and **33** illustrate the construction of a microchannel reactor using waveforms.

DETAILED DESCRIPTION OF THE INVENTION

[0067] All ranges and ratio limits disclosed in the specification and claims may be combined in any manner. It is to be understood that unless specifically stated otherwise, references to "a," "an," and/or "the" may include one or more than one, and that reference to an item in the singular may also include the item in the plural. All combinations specified in the claims may be combined in any manner.

[0068] The term "heavy oil" refers to C_5+ hydrocarbons produced by the gasification, liquefaction or pyrolysis of solid carbonaceous materials (e.g., coal, shale, tar sand, bitumen, biomass, and the like). Heavy oils may also comprise crude oil fractions with an initial boiling point of about 250° C. or above. Heavy oils include vacuum gas oils, atmospheric residiuum, vacuum residiuum, light catalytic cracking oil, heavy catalytic cracking oil, and the like. Heavy oils may have polyaromatic concentrations above about 2% by weight and total aromatic concentrations above about 10% by weight. Heavy oils may have heteroatom concentrations above about 2% by weight, the heteroatoms being sulfur, nitrogen, oxygen and/or metal (e.g., Ni, V, and the like).

[0069] The term "pyrolysis oil" refers to a synthetic oil which is extracted from biomass as well as other carbonaceous materials using pyrolysis. Pyrolysis oil has tar-like characteristics and often contains high levels of heteroatoms such as sulfur, nitrogen, oxygen and/or metal (e.g., Ni, V, and the like). Pyrolysis oil may be referred to as pyrolytic oil or bio-oil.

[0070] The term "middle distillate oil" refers to hydrocarbons boiling in the range of about 125° C. to about 375° C. Middle distillate oils include middle distillate fuels such as kerosene, jet fuel, diesel fuel, heating oil, fuel oil, and the like.

[0071] The term "light oil" refers to hydrocarbons boiling in the range of about 20° C. to about 125° C. Light oils may be referred to as light distillates. Examples include liquefied petroleum gas (LPG), gasoline, naphtha, and the like

[0072] The term "biomass" refers to biological material that may be used as fuel. The biological matter may be living or dead. The term biomass may refer to plant matter grown for use as biofuel. The term biomass may include plant or animal matter used for production of fibers, chemicals or heat. Biomass may include biodegradable wastes that can be burnt as fuel. Biomass may comprise plants such as switchgrass, hemp, corn, poplar, willow, sugarcane, oil palm, and the like.

[0073] The term "char" refers to a solid material that remains after gases have been driven out or released from a carbonaceous material. Char may be formed during the combustion of a carbonaceous material.

[0074] The term "tar" refers to a viscous black liquid derived from a carbonaceous material, for example, by pyrolysis.

[0075] The term "process intensification" refers to the miniaturization of unit operations and processes where a smaller compact piece of equipment takes the place of a larger piece of equipment or multiple pieces of equipment, but still provides for the same capacity or mass flow rate as the larger piece of equipment or multiple pieces of equipment. In one embodiment, process intensification may be achieved using catalytic distillation in order to conduct reactions and separations in integrated equipment. In one embodiment, process intensification may be achieved using microchannel process technology where chemical processors are employed that are characterized by parallel arrays of microchannels. Processes are intensified using microchannel process technology by decreasing transfer resistance between process fluids and channel walls. Process intensification allows for use of more active catalysts than conventional processes, greatly increasing the throughput per unit volume. As a result of process intensification, overall system volumes can be reduced by about ten to one hundred fold or more when compared to conventional hardware.

[0076] The term "process intensification conditions" refers to a process conducted in a reactor where as a result of enhanced mass and/or energy transfer the volume of the reactor is reduced by at least about 2 fold, or at least about 10 fold, or at least about 50 fold, or at least about 100 fold, as compared to a conventional reactor and yet the throughput of product in the reactor is the same or greater than the throughput of product in the conventional reactor.

[0077] The term "hydroprocessing" process refers to a hydrocracking process or a hydrotreating process.

[0078] The term "hydrotreating process" refers to a process wherein heteroatoms bonded to one or more hydrocarbon compounds are reacted with hydrogen to form heteroatom containing compounds. The heteroatom containing compounds may then be separated from the hydrocarbon compounds. The heteroatoms may include sulfur, nitrogen, oxygen, and/or metals (e.g., Ni, V, and the like).

[0079] The term "hydrocracking" process refers to a process wherein hydrocarbon molecules are split into smaller molecules. For example, a C_{1-2} alkane may be hydrocracked to form a C_7 alkane and a C_5 alkane. The hydrocracked products may be isomerized. The hydrocracked products may comprise straight chain hydrocarbons, branched chain hydrocarbons (e.g., isoparaffins) and/or ring compounds.

[0080] The term "hydrocarbon" refers to purely hydrocarbon compounds; that is, aliphatic compounds, (e.g., alkane, alkene or alkyne), alicyclic compounds (e.g., cycloalkane, cycloalkylene), aromatic compounds, aliphatic- and alicyclic-substituted aromatic compounds, aromatic-substituted aliphatic compounds, aromatic-substituted alicyclic compounds, and the like. The term "hydrocarbon" also refers to substituted hydrocarbon compounds; that is, hydrocarbon compounds containing non-hydrocarbon substituents. Examples of the non-hydrocarbon substituents may include hydroxyl, acyl, nitro, etc. The term "hydrocarbon" also refers to hetero substituted hydrocarbon compounds; that is, hydrocarbon compounds which contain atoms other than carbon in a chain or ring otherwise containing carbon atoms. The heteroatoms may include, for example, nitrogen, oxygen, sulfur and/or metals (e.g., Ni, V, and the like).

[0081] The term "microchannel" refers to a channel having at least one internal dimension of height or width of up to about 10 millimeters (mm), and in one embodiment up to about 5 mm, and in one embodiment up to about 2 mm. An example of a microchannel that may be used with the inventive process is illustrated in FIG. **1**. Referring to FIG. **1**, microchannel **10** has a height (h), width (w) and length (l). Fluid flows through the microchannel **10** in the direction indicated by arrows **12** and **14**. Both the height (h) and width (w) are perpendicular to the bulk flow direction of the flow of fluid in the microchannel **10**. The microchannel may comprise at least one inlet and at least one outlet wherein the at least one inlet is distinct from the at least one outlet. The microchannel may not be merely an orifice. The microchannel may not be merely a channel through a zeolite ora mesoporous material. The length of the microchannel may be at least about two times the height or width, and in one embodiment at least about five times the height or width, and in one embodiment at least about ten times the height or width. The height or width may be referred to as the gap between opposed internal walls of the microchannel. The internal height or width of the microchannel may be in the range of about 0.05 to about 10 mm, and in one embodiment from about 0.05 to about 5 mm, and in one embodiment from about 0.05 to about 2 mm, and in one embodiment from about 0.05 to about 1.5 mm, and in one embodiment from about 0.05 to about 1 mm, and in one embodiment from about 0.05 to about 0.75 mm, and in one embodiment from about 0.05 to about 0.5 mm. The other internal dimension of height or width may be of any dimension, for example, up to about 3 meters, and in one embodiment about 0.01 to about 3 meters, and in one embodiment about 0.1 to about 3 meters. The length of the microchannel may be of any dimension, for example, up to about 10 meters, and in one embodiment from about 0.5 to about 10 meters, and in one embodiment from about 0.05 to about 6 meters, and in one embodiment from about 0.05 to about 3 meters, and in one embodiment about 0.05 to about 2 meters, and in one embodiment from 0.05 to about 1.5 meters, and in one embodiment from about 0.1 to about 0.7 meter. The microchannel may have a cross section having any shape, for example, a square, rectangle, circle, semi-circle, trapezoid, etc. The shape and/or size of the cross section of the microchannel may vary over its length. For example, the height or width may taper from a relatively large dimension to a relatively small dimension, or vice versa, over the length of the microchannel.

[0082] The term "process microchannel" refers to a microchannel wherein a process is conducted. The process may be a hydrocracking or hydrotreating process.

[0083] The term "microchannel reactor" refers to an apparatus comprising one or more process microchannels wherein a reaction process is conducted. The process may be a hydrocracking process or a hydrotreating process. When two or more process microchannels are used, the process microchannels may be operated in parallel. The microchannel reactor may include a header or manifold assembly for providing for the flow of reactants into the one or more process microchannels, and a footer or manifold assembly providing for the flow of product out of the one or more process microchannels. The microchannel reactor may further comprise one or more heat exchange channels adjacent to and/or in thermal contact with the one or more process microchannels. The heat exchange channels may provide heating and/or cooling for the fluids in the process microchannels. The heat exchange channels may be microchannels. The microchannel reactor may include a header or manifold assembly for providing for the flow of heat exchange fluid into the heat exchange channels, and a footer or manifold assembly providing for the flow of heat exchange fluid out of the heat exchange channels.

[0084] The term "conventional reactor" refers to a reactor that is not a microchannel reactor.

[0085] The term "microchannel processing unit" refers to an apparatus comprising one or more process microchannels wherein a process is conducted. The process may be a reaction process or it may be any other unit operation wherein one or more fluids are treated.

[0086] The term "volume" with respect to volume within a process microchannel includes all volume in the process microchannel a process fluid may flow through or flow by. This volume may include volume within surface features that may be positioned in the process microchannel and adapted for the flow of fluid in a flow-through manner or in a flow-by manner.

[0087] The term "adjacent" when referring to the position of one channel relative to the position of another channel means directly adjacent such that a wall or walls separate the two channels. In one embodiment, the two channels may have a common wall. The common wall may vary in thickness. However, "adjacent" channels may not be separated by an intervening channel that may interfere with heat transfer between the channels. One channel may be adjacent to another channel over only part of the another channel. For example, a process microchannel may be longer than and extend beyond one or more adjacent heat exchange channels.

[0088] The term "thermal contact" refers to two bodies, for example, two channels, that may or may not be in physical contact with each other or adjacent to each other but still exchange heat with each other. One body in thermal contact with another body may heat or cool the other body.

[0089] The term "fluid" refers to a gas, a liquid, a mixture of a gas and a liquid, or a gas or a liquid containing dispersed solids, liquid droplets and/or gaseous bubbles. The droplets and/or bubbles may be irregularly or regularly shaped and may be of similar or different sizes.

[0090] The terms "gas" and "vapor" have the same meaning and are sometimes used interchangeably.

[0091] The term "residence time" or "average residence time" refers to the internal volume of a space within a channel occupied by a fluid flowing in the space divided by the average volumetric flow rate for the fluid flowing in the space at the temperature and pressure being used.

[0092] The terms "upstream" and "downstream" refer to positions within a reactor or a channel (e.g., a process microchannel) or in a process or process flow sheet that is relative to the direction of flow of a fluid in the reactor, channel, process or process flow sheet. For example, a position within a reactor or channel or process or process flow sheet not yet reached by a portion of a fluid stream flowing toward that position would be downstream of that portion of the fluid stream. A position within the reactor or channel or a process or process flow sheet already passed by a portion of a fluid stream flowing away from that position would be upstream of that portion of the fluid stream. The terms "upstream" and "downstream" do not necessarily refer to a vertical position since the reactor or channels used herein may be oriented horizontally, vertically or at an inclined angle.

[0093] The term "shim" refers to a planar or substantially planar sheet or plate. The thickness of the shim may be the smallest dimension of the shim and may be up to about 4 mm, and in one embodiment in the range from about 0.05 to about 2 mm, and in one embodiment in the range of about 0.05 to about 1 mm, and in one embodiment in the range from about 0.05 to about 0.5 mm. The shim may have any length and width. Process microchannels and/or heat exchange channels may be positioned on or in a shim.

[0094] The term "surface feature" refers to a depression in a channel wall and/or internal channel structure (e.g., fin) and/or a projection from a channel wall and/or internal channel structure that disrupts flow within the channel. Examples of surface feature designs that may be used are illustrated in FIGS. **14**, **15** and **24**. The surface features may be in the form of circles, spheres, hemispheres, frustrums, oblongs, squares, rectangles, angled rectangles, checks, chevrons, vanes, air foils, wavy shapes, and the like. Combinations of two or more of the foregoing may be used. The surface features may contain subfeatures where the major walls of the surface features further contain smaller surface features that may take the form of notches, waves, indents, holes, burrs, checks, scallops, and the like. The surface features may have a depth, a width, and a length. The surface features may be formed on or in one or more of the interior walls of the process microchannels and/or heat exchange channels used in accordance with the inventive process. The surface features may be referred to as passive surface features or passive mixing features. The surface features may be used to disrupt flow (for example, disrupt laminar flow streamlines) and create advective flow at an angle to the bulk flow direction.

[0095] The term "waveform" refers to a contiguous piece of thermally conductive material that is transformed from a planar object to a three-dimensional object. The waveform may be used to form one or more microchannels. The waveform may comprise a right angled corrugated insert which may be sandwiched between opposed planar sheets or shims. In this manner one or more microchannels may be defined on three sides by the waveform and on the fourth side by one of the planar sheets or shims. The waveform may be made of any of the thermally conductive materials disclosed herein as being useful for making the microchannel reactor. These may include copper, aluminum, stainless steel, and the like. The thermal conductivity of the waveform may be about 1 W/m-K or higher. The waveform may comprise a composite material which includes two or more layers, where the thermal conductivity of the two or more materials may differ by about 20% or more. The waveform may comprise three layered constructions wherein, for example, an aluminum or copper layer may be positioned between two stainless steel layers. A thermally conductive waveform may be used to remove the heat of reaction while retaining an inert surface for contacting the catalyst. A composite waveform may be used for any exothermic reaction, including a hydroprocessing reactions.

[0096] The term "bulk flow direction" refers to the vector through which fluid may travel in an open path in a channel.

[0097] The term "bulk flow region" refers to open areas within a channel (e.g., a process microchannel). A contiguous bulk flow region may allow rapid fluid flow through a channel without significant pressure drop. In one embodiment, the flow in the bulk flow region may be laminar. A bulk flow region may comprise at least about 5% of the internal volume and/or cross-sectional area of a microchannel, and in one embodiment from about 5% to about 100%, and in one embodiment from about 5% to about 99%, and in one embodiment about 5% to about 95%, and in one embodiment from about 5% to about 90%, and in one embodiment from about 30% to about 80% of the internal volume and/or cross-sectional area of the microchannel.

[0098] The term "open channel" refers to a channel (e.g., a microchannel) with a gap of at least about 0.01 mm that extends all the way through the channel such that fluid may flow through the channel without encountering a barrier to flow. The gap may have an internal dimension normal to the flow of fluid through the microchannel in the range from about 0.01 to about 10 mm, and in one embodiment from about 0.01 to about 5 mm, and in one embodiment from about 0.01 to about 2 mm, and in one embodiment from about 0.01 to about 1 mm.

[0099] The term "cross-sectional area" of a channel (e.g., process microchannel) refers to an area measured perpendicular to the direction of the bulk flow of fluid in the channel and may include all areas within the channel including any surface features that may be present, but does not include the channel walls. For channels that curve along their length, the cross-sectional area may be measured perpendicular to the direction of bulk flow at a selected point along a line that parallels the length and is at the center (by area) of the channel. Dimensions of height and width may be measured from one interior channel wall to the opposite interior channel wall. These dimensions may be average values that account for variations caused by surface features, surface roughness, and the like.

[0100] The term "open cross-sectional area" of a channel (e.g., process microchannel) refers to an area open for bulk fluid flow in a channel measured perpendicular to the direction of the bulk flow of fluid flow in the channel. The open cross-sectional area may not include internal obstructions such as surface features and the like which may be present.

[0101] The term "superficial velocity" for the velocity of a fluid flowing in a channel refers to the velocity resulting from dividing the volumetric flow rate of the fluid at the inlet temperature and pressure of the channel divided by the cross-sectional area of the channel.

[0102] The term "free stream velocity" refers to the velocity of a stream flowing in a channel at a sufficient distance from the sidewall of the channel such that the velocity is at a maximum value. The velocity of a stream flowing in a channel is zero at the sidewall if a no slip boundary condition is applicable, but increases as the distance from the sidewall increases until a constant value is achieved. This constant value is the "free stream velocity."

[0103] The term "process fluid" refers to reactants, product, diluent and/or other fluid that enters, flows in and/or flows out of a process microchannel.

[0104] The term "reactants" refers to hydrocarbon reactants and hydrogen when used with reference to the inventive hydroprocessing process.

[0105] The term "reaction zone" refers to the space within a microchannel wherein a chemical reaction occurs or wherein a chemical conversion of at least one species occurs. The reaction zone may contain one or more catalysts.

[0106] The term "graded catalyst" refers to a catalyst with one or more gradients of catalytic activity. The graded catalyst may have a varying concentration or surface area of a catalytically active metal. The graded catalyst may have a varying turnover rate of catalytically active sites. The graded catalyst may have physical properties and/or a form that varies as a function of distance. For example, the graded catalyst may have an active metal concentration that is relatively low at the entrance to a process microchannel and increases to a higher concentration near the exit of the process microchannel, or vice versa; or a lower concentration of catalytically active metal nearer the center (i.e., midpoint) of a process microchannel and a higher concentration nearer a process microchannel wall, or vice versa, etc. The thermal conductivity of a graded catalyst may vary from one location to another within a process microchannel. The surface area of a graded catalyst may be varied by varying size of catalytically active metal sites on a constant surface area support, or by varying the surface area of the support such as by varying support type or particle size. A graded catalyst may have a porous support where the surface area to volume ratio of the support is higher or lower in different parts of the process microchannel followed by the application of the same catalyst coating everywhere. A combination of two or more of the preceding embodiments may be used. The graded catalyst may have a single catalytic component or multiple catalytic components (for example, a bimetallic or trimetallic catalyst). The graded catalyst may change its properties and/or composition gradually as a function of distance from one location to another within a process microchannel. The graded catalyst may comprise rimmed particles that have "eggshell" distributions of catalytically active metal within each particle. The graded catalyst may be graded in the axial direction along the length of a process microchannel or in the lateral direction. The graded catalyst may have different catalyst compositions, different loadings and/or numbers of active catalytic sites that may vary from one position to another position within a process microchannel. The number of catalytically active sites may be changed by altering the porosity of the catalyst structure. This may be accomplished using a washcoating process that deposits varying amounts of catalytic material. An example may be the use of different porous catalyst thicknesses along the process microchannel length, whereby a thicker porous structure may be left where more activity is required. A change in porosity for a fixed or variable porous catalyst thickness may also be used. A first pore size may be used adjacent to an open area or gap for flow and at least one second pore size may be used adjacent to the process microchannel wall.

[0107] The term "volume of catalyst" or "cubic meter of catalyst" refers to the volume of the catalytically active portion of a catalyst. For a bed of particulate solids the terms "volume of catalyst" or "cubic meter of catalyst" may refer to the volume of the space in which the active catalyst is loaded.

[0108] The term "heat exchange channel" refers to a channel having a heat exchange fluid in it that gives off heat and/or absorbs heat. The heat exchange channel may absorb heat from or give off heat to an adjacent channel (e.g., process microchannel) and/or one or more channels in thermal contact with the heat exchange channel. The heat exchange channel may absorb heat from or give off heat to channels that are adjacent to each other but not adjacent to the heat exchange channel. In one embodiment, one, two, three or more channels may be adjacent to each other and positioned between two heat exchange channels.

[0109] The term "heat transfer wall" refers to a common wall between a process microchannel and an adjacent heat exchange channel where heat transfers from one channel to the other through the common wall.

[0110] The term "heat exchange fluid" refers to a fluid that may give off heat and/or absorb heat.

[0111] The term "heat exchange medium" refers to a substance or device that absorbs heat or gives off heat and may be used to cool or heat another substance or device. The another substance or device may be, for example, a channel that is adjacent to or in thermal contact with the heat exchange medium. An example of a heat exchange medium would be a heat exchange fluid in a heat exchange channel.

[0112] The term "conversion of reactant" refers to the reactant mole change between a fluid flowing into a microchannel reactor and a fluid flowing out of the microchannel reactor divided by the moles of reactant in the fluid flowing into the microchannel reactor.

[0113] The term "converted basis yield" or "CBY" is used herein with respect to a hydrocracking process to refer to the mass of product with 10 to 22 carbon atoms, minus the mass of feed with 10 to 22 carbon atoms, divided by the mass of feed with more than 22 carbon atoms. Converted basis yield or CBY may be represented by the expression:

$$\mathrm{CBY}=[(\text{Mass } C_{10}\text{-}C_{22}\text{ Product})-(\text{Mass } C_{10}\text{-}C_{22}\text{ Feed})]\div(\text{Mass } C_{22}^{+}\text{Feed})$$

[0114] The term "total basis yield" or "TBY" is used herein with respect to hydrocracking to refer to the mass of product with 10 to 22 carbon atoms minus the mass of feed with 10 to 22 carbon atoms divided by the mass of feed. Total base yield or TBY may be represented by the expression:

$$TBY=[(\text{Mass } C_{10}\text{-}C_{22} \text{ Product})-(\text{Mass } C_{10}\text{-}C_{22} \text{ Feed})]+(\text{Mass Feed})$$

[0115] The term "selectivity" is used herein with respect to a hydrocracking process to refer to the mass of product with 10 to 22 carbon atoms minus the mass of feed with the 10 to 22 carbon atoms divided by the mass of feed with more than 22 carbon atoms minus the mass of product with more than 22 carbon atoms. Selectivity may be represented by the expression:

$$\text{Selectivity}=[(\text{Mass } C_{10}\text{-}C_{22} \text{ Product})-(\text{Mass } C_{10}\text{-}C_{22} \text{ Feed})]+[(\text{Mass } C_{22}{}^{+}\text{Feed})-(\text{Mass } C_{22}{}^{+}\text{Product})]$$

[0116] The term "cycle" is used herein to refer to a single pass of the reactants through a process microchannel.

[0117] The term "solid substrate" may refer to a granular particle with a mean diameter of less than about 2 mm, and in one embodiment less than about 1 mm, and in one embodiment in the range from about 0.01 to about 2 mm, and in one embodiment in the range from about 0.05 to about 2 mm, and in one embodiment in the range from about 0.05 to about 1.5 mm, and in one embodiment in the range from about 0.05 to about 1 mm, and in one embodiment in the range from about 0.05 mm to about 0.5 mm. The solid substrate may comprise a continuous porous medium that substantially spans the gap of a microchannel. The porous medium may be in the form of a foam, wad, strands, and/or monolith with either regular or irregular shaped pores. The pores may be interconnected. The porous medium may comprise a waveform with a porosity throughout the thickness of the waveform of from about 5% to about 95% or with a porosity for a portion of the thickness of the waveform ranging from about 5% to about 95%. The solid substrate may be housed continuously throughout the entire length of a process microchannel or part of the length of a process microchannel. The solid substrate may be housed in several regions along the length of a process microchannel. The width and/or height of the process microchannel within the one or more regions may vary along the length of the process microchannel.

[0118] The term "quench" refers to a process by which a chemical reaction is terminated using a rapid reduction in temperature of the reaction mixture, a rapid introduction of a reactant or non-reactant fluid into the reaction mixture, or flowing the reaction mixture through a restricted opening or passageway having a dimension at or below the quench diameter.

[0119] The term "quench diameter" refers to the internal dimension (e.g., height, width, diameter) of an opening or passageway for a reaction mixture to flow through below which the reaction terminates.

[0120] The term "ash" refers to the solid residue that remains after a carbonaceous material is burned.

[0121] The term "mm" may refer to millimeter. The term "nm" may refer to nanometer. The term "ms" may refer to millisecond. The term "μs" may refer to microsecond. The term "μm" may refer to micron or micrometer. The terms "micron" and "micrometer" have the same meaning and may be used interchangeably. The term m/s may refer to meters per second. Unless otherwise indicated, all pressures are expressed in terms of absolute pressure.

[0122] The inventive process involves reacting heavy oil and hydrogen in the presence of a hydroprocessing catalyst in a reactor under process intensification conditions to form an upgraded hydrocarbon product. The reactor may be in the form of one or more process microchannels, or in the form of a microchannel reactor containing a plurality of process microchannels. The hydroprocessing catalyst may be a hydrotreating catalyst or a hydrocracking catalyst.

[0123] Heavy oil typically contains heteroatoms (e.g., nitrogen, sulfur, oxygen and or metals such as Ni, V, and the like) and the hydroprocessing process may be used to eliminate or reduce the level of heteroatoms in the product produced by the process. The hydrogen reacts with the heteroatoms to produce heteroatom containing compounds which may then be separated from the hydroprocessed hydrocarbon product. The process may be used to reduce the concentration of heteroatoms by to at least about 50% by weight, or at least about 70% by weight, or at least about 90% by weight, or at least about 95% by weight, or at least about 99% by weight. Surprisingly, when the process is conducted under process intensification conditions and the hydroprocessing catalyst is a hydrotreating catalyst, the process also hydrocracks the oil to form a hydrotreated hydrocarbon product which may comprise more useful upgraded hydrocarbon products (e.g., middle distillate oil, light oil, or a mixture thereof).

[0124] In one embodiment, the hydrotreated hydrocarbon product may be further processed in a reactor under process intensification conditions, such as in one or more process microchannels, or in one or more microchannel reactors, to provide further hydrocracking and upgrading of the hydrotreated hydrocarbon product. In this embodiment, the hydrotreated hydrocarbon product, which may be referred to as an intermediate hydrocarbon product, reacts with hydrogen in the presence of a hydrocracking catalyst to further hydrocrack the hydrotreated hydrocarbon product and form the desired upgraded hydrocarbon product. The hydrotreating and hydrocracking processes may be conducted in the same process microchannel or microchannel reactor, or in different process microchannels or microchannel reactors.

[0125] The hydrotreating reaction requires reaction between hydrogen and heavy oil in the presence of a hydrotreating catalyst. As indicated above, the product produced by the hydrotreating reaction can be further hydrocracked to form an upgraded hydrocarbon product. Each of these reactions may be referred to as hydroprocessing reactions.

[0126] In one embodiment of the invention, the overall process for converting a heavy oil source (e.g., coal, shale, tar sand, bitumen, biomass, and the like) to an upgraded hydrocarbon product is illustrated in FIG. **3**. Referring to FIG. **3**, the heavy oil source is converted to heavy oil using gasification, pyrolysis or liquefaction process. The gasification, pyrolysis or liquefaction processes may be conducted using conventional techniques or they may be conducted in a microchannel reactor. Gases and char may be separated from heavy oil which can be subjected to an optional cracking process prior to hydroprocessing in accordance with the inventive process. The optional cracking process may be a thermal cracking and/or catalytic cracking process. This cracking process may be conducted using microchannel process technology or conventional process technology.

[0127] The heavy oil is advanced to a Stage 1 microchannel reactor wherein the heavy oil undergoes hydrotreating. In the hydrotreating process the heavy oil is reacted with hydrogen in the presence of a hydrotreating catalyst under process intensification conditions. The heavy oil typically contain heteroatoms (e.g., sulfur, nitrogen, oxygen and/or metals such as Ni, V, and the like). The heteroatoms react with the hydrogen to form heteroatom-containing compounds which can be separated from the hydrotreated heavy oil using conventional or microchannel process techniques (e.g., vaporization, condensation, filtration, ionic liquid separation, temperature swing adsorption, pressure swing adsorption, and the like). At least about 50% by weight of the heteroatoms in the heavy oil may be reacted and separated of the heteroatoms in the heavy oil may be reactant and separated, or at least about 70% by weight, or at least about 90% by weight, or at least about 95% by weight, or at least about 99% by weight. Surprisingly, the hydrotreating process, when conducted under process intensification conditions such as provided when conducting the process in a process microchannel or microchannel reactor, also results in a hydrocracking of the heavy oil wherein at least some of the hydrocarbons in the oil are hydrocracked to form upgraded hydrocarbon products such as middle distillate or light oils. Vapor and water may be separated from the hydrotreated product. The hydrotreated product, which may be referred to as an intermediate hydrocarbon product, may then be further processed during Stage 2 in a process microchannel or microchannel reactor by reacting the hydrotreated hydrocarbon product with hydrogen in the presence of a hydrocracking catalyst to provide additional hydrocracking with the result being the formation of an upgraded hydrocracked hydrocarbon product, which may be in the form of a hydrocracked liquid product. Vapor and water may be separated from the hydrocracked liquid product.

[0128] The hydrotreating Stage 1 process and hydrocracking Stage 2 process may be conducted in separate microchannel reactors, with the hydrocracking Stage 2 reactor being connected in series to the hydrotreating Stage 1 reactor, the Stage 2 hydrocracking reactor is downstream of the Stage 1 hydrotreating reactor. This is illustrated in FIG. **4**. Referring to FIG. **4**, a plurality of Stage 1 microchannel reactors are housed within a first stage microchannel reactor housing vessel, which may be referred to as a microchannel reactor assembly. In FIG. **4**, two Stage 1 microchannel reactors are shown in phantom, although any desired number of Stage 1 microchannel reactors can be housed within the first stage microchannel reactor housing vessel, for example, from 1 to about 50 Stage 1 microchannel reactors, or from about 3 to about 30 reactors, or from about 3 to about 25 reactors, or from about 5 to about 20 reactors, or from about 10 to about 20 reactors, or about 15 reactors. In the Stage 1 microchannel reactors, heavy oil is reacted with hydrogen in the presence of a hydrotreating catalyst under process intensification conditions to form a hydrotreated product. As indicated above, the heavy oil contains heteroatoms which during the hydrotreating reaction react with hydrogen to form heteroatom-containing compounds. The heavy oil also undergoes hydrocracking wherein at least some of the hydrocarbon compounds are hydrocracked. The heteroatom-containing compounds can be separated from the hydrotreated product. This is not shown in FIG. **4**. The hydrotreated product is at least partially hydrocracked and thus is in the form of a more useable upgraded hydrocarbon product. The hydrotreated hydrocarbon product may have use, for example, as a middle distillate or light oil.

[0129] The hydrotreated product, which may be referred to as an intermediate hydrocarbon product, may be further processed during Stage 2 wherein the hydrotreated product is hydrocracked in the Stage 2 microchannel reactors. The Stage 2 microchannel reactors are housed within the second stage microchannel reactor housing vessel, which may be referred to as a microchannel reactor assembly. The Stage 2 microchannel reactors are shown in phantom in FIG. **4**. In FIG. **4**, two Stage 2 microchannel reactors are illustrated, but any desired number, for example, from 1 to about 50 microchannel reactors, or from 1 to about 30 reactors, or from about 3 to about 25 reactors, or from about 5 to about 20 reactors, or from about 10 to about 20 reactors, or about 15 reactors may be used. In the Stage 2 microchannel reactors, the hydrotreated product from Stage 1 and hydrogen contact a hydrocracking catalyst under process intensification conditions and undergo a hydrocracking reaction. The resulting hydrocracked product, which may be referred to as an upgraded hydrocarbon product, and may be useful as a middle distillate or light oil.

[0130] The Stage 1 and Stage 2 microchannel reactor housing vessels contain internal manifolds for flowing reactants into the microchannel reactors and flowing product out of the microchannel reactors. The hydrotreating and hydrocracking reactions are exothermic, and heat exchange fluid flows in heat exchange channels in the Stage 1 and Stage 2 microchannel reactors to control the temperature of the reactions. Internal manifolds within the Stage 1 and Stage 2 microchannel reactor housing vessels are provided to permit the flow of heat exchange fluid into the microchannel reactor housing vessels, through heat exchange channels in the microchannel reactors, and then out of the microchannel reactor housing vessels.

[0131] The Stage 1 hydrotreating step and Stage 2 hydrocracking step of the inventive process can be conducted in a single microchannel or microchannel reactor. These process steps can be conducted in a single microchannel by positioning separate hydrotreating and hydrocracking catalysts in the same microchannel, the hydrocracking catalyst being downstream of the hydrotreating catalyst. Heavy oil and hydrogen flow through the microchannel in contact with the hydrotreating catalyst to react under process intensification conditions and form a hydrotreated product. Additional hydrogen may be added to the microchannel downstream of the hydrotreating catalyst. The hydrotreated product and hydrogen flow through the microchannel in contact with the hydrocracking catalyst to react under process intensification conditions and to form the desired hydrocracked product, which may be referred to as an upgraded hydrocarbon product.

[0132] The Stage 1 hydrotreating process and Stage 2 hydrocracking process may be conducted in a single microchannel reactor. This is illustrated in FIG. **5**. Referring to FIG. **5**, process microchannel layers A and B are positioned one above the other with a heat exchange channel layer positioned between the process microchannel layers. Heavy oil and hydrogen flow through the process microchannel layer A in contact with a hydrotreating catalyst to react under process intensification conditions and form a hydrotreated product, which may be referred to as an intermediate hydrocarbon product. The hydrotreated product flows from process microchannel layer A to process microchannel layer B where it flows with additional hydrogen in contact with a hydrocracking catalyst to react and form the desired hydrocracked product, which may be referred to as an upgraded hydrocarbon product. Heat exchange fluid flows through the heat exchange channel layer and is used to control the temperature in the process microchannel layers.

[0133] With enhanced mass and energy transfer characteristics that are available when conducting the inventive process under process intensification conditions such as those available when conducting the process in process microchannels or microchannel reactors, it is possible to hydroprocess, that is, hydrotreat and/or hydrocrack, heavy oil more efficiently using an increased liquid hourly space velocity (LHSV), a reduced temperature, a reduced pressure, and/or a reduced H_2 oil (i.e., heavy oil or intermediate hydrocarbon product) feed ratio, as compared to conventional processing, that is, processes not employing process intensification conditions such as available when using microchannels or microchannel reactors. When conducting the inventive process under process intensification conditions in process microchannel or microchannel reactors, the temperature within the process microchannels or microchannel reactors may be in the range from about 100 to about 500° C., and in one embodiment from about 250 to about 400° C. The pressure within the process microchannels or microchannel reactors may be in the range from about 0.5 to about 25 MPa and in one embodiment from about 1 to about 20 MPa. The pressure within the process microchannels or microchannel reactors may be in the range from about 100 to about 3000 pounds per square inch gauge (psig) (from about 0.69 to about 20.7 MPa), and in one embodiment from about 500 to about 2000 psig (from about 3.45 to about 13.8 MPa). The LHSV within the process microchannels or microchannel reactor may be in the range from about 0.1 to about 200 hr^{-1}, and in one embodiment from about 1 to about 100 hr^{-1}. As indicated above, the hydrotreating and hydrocracking processes may be conducted in separate stages within a process microchannel, or within separate microchannels within a microchannel reactor, or within separate microchannel reactors. In each case, the reaction may be conducted in a first stage for hydrotreating and a second stage for hydrocracking. In the first stage, the LHSV may be in the range from about 0.1 to about 50 hr^{-1}, and in one embodiment from about 5 to about 50 hr^{-1}. In the second stage the LHSV may be in the range from about 0.1 to about 20 hr^{-1}, and in one embodiment from about 1 to about 20 hr^{-1}.

[0134] When the Stage 1 and Stage 2 reactions are conducted in a single process microchannel, multiple reaction zones within the process microchannel may be employed. Each zone may contain a different catalyst, or be operated at a different temperature, or the fluids flowing in the process microchannel may flow in different zones at different superficial velocities. The employment of different superficial velocities within different zones within a process microchannel may be achieved by employing different internal dimensions (e.g., different heights and/or widths) for the microchannel. The ratio of H_2 to oil (i.e., heavy oil or intermediate hydrocarbon product) may be varied by the addition of additional amounts of H_2 between the separate reaction zones.

[0135] With the inventive process employing one or more process microchannels, one or more microchannel reactors, or one or more microchannel reactor assemblies, it is possible to conduct the process at any desired production level. For example, it is possible to process heavy oil at relatively low levels of production and yet conduct the hydroprocessing process at an efficient and cost effective level. For example, it is possible to convert a heavy oil source such as biomass to heavy oil and then hydroprocess the heavy oil in a single plant at a relatively low production level of, for example, up to about 5000 barrels per day (bpd) of heavy oil, or even less, for example, up to about 500 bpd. The plant site may be used to both hydrotreat and hydrocrack the heavy oil to provide an upgraded hydrocarbon product for transport from the plant, e.g., via truck transport or pipeline, or for further refining at the plant. The plant may also be used to initially convert the heavy oil source material, e.g., biomass, to heavy oil and then hydrotreat to form an intermediate hydrocarbon product at the plant followed by transportation of the intermediate hydrocarbon product to another location for further processing. The intermediate hydrocarbon product is suitable for transportation although it may contain a higher heteroatom content than desired for a finished upgraded hydrocarbon product. The high heteroatom content can be removed by further hydroprocessing. For example, the heavy oil may be converted to a partially hydrogenated intermediate hydrocarbon product in which more than about 50% by weight of the heteroatom components are converted on site, and then the partially hydrotreated intermediate hydrocarbon product is transported to a facility for blending with other hydrocarbons for further refining.

[0136] The inventive process may be used to convert heavy oil vapor to an upgraded hydrocarbon product. This process is illustrated in FIG. **27**. Referring to FIG. **27**, heavy oil and oxygen are gasified in a heavy oil gasifier. The gasification step may be conducted in a counter-current fixed bed gasifier, a co-current fixed bed gasifier, a fluidized bed gasifier or an entrained flow gasifier. In the gasifier, heavy oil vapor and char are formed. The char is separated from the heavy oil vapor. In alternative embodiments, the heavy oil vapor may be created by pyrolysis. The heavy oil vapor is cooled to a temperature in the range of about 200° C. to about 500° C., and in one embodiment from about 350° C. to about 450° C. The cooled heavy oil vapor is reacted with hydrogen in the presence of a hydrocracking catalyst in a condenser hydrocracker under process intensification conditions. The condenser hydrocracker comprises one or more process microchannels or one or more microchannel reactors. The heavy oil vapor and hydrogen may be mixed with each other in the condenser hydrocracker or upstream of the condenser hydrocracker. In the condenser hydrocracker, the heavy vapor is condensed and hydrocracked to form an upgraded hydrocarbon product. Heat exchange fluid flows in and out of the condenser hydrocracker to provide coolant to control the hydrocracking reaction, which is exothermic, and to condense the upgraded hydrocarbon product. The upgraded hydrocarbon product flows out of the condenser hydrocracker, and then through a heat exchanger where it is further cooled and flows to a liquid/vapor phase separator. In the liquid/vapor phase separator, the upgraded hydrocarbon product is separated into a vapor and an upgraded hydrocarbon liquid product. The vapor may be recycled to the condenser hydrocracker or it may be used as a valuable hydrocarbon vapor product, or it may be vented to an exhaust.

[0137] The condenser-hydrocracker shown in FIG. **27** is illustrated in FIGS. **28** and **29**. The condenser hydrocracker comprises one or more vertically oriented process microchannels containing a hydrocracking catalyst. The heavy oil vapor and hydrogen flow downwardly through the process microchannels in contact with the hydrocracking catalyst, condense and undergo a hydrocracking reaction. Heat exchange fluid flows through heat exchange channels that are aligned in a cross-current direction relative to the flow of fluid in the process microchannels. The heat exchange fluid provides coolant to control the reaction, which is exothermic, and condense the hydrocracked hydrocarbon product.

[0138] The heavy oil vapor may be hydrocracked in a two-stage hydrocracking process. This is illustrated in FIG. **30**.

Referring to FIG. **30**, heavy oil vapor and hydrogen flow into hydrocracking reactor Stage 1 where the heavy oil vapor and hydrogen contact a hydrocracking catalyst, react under process intensification conditions and form a first hydrocracked hydrocarbon product. The first hydrocracked hydrocarbon product flows to a liquid/vapor separator where heavy upgraded oil is separated from vaporous oil. The vaporous oil is combined with hydrogen and flows to hydrocracking reactor Stage 2 where the vaporous oil and hydrogen react in the presence of a hydrocracking catalyst under process intensification conditions to form a second hydrocracked hydrocarbon product. The second hydrocracked hydrocarbon product is advanced to a liquid/vapor phase separator where it is separated into a light upgraded oil and vapor. The vapor can be recycled to the Stage 1 or Stage 2 hydrocracking reactor or it can be vented to exhaust. The vapor may also be employed as a valuable hydrocarbon product.

[0139] The heavy oil may be hydrocracked in a catalytic distillation column in which one or more catalyst beds comprising hydrotreating or hydrocracking catalysts are positioned in a distillation column.

[0140] The heavy oil may be hydrocracked in a series of condenser hydrocrackers positioned in a distillation column. This is illustrated in FIG. **31**. Referring to FIG. **31**, heavy oil vapor and hydrogen are advanced to distillation column **500** which, as illustrated, contains three condenser hydrocrackers **502**, **504** and **506**, positioned one above another, a distillate end **510** and a bottoms end **512**. It will be understood that any number of condenser hydrocrackers may be employed in the distillation column **500**, for example, from 1 to about 1000 condenser hydrocrackers may be used, or from 1 to about 100, or from 1 to about 20, or from 1 to about 10, or from 1 to about 5. The distillation column **500** has a distillate end **510** and bottoms end **512**. Heavy oil vapor and hydrogen flow upwardly through each of the condenser hydrocrackers **502**, **504** and **506** toward the distillate end **510**. In each condenser hydrocracker heavy oil vapor contacts a hydrocracking catalyst, and condenses and undergoes a hydrocracking reaction under process intensification conditions. The catalyst in each of the condenser hydrocrackers **502**, **504** and **506** may be in the form of a packing (e.g., bales, monoliths, structured packings comprising catalyst, structured packing coated with catalyst, foams, felts, honeycombs, and the like). Hydrocarbon vapor flows out of the distillate end **510** of the distillation column **500**. The hydrocarbon vapor flowing out of the distillation column **500** is cooled in heat exchanger **514** and advanced to a liquid/vapor phase separator **516**. In the liquid/vapor phase separator **516**, the distillate is separated into a gas and a light oil. The gas contains H_2 and may be recycled to a gasifier where the heavy oil is vaporized. The light oil is either removed as a valuable product or recycled back through the distillation column **500** flowing toward the bottoms end **512** for further hydrocracking. At midway points in the distillation column Oil Cut Number **1** and Oil Cut Number **2** are removed from the distillation column. Other oil cuts not shown in the drawings may also be removed. Oil Cut Numbers **1** and **2** may be referred as middle distillates. A bottoms fraction is extracted from the bottoms end **512** of the distillation column.

[0141] The heavy oil source material may comprise any carbonaceous material that can be converted to a heavy oil. The carbonaceous material may be a solid carbon-containing material. The carbonaceous material may comprise coal, shale, tar sand, bitumen or biomass. The carbonaceous material may comprise a food resource such as corn, soybean, and the like. The carbonaceous material may comprise a non-food resource. The non-food resource may be referred to as a second generation biofuel. The non-food resource may comprise any carbonaceous material not generally used as a food. The non-food resource may be referred to as a non-food carbonaceous material. Examples of the non-food carbonaceous materials that may be used may comprise coal (e.g., low grade coal, high grade coal, and the like), oil (e.g., crude oil, heavy oil, tar sand oil, and the like), biomass, solid wastes, or a mixture of two or more thereof. The non-food carbonaceous material may comprise municipal solid waste (MSW), hazardous waste, refuse derived fuel (RDF), tires, petroleum coke, trash, garbage, biogas from a digester, sewage sludge, animal waste (e.g., chicken manure, turkey manure, cow manure, horse manure, as well as other animal waste), agricultural waste, corn stover, switch grass, timber, wood cuttings, grass clippings, construction demolition materials, plastic materials (e.g., plastic waste), cotton gin waste, landfill gas, natural gas, and the like. The non-food carbonaceous material may comprise polyethylene or polyvinyl chloride. Mixtures of two or more of any of the foregoing may be used.

[0142] The carbonaceous material may contain solids or solid forming species. These may include products derived from coal (which may contain coal ash constituents) biomass (minerals, etc.), animal derived products (chicken fat, fryer oils, etc.), heavy crudes (which often contain Ni and/or V species). It may therefore be necessary to remove these species prior to processing, whether using conventional or microchannel operations. The removal process may include filtration (especially for coal or mineral ashes and for animal derived feeds, for example, chicken fat may contain feathers, beaks, bones, etc.) or reactive removal such as a guard bed, which may comprise a removable cartridge in a microchannel reactor system. This may be particularly important for Ni, V, and the like, in heavy crudes where the metals may not be formed as a solid until the metal compounds are decomposed by higher temperatures, with or without additional reactants, for example, H_2.

[0143] Conventional hydrotreating and hydrocracking catalysts may be used. Examples of conventional hydrotreating and hydrocracking catalysts may include those with a support which may comprise an amorphous material (e.g., alumina, silica alumina, titania, zirconia, or a combination of two or more thereof), zeolite, layered clay, pillared clay, or any material with acid sites, or a combination of two or more of the foregoing materials. The support may be further impregnated with a metal species which enhances hydrotreating or hydrocracking. The metal species may comprise platinum, palladium, nickel, molybdenum, tungsten, or a combination of two or more of the foregoing metals. As a result of the inventive process being conducted under process intensification conditions, the catalyst may be in a more active form than those used in conventional processes.

[0144] The use of microchannels for hydrotreating and hydrocracking reactions provides for process intensification conditions on a number of fronts. These may include kinetics, pressure drop, heat or energy transfer, and mass transfer. Conventional hydroprocessing reactions (e.g., hydrocracking reactions and hydrotreating reactions) not employing microchannel processing may be constrained by heat removal and require catalysts of sufficient but not high activity. On the other hand, microchannels may allow for higher activity catalysts than may be typically used with conventional reactors. For example, the heat of reaction may be removed more effectively with a microchannel reactor than with a conventional reactor by using heat exchange channels interspersed or in thermal contact with process microchannels in the microchannel reactor. A microchannel processing unit may be used as a polishing unit downstream of a conventional hydroprocessing unit in order to add additional hydrotreating and/or hydrocracking to the product produced by the conventional hydroprocessing unit.

[0145] Although the microchannel dimension of height or width may be smaller than the diameter of a conventional reactor, pressure drop may be dominated by flow through the catalyst bed, which may comprise a packed bed, porous media, or other catalyst form. The catalyst may take the form of pellets, beads, particles, foam, wad, felt, honeycomb, or other structure with either regular or irregular shape or form. Flow lengths in the process microchannel may range from 0.05 to about 10 meters, and in one embodiment from about 0.05 to about 5 meters, and in one embodiment from about 0.05 to about 2 meters, and in one embodiment from about 0.1 to about 1.5 meters, and in one embodiment from about 0.1 to about 1 meter, and in one embodiment from about 0.1 to about 0.7 meter. Shorter flow lengths may allow for a reduction in catalyst particle diameter to achieve a net neutral or lower process pressure drop than with a conventional hydrocracker. In some embodiments, a higher pressure drop may be useful. Further, the inlet pressure of the liquid stream and the gaseous stream may not be the same. A pressure drop or pressure let down before the reaction zone within a process microchannel may be useful to control the flow distribution of the gas and liquid. The inlet pressure of the liquid may be greater than the inlet pressure for gas. The pumping power for a liquid may be less than the compression required for a gas. Alternatively, the gas may be at a higher inlet pressure than the liquid.

[0146] For the hydrotreating and hydrocracking reactions, heat release control may require reactor designs with interstage cooling, liquid redistribution, and/or quench sections. Microchannel reactors employing process microchannels for conducting the hydroprocessing reactions may employ local heat removal with heat exchange or coolant channels interspersed with the process microchannels.

[0147] Microchannel reactors may be used to enable a reduction in both intraparticle and interparticle mass transfer resistance. When using a catalyst in the form of catalyst particles or particulates, the average particle diameter may be in the range from about 0.01 to about 1.5 mm, and in one embodiment from about 0.05 to about 0.5 mm, and in one embodiment from about 0.1 to about 0.3 mm. On the other hand, a conventional hydrocracker may use a catalyst pellet with an average diameter that ranges from about 2 to about 10 mm.

[0148] The reduction in catalyst particle diameter may improve the effective use of internal catalyst sites over conventional hydrocracking reactors. The effectiveness factor for a catalyst may be a function of the Thiele modulus. For a spherical catalyst particle, the Thiele modulus is proportional to the radius divided by 3. For equal intrinsic reaction rates on the active catalyst sites, a ten-fold reduction in the catalyst diameter will result in a tenfold reduction in the Thiele modulus. The Thiele modulus is not directly proportional to effectiveness factor. For a Thiele modulus less than one a fairly high effectiveness factor may be expected. If the Thiele modulus is greater than one, a much steeper decline in the effectiveness factor may be expected. The actual impact of particle size depends upon the intrinsic reaction rates, the diffusivity of reactants within the catalyst particle, and the tortuosity of mass diffusion within the catalyst particle.

[0149] The reduction in interparticle mass transfer resistance may be less straightforward. The microchannel dimension and associated small catalyst particles housed therein may promote capillary forces over viscous and body forces. The net result may be a well dispersed liquid film that improves the contact of all phases with the catalyst to improve the apparent catalyst activity.

[0150] The Capillary number (Ca) defines the ratio of viscous to interfacial forces

$$Ca = \frac{\mu \text{ velocity}}{\sigma}$$

where the viscosity of a liquid feedstock can been approximated using known high temperature and high pressure hydrocarbon data and surface tension values. In this formula μ velocity refers to viscosity, and δ refers to surface tension. For example, the viscosity of an eicosane fluid at 200 psi and 261° C. is 0.338 cP. Creating a functional dependency on temperature for this fluid results in an exponential dependency, where the viscosity is proportional to 3.53×exp(−0.0091×Temperature (in degrees C.)). For a 370° C. hydrocracking reaction mixture, the viscosity is approximated as 0.12 cP. Measurements of the surface tension of the feedstock on the catalyst particle are roughly one-third the surface tension of water. For a reaction system with an actual linear velocity of 0.3 m/s, which corresponds to a hydrocracking process with a LHSV of 30 hr^{-1}, a bed void of 0.35, and 1500:1 hydrogen to feed ratio, the estimated capillary number is about 1.5×10^{-3}. For this reaction condition, the conversion of a hydrocarbon product with a boiling point below 350° C. may be essentially complete, or greater than 99%. In one embodiment, the conversion may be greater than 50%, or greater than 80%, per pass. The capillary number for a multiphase reaction in a microchannel reactor may be in the range from about 10^{-2} to about 10^{-6}.

[0151] The Bond number (Bo) defines the ratio of body forces (e.g., gravity) to interfacial forces (capillary forces). For low Bond numbers, interfacial capillary forces that spread the liquid throughout the reaction chamber may be stronger than gravitational forces that force the liquid to coalesce and drip or trickle through the reactor.

$$Bo = \frac{\rho g L^2}{\sigma},$$

where the density of the feedstock can be approximated by known high temperature and high pressure hydrocarbon data and surface tension values for the liquid hydrocarbon feedstock. In this formula, ρ refers to density, g refers to the gravitational constant, L refers to the critical length, and δ refers to surface tension. A bond number may be calculated for a microchannel, e.g. channel bond number, where the critical length is the smallest channel dimension which is typically the channel gap or height of the microchannel. A bond number may be calculated for the particle, e.g. particle bond number, where the critical length is the particle diameter. A bond number may be calculated for the microchannel length, e.g. length bond number, where the critical length is the flow length of the reactor itself. The three bond numbers may help determine whether the hydrocracker liquid may preferentially spread via capillary forces in the defined critical length or fall with gravity.

[0152] The channel bond number may be in the range from about 0.001 to about 2. The bond number may be less than about 1, and in one embodiment in the range from about 0.001 to about 0.999, and in one embodiment from about 0.01 to about 0.95, and in one embodiment from about 0.1 to about 0.9. Using the numbers from the previous example for a microchannel reaction zone with a height of 1.75 mm and a liquid density of 0.6 gm/cc, the Bond number is 0.75. For smaller reaction zones, the Bond number reduces further and is 0.25 for a reaction zone with a height of 1 mm.

[0153] The channel Bond number for a hydroprocessing reaction zone or other multiphase reaction zones with an internal dimension below about 2 mm may be less than about 1. This suggests that the interfacial forces to disperse the liquid within the microchannel may be greater than gravitational forces thus showing the propensity for the liquid to wet the walls of the microchannel rather than coalesce and flow down the channel walls with rivulets. The channel Bond number for a conventional hydrocracking reactor bed with a diameter as large as 4.5 meters may be greater than about 10, and typically greater than about 100 or greater than about 1000. This suggests that gravity dominates in flow of liquid within the reactor vessel. The conventional hydrocracker or multiphase reaction chamber faces challenges to keep the liquid well dispersed and to avoid liquid flow channeling or rivulets within the packed bed.

[0154] The Bond number for a catalyst particle placed within a microchannel may be many orders of magnitude below about 1, suggesting the capillary force may be sufficient to overcome those forces exerted by gravity and thus the liquid may well wet the particles rather than coalesce and trickle around the particles in poorly dispersed streams. For a conventional hydrocracking reactor particle diameter, the particle Bond number may exceed 1 because the catalyst particle exceeds 2 mm and is typically in the range from about 3 to 50 mm. For the hydrocracking reaction fluid properties, the particle Bond number may approach 1 for a particle diameter of about 2 mm. The flow of liquid in a conventional hydroprocessing reactor or other multiphase reactor may be dominated by gravity and viscous forces rather than the capillary forces which may act to spread the liquid laterally throughout the bed. Experiments have been conducted with a 1.5 mm particle and a 3 mm particle, where a liquid oil flows in a downflow orientation with a co-flow of nitrogen gas under ambient conditions. The experiment with the 3 mm particle forms uneven flow and rivulets where the liquid does not fully wet the particle. In comparison, the experiment with the 1.5 mm particle demonstrates a well wet liquid and stable flow. There are no rivulets observed for liquid flow past the 1.5 mm particles where the particle bond number is less than about 1.

[0155] In an alternate embodiment with the use of a structured catalyst which is made of any contiguous porous material unlike a discontinuous particle bed which is comprised of discrete particles touching each other but not otherwise joined or fused, the critical length is defined by the minimum dimension of the porous structure. As an example, if a porous felt, foam, wad, regular structure, or graded structure with internal porosity has a thickness of 1 mm and a length and width greater than 1 mm, the particle bond number would be calculated to be roughly 0.5 for the test conditions of a flowing oil at 370° C. The use of a particle bond number includes the extension to a porous structure with a small critical dimension such that the particle bond number is less than about 1.

[0156] Laboratory test reactors for conventional hydrocrackers are often tested with very small particles interspersed around conventional pellets to improve the lateral flow of liquid in the reactor. While this dual sized particle solution may not be practical from a pressure drop perspective for a conventional hydrocracker, it shows the importance of internal liquid distribution on the performance of the catalyst and that the large catalyst particles selected for conventional hydrocracking reactors may retain poor wetting by the liquid.

[0157] The result may be that the small catalyst particles in microchannels may create a fluidic environment dominated by capillary forces for the reaction. Unlike conventional hydrocrackers, where the liquid channels within the bed, liquid flow in a microchannel may remain well dispersed across the channel. A conventional reactor requires periodic collection and redistribution of liquid within the reactor, whereas a microchannel may not. Further, a laterally well distributed liquid flow allows a gas to shear or thin the liquid film rather than segment the reactor bed into unsteady and intermittent zones of gas and liquid films.

[0158] The length bond number for a microchannel will typically exceed 1 as it does for a conventional hydrocracking reactor. The length bond number may not be the critical parameter, where the particle and channel bond number are more important for establishing well wetted catalyst particles with stable liquid flow. An additional component to reducing mass transfer resistance for the contact of the gas, liquid, and solid catalyst may be built upon processes with a particle bond number less than about 1. The stable and thin films may be further thinned by the high gas velocity.

[0159] With a laterally well dispersed liquid film within a microchannel reactor, that has sufficient capillary force to resist segmentation or flow rivulets, the film thickness may be further thinned by high gas velocity in the microchannel. The reduction in liquid film around the particle may reduce the mass transfer resistance for a gas such as hydrogen to access the catalyst particle. For a hydroprocessing reaction, the mean film thickness for the liquid when using hydrogen gas with a 0.24 m/s superficial velocity may be about 5 microns. For a hydrogen gas with a velocity of 0.009 m/s passing against a thin film of the hydrocarbon liquid, a mean film thickness of about 20 microns may be expected. For these two cases, a four-fold reduction in liquid film thickness may correspond to a 16 fold reduction in time for the gaseous hydrogen to diffuse through the liquid film to the catalyst surface. Further, the time for the liquid reactant to diffuse within the liquid film to the catalyst on and in the catalyst particles or surface may also be reduced roughly with the square of the film thickness. Given that diffusivity of a liquid may be two to three orders of magnitude greater than the diffusion of a gas, the liquid diffusion within the liquid layer to the catalyst surface may dominate the transport resistance contribution to the overall apparent rate of reaction. The surface rate of reaction on the catalyst may be rate limiting. From a control volume analysis around a catalyst particle, a comparison of diffusion time to convection time may suggest the importance of reduced film thickness on the hydroprocessing reaction rate. As the amount of time available for a gas such as hydrogen to diffuse through a thicker liquid film increases, the corresponding amount of additional gas fed to the reaction system in excess may decrease thus providing surprising results with a lower excess hydrogen required for a microchannel hydrocracker.

[0160] The diffusion time for a thin film may be the square of the diffusion distance divided by the diffusivity. The diffusivity for hydrogen in a hydrocarbon liquid may be about 4.3×10^{-4} cm^2/s. For a 20 micron film thickness, the diffusion time may be about 10 ms. For a 5 micron film thickness, the time for diffusion across the thin film surrounding a catalyst particle may be about 0.5 ms.

[0161] The convection time in a control volume around a catalyst particle of about 110 microns diameter for a superficial gas velocity of about 0.3 m/s may be about 1 ms. For the same microchannel dimensioned particle size of a mean diameter of about 110 microns, the impact of a film thickness ranging from about 5 microns to about 20 microns imparts a capture number difference of about 2 to about 0.1. The capture number is the time for convection divided by the time for diffusion. For the 5 micron thin film, the gas spends roughly twice the amount of time around the catalyst as it takes to diffuse to the active catalyst sites. For the 20 micron film at equal superficial gas velocity, the gas requires roughly ten times more time to diffuse to the catalyst sites (10 ms) than available as it flows around the particle (1 ms). In this latter case, there may be much more catalyst required to achieve the same level of reaction. This excess catalyst may range from about 2 to about 200 times more catalyst as compared to a high velocity microchannel. The result may be that a higher excess amount of hydrogen is required as the capture number drops below 1.

[0162] For a larger particle size, as expected in a conventional reactor (where roughly 2 mm is near the low end of diameter), the convection time in a control volume around a catalyst particle is longer. However, the flow dynamics of the lower velocity gas around this larger particle also give rise to much thicker films. For a 100 micron liquid film that is either regular or intermittent flowing or trickling down a conventional reactor, the required time for diffusion across the film is roughly about 200 milliseconds. Correspondingly, for a superficial velocity of about 0.02 m/s, the convection time in a control volume around a 2 mm particle is roughly 100 ms. The capture number may remain less than 1, near 1 or even greater than 1, suggesting the importance of excess hydrogen that may remain in the liquid film to conduct the reaction in a conventional hydrocracker. The thick films found in a conventional hydrocracker may require substantially more mass transfer time for the hydrogen and liquid reactants to reach the solid catalyst particle to react.

[0163] The result of this may be less access of the hydrogen to the catalyst. A conventional hydrocracker may overcome this limitation by increasing the amount of hydrogen excess fed to the system. A microchannel reaction system offers the potential to reduce the amount of excess hydrogen.

[0164] The inventive process is applicable to any hydroprocessing reaction conducted in a microchannel when the particle Bond number is less than about 1 and/or the reaction chamber Bond number is less than about 1.

[0165] The heavy oil feed, intermediate hydrocarbon product feed and/or H_2 feed may be introduced into a manifold on one side of the reactor. Flow may traverse laterally across the reactor or a shim through a submanifold. From the submanifold, flow may pass through a flow restriction section, where pressure drop may be imparted to improve the uniformity of the flow in each of the mating microchannels. The flow may then pass through connection apertures to enter the reactor. The connection apertures may be positioned upstream from the catalyst, but in alternate embodiments the connection apertures may be adjacent to the catalyst. In one embodiment, the liquid may flow through the submanifold and through adjacent connection apertures. The connection apertures may be regular or irregular in shape.

[0166] The heavy oil feed composition and/or intermediate hydrocarbon product feed composition may include one or more diluent materials. Examples of such diluents may include inert compounds such as nitrogen or non-reactive hydrocarbon diluents, and the like. The diluent concentration may be in the range from zero to about 99% by weight based on the weight of the hydrocarbon reactant, and in one embodiment from zero to about 75% by weight, and in one embodiment from zero to about 50% by weight. The diluents may be used to reduce the viscosity of viscous liquid reactants. An advantage of at least one embodiment of the invention is that the use of such diluents is avoided, and operation of the inventive process is more efficient and compact.

[0167] The viscosity of the heavy oil feed composition and/or intermediate hydrocarbon product feed composition may be in the range from about 0.001 to about 1000 centipoise, and in one embodiment from about 0.01 to about 100 centipoise, and in one embodiment from about 0.1 to about 10 centipoise. The heavy oil feed composition and/or intermediate hydrocarbon product feed composition may be in the form of a liquid, a gas, or a combination thereof.

[0168] The ratio of hydrogen to oil in the heavy oil feed composition and/or intermediate hydrocarbon product feed composition may be in the range from about 10 to about 6000 standard cubic centimeters (sccm) of hydrogen per cubic centimeter (ccm) of oil, and in one embodiment from about 50:1 to about 4000:1 sccm/ccm, and in one embodiment from about 100:1 to about 2000:1 sccm/ccm, and in one embodiment from about 300:1 to about 1500:1 sccm/ccm. The hydrogen feed may further comprise water, methane, carbon dioxide, carbon monoxide or nitrogen.

[0169] The H_2 in the hydrogen feed may be derived from another process such as a steam reforming process (product stream with H_2/CO mole ratio of about 3), a partial oxidation process (product stream with H_2/CO mole ration of about 2), an autothermal reforming process (product stream with H_2/CO mole ratio of about 2.5), a CO_2 reforming process (product stream with H_2/CO mole ratio of about 1), a coal gasification process (product stream with H_2/CO mole ratio of about 1), and combinations thereof. With each of these feed streams the concentration of H_2 may be increased through the use of water-gas shift and/or the H_2 may be separated from the remaining ingredients using conventional techniques such as membranes or adsorption.

[0170] The upgraded hydrocarbon product made by the inventive process may be a middle distillate fraction boiling in the range of about 260-700° F. (127-371° C.). The term "middle distillate" is intended to include the diesel, jet fuel and kerosene boiling range fractions. The terms "kerosene" and "jet fuel" boiling range are intended to refer to a temperature range of 260-550° F. (127-288° C.) and "diesel" boiling range is intended to refer to hydrocarbon boiling points between about 260 to about 700° F. (127-371° C.). The product may be a gasoline or naphtha fraction. These are normally considered to be the C_5 to 400° F. (204° C.) endpoint fractions.

[0171] The product produced from the inventive process may comprise C_5^+ hydrocarbons with an iso/normal ratio greater than about 0.5. The product may comprise C_{20}^+ hydrocarbons with an iso/normal ratio that is greater than about 1. The product may comprise C_{10}^+ hydrocarbons with an iso/normal ratio greater than about 1 when the weight hourly space velocity (WHSV) for the flow of liquid product is less than about 20 hr^{-1}. The cloud point for the product may be less than about −10° C.

[0172] When the inventive process is conducted using, for example, a low operating pressure or low hydrogen partial pressure, the resulting product that is formed may comprise straight chain aliphatic compounds as well as alicyclic and aromatic compounds. The formation of alicyclic and aromatic compounds is undesirable and is typically avoided in conventional processing using non-microchannel reactors due to the fact that these compounds tend to interfere with the catalyst. However, the formation of these compounds is permissible with the inventive process due to the fact that the catalyst can be regenerated periodically without causing significant production disruptions.

[0173] The reactants or process feed may further comprise a recycle stream from which the hydrocracked products, and optionally other components, have been separated out, for example, by distillation or partial condensation.

[0174] The reactants may comprise one or more gases at reaction conditions which react to form a liquid. The reactants may comprise one or more gases that form a liquid that continues to react. The reactants may comprise a liquid and gas at reaction conditions that flow concurrently through the process microchannel. The reactants may comprise one or more liquids that are fed with an inert gas to improve interfacial contact with the catalyst to enhance the reaction rate.

[0175] The local conditions in a process microchannel or a microchannel reactor may be controlled via tailoring temperature and/or composition profiles via one or more of the following: heat exchange with heat exchange channels adjacent to or in thermal contact with the one or more process microchannels in the microchannel reactor; heat exchange with multiple combinations of heat exchange channels strategically placed to correspond to individual reaction sections within the process microchannels; addition of one or more reactants and/or diluents using staged addition along the axial length of the process microchannels. An isothermal reactor profile may be employed. With such a thermal profile, a partial boiling heat exchange fluid may be used. A tailored temperature profile along the length of the process microchannels may be used. Heat may be removed with a single phase fluid, such as a hot oil, steam, a gas or the like. The heat exchange fluid may flow in a direction that is co-current, counter-current or cross-current to the flow of the process fluids in the process microchannels. The heat exchange fluid may comprise one of reacting species or non-reacting species that subsequently joins the reaction mixture after receiving heat from the reaction. The heat exchange fluid may be used to remove exothermic reaction heat from the process microchannels, and to preheat the reactants entering the process microchannels. The reactants may be preheated to substantially the reaction conditions or they may be partially preheated from the inlet temperature of the feed to an intermediate temperature between the average reaction temperature and the inlet temperature. The heavy oil or intermediate hydrocarbon reactant may enter the reactor at a temperature below the reaction temperature to minimize coking and then be heated to the reaction temperature in the reactor. The heavy oil or intermediate hydrocarbon reactant entering the microchannel reactor may be at a temperature that is about 10° C., or about 50° C., or about 100° C., or more, less than the reaction temperature. In one embodiment, the heavy oil or intermediate hydrocarbon reactant entering the microchannel reactor may be at a temperature that is in the range from about 200° C. to about 250° C., and the reaction temperature in the microchannel reactor may be in the range from about 300° C. to about 400° C.

[0176] In order to control the exothermic reaction via heat exchange with a heat exchange medium, for example, a heat exchange fluid, the process may employ a heat flux at or near the entrance to the microchannel reactor that is higher than the heat flux near the outlet of the microchannel reactor.

[0177] The microchannel reactor used with the inventive process may contain one or more repeating units, as discussed below. Each of the repeating units discussed below contains one or more process microchannels and one or more heat exchange channels. Examples of some of the repeating units that may be used are illustrated in FIGS. **8-13** and **25-26**. Each of the process microchannels may contain one or more reaction zones wherein the reactants react to form the desired product. A catalyst in solid form may be present in the one or more reaction zones. The catalyst may comprise a homogeneous catalyst immobilized on a solid. Each repeating unit may contain one or more heat exchange channels. In one embodiment, each process microchannel may be combined with one or more adjacent reactant stream channels to provide for the staged addition of hydrogen into the process microchannel. The process microchannel and the adjacent reactant stream channel may have a common wall with a plurality of openings in the common wall. These openings may be used to provide for the flow of hydrogen from the adjacent reactant stream channel into the process microchannel. A feed stream header may be used for distributing mixtures of the reactants to the process microchannels. Alternatively, one feed stream header may be used for distributing hydrocarbon reactants (i.e., heavy oil or intermediate hydrocarbon reactant) to the process microchannels, and another header may be used to distribute H_2 to the adjacent reactant stream channels.

[0178] Although an advantage of the inventive process is that a high converted basis yield to the desired intermediate hydrocarbon product or upgraded hydrocarbon product may be obtained with one pass through the microchannel reactor, in one embodiment, one or more hydrocarbon reactants may be separated from the hydrotreated or hydrocracked product using conventional or microchannel techniques and recycled back through the microchannel reactor. The hydrotreated or hydrocarbon reactants may be recycled through the microchannel reactor any number of times, for example, one, two, three, four times, etc.

[0179] The reactants may be preheated prior to entering the microchannel reactor. The reactants may be preheated to the average temperature employed in the reaction zone of the one or more process microchannels used in the microchannel reactor or to a temperature that is less than the average temperature employed in the reaction zone. The hydrotreating and hydrocracking processes are exothermic. In order to control the reaction, heat may be transferred from the process microchannels to a heat exchange medium. That is, during the inventive process the process microchannels may be cooled using a heat exchange medium. The heat exchange medium may comprise a heat exchange fluid in one or more heat exchange channels. The heat exchange channels may be adjacent to and/or in thermal contact with the process microchannels. The heat exchange channels may be microchannels. Heat transfer between the process fluids and heat exchange fluid may be effected using convective heat transfer. In one embodiment, heat transfer may be enhanced using a heat exchange fluid wherein the heat exchange fluid undergoes an endothermic reaction and/or a full or partial phase change (e.g., partial boiling). Multiple heat exchange zones may be employed along the length of the process microchannels to provide for different temperatures at different locations along the axial lengths of the process microchannels. Also, at the end of the reaction the product may be quenched in order to reduce or eliminate the formation of undesired by-products. Quenching may be effected in the microchannel reactor or downstream of the microchannel reactor.

[0180] With the inventive process, intermixing of the gaseous and liquid phases may be enhanced using catalyst beds employing relatively small particulate solids, for example, particulate solids with average diameters in the range from about 0.01 to about 1.5 mm, and in one embodiment from about 0.05 to about 0.5 mm, and in one embodiment from about 0.1 to about 0.3 mm.

[0181] The microchannel reactor may be used in combination with one or more storage vessels, pumps, compressors, valves, microprocessors, flow control devices, and the like, which are not shown in the drawings, but would be apparent to those skilled in the art.

[0182] The microchannel reactor may be constructed as illustrated in FIGS. **2**A-**2**C. Referring to FIG. **2**A, microchannel reactor **100** comprises a plurality of process microchannels **110**, reactant stream channels **150** and heat exchange channels **170** positioned side-by-side to provide microchannel reactor **100** in the form of a cubic block. The cubic block may have a length in the range from about 10 to about 1000 cm, and in one embodiment in the range from about 20 to about 200 cm. The cubic block may have a width in the range from about 10 to about 1000 cm, and in one embodiment in the range from about 20 to about 200 cm. The cubic block may have a height in the range from about 10 to about 1000 cm, and in one embodiment in the range from about 20 to about 200 cm. The heavy oil or intermediate hydrocarbon enters the process microchannels **110** as indicated by arrow **112**. H_2 enters reactant stream channels **150** as indicated by arrow **152**. The H_2 flows from the reactant stream channels **150** into the process microchannels **110** where it contacts the heavy oil or hydrocarbon intermediate product. The reactants react and product flows out of the process microchannels **110** as indicated by arrow **118**. Heat exchange fluid enters the heat exchange channels **170** as indicated by arrow **172**. Heat exchange fluid flows out of the heat exchange channels **170** as indicated by arrow **174**.

[0183] Referring to FIGS. **2**B and **2**C, the microchannel reactor **100** has a feed stream header **114** to provide for the flow of the heavy oil or intermediate hydrocarbon reactant into the process microchannels **110**, a reactant stream channel header **154** to provide for the flow of H_2 into the reactant stream channels **150**, a product footer **120** to provide for the flow of product out of the process microchannels **110**, and a heat exchange inlet header **176** to provide for the flow of heat exchange fluid into the heat exchange channels **170**. As shown in FIGS. **2**C and **6**, the heat exchange fluid flows out of heat exchange channels through side **111** of the microchannel reactor **100** into the interior of the microchannel housing vessel.

[0184] The microchannel reactor may contain a plurality of repeating units, each of which may include one or more process microchannels and one or more heat exchange channels. Staged addition of the H_2 may be used (as indicated in FIGS. **2**A, **2**B and **2**C), and when used, the repeating units contain one or more reactant stream channels positioned adjacent to each process microchannel. The repeating units that may be used include repeating units **200**, **200**A, **200**B, **200**C, **200**D, **200**E, **200**F and **200**G illustrated in FIGS. **8**-**13** and **25**-**26**, respectively. The microchannel reactor may comprise from 1 to about 1000 or more of the repeating units **200**, **200**A, **200**B, **200**C, **200**D, **200**E, **200**F or **200**G, and in one embodiment from about 10 to about 500 of such repeating units. The catalyst used in the repeating units **200**, **200**A, **200**B, **200**C, **200**D, **200**E, **200**F or **200**G may be in any form, including particulate solids or the various catalyst structured forms described below.

[0185] Repeating unit **200** is illustrated in FIG. **8**. Referring to FIG. **8**, process microchannel **210** is positioned adjacent to heat exchange channel **230**. The heat exchange channel **230** may be a microchannel. A common wall **232** separates the process microchannel **210** and the heat exchange channel **230**. The common wall **232** may be referred to as a heat transfer wall. The process microchannel **210** includes reaction zone **212**. A catalyst (not shown in the drawing) is positioned in the reaction zone **212**. The reactants or reactant composition (i.e., heavy oil or intermediate hydrocarbon product, and hydrogen) flow into the reaction zone **212**, as indicated by arrow **214**, contact the catalyst in reaction zone **212**, and react to form the desired product. The product comprises an intermediate hydrocarbon product or upgraded hydrocarbon product. The product flows out of the process microchannel **210** as indicated by arrow **216**. Heat exchange fluid flows in the heat exchange channel **230** in a direction that is cross-current to the flow of reactants and product in the process microchannel **210** (that is, into or out of the page, as illustrated in FIG. **8**). The process conducted in the process microchannel **210** is exothermic and the heat exchange fluid provides cooling for the reaction. Alternatively, the heat exchange fluid may flow through the heat exchange channel **230** in a direction that is counter-current to the flow of reactants and product in the process microchannel **210** or co-current to the flow of the reactants and product in the process microchannel **210**.

[0186] Repeating unit **200**A is illustrated in FIG. **9**. Referring to FIG. **9**, process microchannel **210** is positioned adjacent to reactant stream channel **250**. The process microchannel **210** includes reaction zone **212**. The process microchannel **210** and reactant stream channel **250** have a common wall **252**. The common wall **252** has a plurality of openings **254** that are of sufficient dimension to permit the flow of hydrogen from the reactant stream channel **250** into the process microchannel **210** as indicated by arrows **256**. This hydrogen reactant may be referred to as a staged addition reactant or the second reactant. The openings **254** may be referred to as apertures. The section **258** in the common wall **252** containing the openings **254** may be referred to as an apertured section. Heat exchange channel **230** is positioned adjacent to the process microchannel **210**. The heat exchange channel **230** and the process microchannel **210** have a common wall **232**. The common wall **232** may be referred to as a heat transfer wall. In operation, the hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product) flows into the process microchannel **210** as indicated by arrow **217**. The hydrogen reactant flows into the reactant stream channel **250** as indicated by arrow **218**, and from the reactant stream channel **250** through the openings **254** into the process microchannel **210**. In the process microchannel **210**, the reactants contact the catalyst in the reaction zone **212** and react to form the desired product which comprises an intermediate hydrocarbon product or an upgraded hydrocarbon product. The reaction is exothermic, and the heat exchange channel **230** provides cooling to control the temperature of the reaction. The heat exchange fluid may flow in the heat exchange channel **230** in a direction that is cross-current relative to the flow of reactants and product in the process microchannel **210**. Alternatively, the heat exchange fluid may flow in a direction that is counter-current or co-current to the flow of reactants and product in the process microchannel **210**.

[0187] The repeating unit **200**B illustrated in FIG. **10** is similar to the repeating unit **200**A illustrated in FIG. **9**, with the exception that the process microchannel **210** is an E-shaped or M-shaped microchannel which includes two reaction zones. Also, two adjacent reactant stream channels are used. With this embodiment, staged addition of the hydrogen is provided for the reaction process. The process microchannel **210** has an E-shape or M-shape with entrances indicated by arrows **217** and **217**A and an outlet indicated by arrow **216**. The process microchannel **210** includes reaction zones **212** and **212**A. Reactant stream channels **250** and **250**A are positioned between the legs of the E-shaped or M-shaped process microchannel **210**. The reactant stream channel **250** and process microchannel **210** have a common wall **252** which contains a plurality of openings **254**. The reactant stream channel **250**A and the process microchannel **210** have a common wall **252**A which contains a plurality of openings **254**A. The hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product) enters the process microchannel **210** as indicated by arrows **217** and **217**A, and flows into the reaction zones **212** and **212**A, respectively. The hydrogen enters the reactant stream channels **250** and **250**A as indicated by arrows **218** and **218**A, respectively. The hydrogen flows from the reactant stream channels **250** and **250**A to and through openings **254** and **254**A into the reaction zones **212** and **212**A, contacts the hydrocarbon reactant and the catalyst, and reacts to form the desired product. The product flows out of the E-shaped or M-shaped process microchannel **210** as indicated by arrow **216**. Heat exchange fluid flows in the heat exchange channel **230** in a direction that is cross-current relative to the flow of reactants and product in the process microchannel **210** and provides cooling for the exothermic reaction. Alternatively, the heat exchange fluid may flow in a direction that is co-current or counter-current relative to the flow of reactants and product in the reaction zones **212** and **212**A.

[0188] Repeating unit **200**C is illustrated in FIG. **11**. Referring to FIG. **11**, repeating unit **200**C comprises process microchannel **210**, heat exchange channel **230**, reactant stream channel **250**, and apertured section **258**. A common wall **252** separates process microchannel **210** and reactant stream channel **250**. The apertured section **258**, which contains openings **254**, is positioned in common wall **252**. The apertured section **258** extends partially along the axial length of process microchannel **210**. The process microchannel **210** has a mixing zone **211**, and a reaction zone **212**. A catalyst **215** is positioned in the reaction zone **212**. The mixing zone **211** is upstream from the reaction zone **212**. The hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product) flows into process microchannel **210**, as indicated by the arrow **217**, and then into the mixing zone **211**. The hydrogen flows into reactant stream channel **250**, as indicated by arrow **218**, and from the reactant stream channel **250** through the openings **254** into mixing zone **211**, as indicated by arrows **256**. The hydrocarbon reactant and the hydrogen contact each other in the mixing zone **211** and form a reactant mixture. The reactant mixture flows from the mixing zone **211** into the reaction zone **212**, contacts the catalyst **215**, and reacts to form the desired product which comprises an intermediate hydrocarbon product or an upgraded hydrocarbon product. The product flows out of the process microchannel **210**, as indicated by arrow **216**. Heat exchange fluid flows in heat exchange channel **230** in a direction that is cross-current to the flow of fluid flowing in process microchannel **210**. Alternatively, the heat exchange fluid may flow in a direction that is counter-current or co-current to the flow of fluid in the process microchannel **210**.

[0189] In an alternate embodiment of the repeating unit **200**C illustrated in FIG. **11**, a supplemental mixing zone may be provided in the process microchannel **210** between the mixing zone **211** and reaction zone **212**. The residence time for mixing in the supplemental mixing zone may be defined using the sum of the total of the flow through the openings **254** and the flow of the first reactant in process microchannel **210**, at standard conditions of temperature (i.e., 0° C.) and pressure (i.e., atmospheric pressure), and the volume defined by the process microchannel **210** between the end of the mixing zone **211** and the beginning of the reaction zone **212**. This residence time for mixing in the supplemental mixing zone may be in the range up to about 500 milliseconds (ms), and in one embodiment from about 0.25 ms to about 500 ms, and in one embodiment from about 0.25 ms to about 250 ms, and in one embodiment from about 0.25 to about 50 ms, and in one embodiment from about 0.25 to about 2.5 ms.

[0190] The repeating unit **200**D illustrated in FIG. **12** is the same as the repeating unit **200**C illustrated in FIG. **11** with the exception that the repeating unit **200**D does not contain the separate mixing zone **211**. With repeating unit **200**D, the hydrogen flows through the openings **254** into the reaction zone **212** where it contacts the hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product) and the catalyst **215**, and reacts to form the desired product which comprises an intermediate hydrocarbon product or an upgraded hydrocarbon product. The product then flows out of the process microchannel **210**, as indicated by arrow **216**.

[0191] The repeating unit **200**E illustrated in FIG. **13** is the same as the repeating unit **200**C illustrated in FIG. **11** with the exception that part of the hydrogen mixes with the hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product) in the mixing zone **211**, and the remainder of the hydrogen mixes with the resulting reactant mixture in the reaction zone **212**. The amount of the hydrogen that mixes with the heavy oil or hydrotreated product in the mixing zone **211** may be from about 1% to about 99% by volume of the hydrogen used in the overall reaction, and in one embodiment from about 5% to about 95% by volume, and in one embodiment from about 10% to about 90% by volume, and in one embodiment from about 20% to about 80% by volume, and in one embodiment from about 30% to about 70% by volume, and in one embodiment from about 40% to about 60% by volume of the hydrogen used in the overall reaction. The remainder of the hydrogen mixes with the resulting reactant mixture in the reaction zone **212**.

[0192] The repeating unit **200**F illustrated in FIG. **25** is the same as the repeating unit **200** in FIG. **8** with the exception that the process microchannel **210** illustrated in FIG. **26** includes a reaction zone **212**, a preheating zone **240** and a quenching zone **245**. The preheating zone **240** is upstream of the reaction zone **212**. The quenching zone **245** is downstream of the reaction zone **212**. The preheating zone **240** is heated by heating section **236**. The reaction zone **212** is cooled by cooling section **234**. The quenching zone **245** is cooled by cooling section **238**. The heating section **236**, and the cooling sections **234** and **238** may each comprise heat exchange channels with appropriate heat exchange fluids flowing in the heat exchange channels. The reactants (i.e., heavy oil or intermediate hydrocarbon reactant, and hydrogen) enter the preheating section **240**, as indicated by **214**, and flow through the preheating section **240** where they are preheated to a desired temperature for entering the reaction zone **212**. The reactants flow from the preheating section **240** into the reaction zone **212** where they undergo reaction to form the desired product. The product flows from the reaction zone **212** through the quenching zone **245** wherein the product is quenched. The product flows from the quenching zone **245** out of the process microchannel **210** as indicated by arrow **218**.

[0193] The repeating unit **200**G illustrated in FIG. **26** is similar to the repeating unit **200**F with the exception that the process microchannel **210** is in the form of a U laying on its side. Also, the preheating zone **240** and the quenching zone **245** are adjacent to each other and exchange heat with each other. The reaction zone **212** of the process microchannel **210** is cooled by the cooling section **234** of heat exchange channel **230**. The reactants (i.e., heavy oil or intermediate hydrocarbon reactant, and hydrogen) enter the process microchannel **210** as indicated by arrow **214**, flow through preheating section **240** where they are preheated and then through reaction zone **212** where the reactants undergo reaction to form the desired product. The product flows from the reaction zone **212** through the quenching zone **245** where the reaction is quenched. The product flows out of the process microchannel **210** as indicated by arrow **218**. The relatively cool reactants flowing in the preheating zone **240** are heated by the relatively hot product flowing through the quenching zone **245**. As a result, heat transfers from the quenching zone **245** to the preheating zone **240**.

[0194] The repeating units **200**F and **200**G provide for quenching the product in the microchannel reactor **100**. Alternatively, the product may be quenched downstream of the microchannel reactor **100**. The product quenching may involve reducing the temperature of the product by at least about 200° C. within a period of up to about 500 milliseconds (ms). The temperature may be reduced by at least about 150° C., and in one embodiment at least about 100° C., within a time period of up to about 500 ms, and in one embodiment up to about 400 ms, and in one embodiment up to about 300 ms, and in one embodiment up to about 200 ms, and in one embodiment up to about 100 ms, and in one embodiment up to about 50 ms, and in one embodiment up to about 35 ms, and in one embodiment up to about 20 ms, and in one embodiment up to about 15 ms, and in one embodiment up to about 10 ms, and in one embodiment within a time period of up to about 5 ms. The temperature may be reduced by at least about 200° C., and in one embodiment at least about 100° C., and in one embodiment at least about 50° C., within a time period of about 5 to about 100 ms, and in one embodiment about 10 to about 50 ms. The product may be quenched in the microchannel reactor as illustrated in FIGS. **25** and **26**, or it may be quenched in a quenching device that is separate from the microchannel reactor. The quenching device may comprise a microchannel heat exchanger. The quenching device may comprise a heat exchanger that is adjacent to or interleaved with the product stream exiting the microchannel reactor. The quenching device may comprise a mixer capable of rapidly mixing the product with a secondary cooling fluid. The secondary cooling fluid may be a low temperature steam.

[0195] The quenching device may comprise a narrow gap or passageway for the process fluids to flow through. The gap or passageway may have a dimension equal to or below the quench diameter for the reaction. In this embodiment, the reaction may terminate as the reactants flow through the gap or passageway as a result of wall collisions. The gap or passageway may have a height or width of up to about 5 mm, and in one embodiment up to about 3 mm, and in one embodiment up to about 1 mm, and in one embodiment up to about 0.5 mm, and in one embodiment up to about 0.1 mm, and in one embodiment up to about 0.05 mm. This quenching device may comprise a microchannel or a plurality of parallel microchannels. This quenching device may comprise part of the process microchannels used with the inventive process downstream of the catalyst contained within the microchannels. The narrow gap or passageway may be used in conjunction with one or more of the other quenching devices (e.g., heat exchangers).

[0196] The heat exchange channels and reactant stream channels may be microchannels or they may have dimensions that would characterize them as not being microchannels. For example, these channels may have internal heights or widths up to about 50 mm, and in one embodiment up to about 25 mm, and in one embodiment up to about 15 mm. The process microchannels are microchannels. Each of the channels may have a cross-section having any shape, for example, a square, rectangle, circle, semi-circle, etc. Each microchannel may have an internal height of up to about 10 mm, and in one embodiment up to about 5 mm, and in one embodiment up to about 2 mm, and in one embodiment up to about 2 mm. The height of each microchannel may be in the range of about 0.05 to about 10 mm, and in one embodiment from about 0.05 to about 5 mm, and in one embodiment from about 0.05 to about 2 mm, and in one embodiment about 0.05 to about 1.5 mm. The width of each of these microchannels may be of any dimension, for example, up to about 3 meters, and in one embodiment from about 0.01 to about 3 meters, and in one embodiment about 0.1 to about 3 meters. The length of each microchannel may be of any dimension, for example, up to about 10 meters, and in one embodiment from about 0.05 to about 10 meters, and in one embodiment from about 0.05 to about 5 meters, and in one embodiment from about 0.05 to about 2 meters, and in one embodiment from about 0.1 to about 2 meters, and in one embodiment from about 0.1 to about 1.5 meters, and in one embodiment from 0.1 to about 1 meter, and in one embodiment from about 0.1 to about 0.7 meter.

[0197] The process microchannels, heat exchange channels and reactant stream channels may have rectangular cross sections and be aligned in side-by-side vertically oriented planes or horizontally oriented stacked planes. These planes may be tilted at an inclined angle from the horizontal. These configurations may be referred to as parallel plate configurations. These channels may be arranged in modularized compact units for scale-up.

[0198] The microchannel reactor may be made of any material that provides sufficient strength, dimensional stability and heat transfer characteristics to permit operation of the inventive process. These materials may include aluminum; titanium; nickel; copper; chromium; alloys of any of the foregoing metals; brass; steel; quartz; silicon; or a combination of two or more thereof. Use of non-metal materials of construction, (e.g., plastic, glass or ceramic materials) may be employed.

[0199] The microchannel reactor may be fabricated using known techniques including wire electrodischarge machining, conventional machining, laser cutting, photochemical machining, electrochemical machining, molding, water jet, stamping, etching (for example, chemical, photochemical or plasma etching) and combinations thereof.

[0200] The microchannel reactor may be constructed by forming shims with portions removed that allow flow passage. A stack of shims may be assembled via diffusion bonding, welding, diffusion brazing, and similar methods to form an integrated device. The microchannel reactor may be assembled using a combination of shims or laminae and partial sheets or strips. In this method, the channels or void areas may be formed by assembling strips or partial sheets to reduce the amount of material required.

[0201] The microchannel reactor may be constructed using waveforms in the form of right angled corrugated inserts. The small width between the tines of the waveform may provide the characteristic microchannel dimensions. The waveforms may be made of copper, stainless steel, and the like. These inserts may be sandwiched between opposing planar sheets or shims. In this manner the microchannels may be defined on three sides by the corrugated insert and on the fourth side by one of the planar sheets. The process microchannels as well as the reactant stream channels and heat exchange channels may be formed in this manner. This is shown in FIGS. **32** and **33**. The hydroprocessing catalyst may be coated on or packed around each waveform either before or after stacking and bonding the layers. Microchannel reactors made using waveforms are disclosed in WO 2008/030467, which is incorporated herein by reference.

[0202] The feed entering the first microchannel reactor for conducting the hydrotreating process may comprise liquid or vaporous heavy oil, or a mixture of liquid and vaporous heavy oil, and gaseous or vaporous hydrogen. The feed entering the second microchannel reactor conducting the hydrocracking process may comprise the hydrotreated product from the first microchannel reactor, and hydrogen. The microchannel reactor may comprise a manifold providing a flow passageway for the reactants to flow into the process microchannels. The microchannel reactor may comprise separate manifolds for flowing the reactants into the process microchannels, one of the manifolds being for the hydrocarbon reactant (i.e., heavy oil or intermediate hydrocarbon product), and the other manifold being for the hydrogen.

[0203] Hydroprocessing may be achieved where there is superior wetting of the catalyst due to the assistance of capillary forces. These may be further assisted by thin layers of liquid on the catalyst for enhanced mass transfer. The architecture for conducting hydroprocessing may include structures such as honeycomb monoliths (metal and/or ceramic), which may be filled or coated with catalyst particles.

[0204] An assembly for microchannel mixing of hydrogen and liquid may be installed upstream of or inside a conventional trickle bed reactor in order to achieve improved contacting.

[0205] One or more of the microchannel reactors **100** may be housed in microchannel reactor housing vessel **300** which is illustrated in FIGS. **6** and **7**. Referring to FIGS. **2**A, **2**B, **2**C, **6** and **7**, the vessel **300** contains twelve microchannel reactors **100**. These are identified in FIG. **7** as microchannel reactors **100-1**, **100-2**, **100-3**, **100-4**, **100-5**, **100-6**, **100-7**, **100-8**, **100-9**, **100-10**, **100-11** and **100-12**. Although twelve microchannel reactors **100** are disclosed in the drawings, it will be understood that the vessel **300** may contain any desired number of microchannel reactors. For example, the vessel **300** may contain from about 1 to about 1000 or more microchannel reactors, and in one embodiment from 1 to about 750, and in one embodiment from 1 to about 500, and in one embodiment from 1 to about 250, and in one embodiment from 1 to about 100, and in one embodiment from about 1 to about 50, and in one embodiment from 1 to about 20 microchannel reactors, and in one embodiment from 5 to about 20 microchannel reactors **100**, and in one embodiment from about 10 to about 20 microchannel reactors. The vessel **300** may be a pressurizable vessel. The vessel **300** includes inlets **310** and **320**, and outlets **330** and **340**. The inlet **310** is connected to a header **114** which is provided for flowing hydrocarbon reactants into the microchannel reactors **100**. An inlet (now shown in FIG. **6** or **7**) is provided for flowing H_2 into the microchannel reactors **100**. The inlet **320** is connected to header **176** which is provided for flowing heat exchange fluid (e.g., steam) into the microchannel reactors **100**. The outlet **330** is connected to footer **120** which provides for the flow of product out of the microchannel reactors **100**. The outlet **340** provides for the flow of the heat exchange fluid out of the heat exchange channels in the microchannel reactors **100**. The vessel **300** also includes a manway with demister **360**, steam outlet **362**, blowdown **364**, pressure relief valve **366**, level transmitter **368**, and temperature control device **370**.

[0206] The housing vessel **300** may be constructed using any suitable material sufficient for operating under the pressures and temperatures required for operating the microchannel reactors **100**. For example, the shell **350** and heads **352** of the vessel **300** may be constructed of cast steel. The flanges, couplings and pipes may be constructed of 316 stainless steel. The vessel **300** may have any desired diameter, for example, from about 10 to about 1000 cm, and in one embodiment from about 50 to about 300 cm, and in one embodiment from about 100 to about 200 cm. The axial length of the vessel **300** may be of any desired value, for example, from about 0.5 to about 50 meters, and in one embodiment from about 1 to about 20 meters, and in one embodiment from about 5 to about 20 meters, and in one embodiment from about 5 to about 10 meters.

[0207] In the design and operation of the microchannel reactor it may be advantageous to provide a tailored heat exchange profile along the length of the process microchannels in order to optimize the reaction. This may be accomplished by matching the local release of heat given off by the hydrotreating or hydrocracking reaction conducted in the process microchannels with heat removal or cooling provided by heat exchange fluid in heat exchange channels in the microchannel reactor. The extent of the hydrotreating or hydrocracking reaction and the consequent heat release provided by the reaction may be higher in the front or upstream sections of the reaction zones in the process microchannels as compared to the back or downstream sections of the reaction zones. Consequently, the matching cooling requirements may be higher in the upstream section of the reaction zones as compared to the downstream sections of the reaction zones. Tailored heat exchange may be accomplished by providing more heat exchange or cooling channels, and consequently the flow of more heat exchange or cooling fluid, in thermal contact with upstream sections of the reaction zones in the process microchannels as compared to the downstream sections of the reaction zones. Alternatively or additionally, a tailored heat exchange profile may be provided by varying the flow rate of heat exchange fluid in the heat exchange channels. In areas where additional heat exchange or cooling is desired, the flow rate of the heat exchange fluid may be increased as compared to areas where less heat exchange or cooling is required. For example, a higher rate of flow of heat exchange fluid may be advantageous in the heat exchange channels in thermal contact with the upstream sections of the reaction zones in the process microchannels as compared to the heat exchange channels in thermal contact with the downstream sections of the reaction zones. Heat transfer from the process microchannels to the heat exchange channels may be designed for optimum performance by selecting optimum heat exchange channel dimensions and/or the rate of flow of heat exchange fluid per individual or groups of heat exchange channels. Additional design alternatives for tailoring heat exchange may relate to the selection and design of the catalyst (such as, particle size, catalyst formulation, packing density, use of a graded catalyst, or other chemical or physical characteristics) at specific locations within the process microchannels. These design alternatives may impact both heat release from the process microchannels as well as heat transfer to the heat exchange fluid. Temperature differentials between the process microchannels and the heat exchange channels, which may provide the driving force for heat transfer, may be constant or may vary along the length of the process microchannels.

[0208] The process microchannels and/or heat exchange channels may contain one or more surface features in the form of depressions in and/or projections from one or more interior walls or interior structures of the process microchannels and/or heat exchange channels. Examples are shown in FIGS. **14**, **15** and **24**. The surface features may be used to disrupt the flow of fluid flowing in the channels. These disruptions in flow may enhance mixing and/or heat transfer. The surface features may be in the form of patterned surfaces. The microchannel reactors may be made by laminating a plurality of shims together. One or both major surfaces of the shims may contain surface features. Alternatively, the microchannel reactors may be assembled using some sheets or shims and some strips, or partial sheets to reduce the total amount of metal required to construct the device. In one embodiment, a shim containing surface features may be paired (on opposite sides of a microchannel) with another shim containing surface features. Pairing may create better mixing or heat transfer enhancement as compared to channels with surface features on only one major surface. In one embodiment, the patterning may comprise diagonal recesses that are disposed over substantially the entire width of a microchannel surface. The patterned surface feature area of a wall may occupy part of or the entire length of a microchannel surface. In one embodiment, surface features may be positioned over at least about 10%, and in one embodiment at least about 20%, and in one embodiment at least about 50%, and in one embodiment at least about 80% of the length of a channel surface. Each diagonal recess may comprise one or more angles relative to the flow direction. Successive recessed surface features may comprise similar or alternate angles relative to other recessed surface features.

[0209] In embodiments wherein surface features may be positioned on or in more than one microchannel wall, the surface features on or in one wall may have the same (or similar) pattern as found on a second wall, but rotated about the centerline of the main channel mean bulk flow direction. In embodiments wherein surface features may be on or in opposite walls, the surface features on or in one wall may be approximately mirror images of the features on the opposite wall. In embodiments wherein surface features are on or in more than one wall, the surface features on or in one wall may be the same (or similar) pattern as found on a second wall, but rotated about an axis which is orthogonal to the main channel mean bulk flow direction. In other words, the surface features may be flipped 180 degrees relative to the main channel mean bulk flow direction and rotated about the centerline of the main channel mean bulk flow. The surface features on or in opposing or adjacent walls may or may not be aligned directly with one another, but may be repeated continuously along the wall for at least part of the length of the wall. Surface features may be positioned on three or more interior surfaces of a channel. For the case of channel geometries with three or fewer sides, such as triangular, oval, elliptical, circular, and the like, the surface features may cover from about 20% to about 100% of the perimeter of the microchannel.

[0210] In one embodiment, a patterned surface may comprise multiple patterns stacked on top of each other. A pattern or array of holes may be placed adjacent to a heat transfer wall and a second pattern, such as a diagonal array of surface features may be stacked on top and adjacent to an open channel for flow. A sheet adjacent to an open gap may have patterning through the thickness of the sheet such that flow may pass through the sheet into an underlying pattern. Flow may occur as a result of advection or diffusion. As an example, a first sheet with an array of through holes may be placed over a heat transfer wall, and a second sheet with an array of diagonal through slots may be positioned on the first sheet. This may create more surface area for adhering a catalyst. In one embodiment, the pattern may be repeated on at least one other wall of the process microchannel. The patterns may be offset on opposing walls. The innermost patterned surfaces (those surfaces bounding a flow channel) may contain a pattern such as a diagonal array. The diagonal arrays may be oriented both "with" the direction of flow or one side oriented with the direction of flow and the opposing side oriented "against" the direction of flow. By varying surface features on opposing walls, different flow fields and degrees of vorticity may be created in the fluid that travels down the center and open gap.

[0211] The surface features may be oriented at angles relative to the direction of flow through the channels. The surface features may be aligned at an angle from about 1° to about 89°, and in one embodiment from about 30° to about 75°, relative to the direction of flow. The angle of orientation may be an oblique angle. The angled surface features may be aligned toward the direction of flow or against the direction of flow. The flow of fluid in contact with the surface features may force some of the fluid into depressions in the surface features, while other fluids may flow above the surface features. Flow within the surface features may conform with the surface feature and be at an angle to the direction of the bulk flow direction in the channel. As fluid exits the surface features it may exert momentum in the x and y direction for an x,y,z coordinate system wherein the bulk flow direction is in the z direction. This may result in a churning or rotation in the flow of the fluids. This pattern may be helpful for mixing.

[0212] Two or more surface feature regions within the process microchannels may be placed in series such that mixing of the fluids may be accomplished using a first surface feature region, followed by at least one second surface feature region where a different flow pattern may be used.

[0213] The surface features may have two or more layers stacked on top of each other or intertwined in a three-dimensional pattern. The pattern in each discrete layer may be the same or different. Flow may rotate or advect in each layer or only in one layer. Sub-layers, which may not be adjacent to the bulk flow path of the channel, may be used to create additional surface area. The flow may rotate in the first level of surface features and diffuse molecularly into the second or more sublayers to promote reaction. Three-dimensional surface features may be made via metal casting, photochemical machining, laser cutting, etching, ablation, or other processes where varying patterns may be broken into discrete planes as if stacked on top of one another. Three-dimensional surface features may be provided adjacent to the bulk flow path within the microchannel where the surface features have different depths, shapes, and/or locations accompanied by sub-features with patterns of varying depths, shapes and/or locations.

[0214] An example of a three-dimensional surface feature structure may comprise recessed oblique angles or chevrons at the interface adjacent the bulk flow path of the microchannel. Beneath the chevrons there may be a series of three-dimensional structures that connect to the surface features adjacent to the bulk flow path but are made from structures of assorted shapes, depths, and/or locations. It may be further advantageous to provide sublayer passages that do not directly fall beneath an open surface feature that is adjacent to the bulk flow path within the microchannel but rather connect through one or more tortuous two-dimensional or three-dimensional passages. This approach may be advantageous for creating tailored residence time distributions in the microchannels, where it may be desirable to have a wider versus more narrow residence time distribution.

[0215] The length and width of a surface feature may be defined in the same way as the length and width of a channel. The depth may be the distance which the surface feature sinks into or rises above the microchannel surface. The depth of the surface features may correspond to the direction of stacking a stacked and bonded microchannel device with surface features formed on or in the sheet surfaces. The dimensions for the surface features may refer the maximum dimension of a surface feature; for example the depth of a rounded groove may refer to the maximum depth, that is, the depth at the bottom of the groove.

[0216] The surface features may have depths that are up to about 5 mm, and in one embodiment up to about 2 mm, and in one embodiment in the range from about 0.01 to about 5 mm, and in one embodiment in the range from about 0.01 to about 2 mm, and in one embodiment in the range from about 0.01 mm to about 1 mm. The width of the surface features may be sufficient to nearly span the microchannel width (for example, herringbone designs), but in one embodiment (such as fill features) may span about 60% or less of the width of the microchannel, and in one embodiment about 50% or less, and in one embodiment about 40% or less, and in one embodiment from about 0.1% to about 60% of the microchannel width, and in one embodiment from about 0.1% to about 50% of the microchannel width, and in one embodiment from about 0.1% to about 40% of the microchannel width. The width of the surface features may be in the range from about 0.05 mm to about 100 cm, and in one embodiment in the range from about 0.5 mm to about 5 cm, and in one embodiment in the range from about 1 to about 2 cm.

[0217] Multiple surface features or regions of surface features may be included within a channel, including surface features that recess at different depths into one or more microchannel walls. The spacing between recesses may be in the range from about 0.01 mm to about 10 mm, and in one embodiment in the range from about 0.1 to about 1 mm. The surface features may be present throughout the entire length of a microchannel or in portions or regions of the channel. The portion or region having surface features may be intermittent so as to promote a desired mixing or unit operation (for example, separation, cooling, etc.) in tailored zones. For example, a one-centimeter section of a channel may have a tightly spaced array of surface features, followed by four centimeters of a flat channel without surface features, followed by a two-centimeter section of loosely spaced surface features. The term “loosely spaced surface features” may be used to refer to surface features with a pitch or feature to feature distance that is more than about five times the width of the surface feature.

[0218] The surface features may be positioned in one or more surface feature regions that extend substantially over the entire axial length of a channel. In one embodiment, a channel may have surface features extending over about 50% or less of its axial length, and in one embodiment over about 20% or less of its axial length. In one embodiment, the surface features may extend over about 10% to about 100% of the axial length of the channel, and in one embodiment from about 20% to about 90%, and in one embodiment from about 30% to about 80%, and in one embodiment from about 40% to about 60% of the axial length of a channel.

[0219] Each surface feature leg may be at an oblique angle relative to the bulk flow direction. The feature span length or span may be defined as being normal to the feature orientation. As an example, one surface feature may be a diagonal depression at a 45 degree angle relative to a plane orthogonal to the mean direction of bulk flow in the main channel with a 0.38 mm opening or span or feature span length and a feature run length of 5.6 mm. The run length may be the distance from one end to the other end of the surface feature in the longest direction, whereas the span or feature span length may be in the shortest direction (that is not depth). The surface feature depth may be the distance way from the main channel. For surface features with a nonuniform width (span), the span may be the average span averaged over the run length.

[0220] A surface feature may comprise a recess or a protrusion based on the projected area at the base of the surface feature or the top of the surface feature. If the area at the top of the surface feature is the same or exceeds the area at the base of the surface feature, then the surface feature may be considered to be recessed. If the area at the base of the surface feature exceeds the area at the top of the surface feature, then it may be considered to be protruded. For this description, the surface features may be described as recessed although it is to be understood that by changing the aspect ratio of the surface feature it may be alternatively defined as a protrusion. For a process microchannel defined by walls that intersect only the tops of the surface features, especially for a flat channel, all surface features may be defined as recessed and it is to be understood that a similar channel could be created by protruding surface features from the base of a channel with a cross section that includes the base of the surface features.

[0221] The process microchannels and/or heat exchange channels may have at least about 20%, and in one embodiment at least about 35%, and in one embodiment at least about 50%, and in one embodiment at least about 70%, and in one embodiment at least about 90% of the interior surface of the channel (measured in cross-section perpendicular to length; i.e., perpendicular to the direction of net flow through the channel) that contains surface features. The surface features may cover a continuous stretch of at least about 1 cm, and in one embodiment at least about 5 cm. In the case of an enclosed channel, the percentage of surface feature coverage may be the portion of a cross-section covered with surface features as compared to an enclosed channel that extends uniformly from either the base or the top of the surface feature or a constant value in-between. The latter may be a flat channel. For example, if a channel has patterned top and bottom surfaces that are each 0.9 cm across (wide) and unpatterned side walls that are 0.1 cm high, then 90% of the surface of the channel would contain surface features.

[0222] The process microchannel may be enclosed on all sides, and in one embodiment the channel may have a generally square or rectangular cross-section (in the case of rectangular channel, surface feature patterning may be positioned on both major faces). For a generally square or rectangular channel, the channel may be enclosed on only two or three sides and only the two or three walled sides may be used in the above described calculation of percentage surface features. In one embodiment, the surface features may be positioned on cylindrical channels with either constant or varying cross section in the axial direction.

[0223] Each of the surface feature patterns may be repeated along one face of the channel, with variable or regular spacing between the surface features in the channel bulk flow direction. Some embodiments may have only a single leg to each surface feature, while other embodiments may have multiple legs (two, three, or more). For a wide-width channel, multiple surface features or columns of repeated surface features may be placed adjacent to one another across the width of the channel. For each of the surface feature patterns, the feature depth, width, span, and spacing may be variable or constant as the pattern is repeated along the bulk flow direction in the main channel. Also, surface feature geometries having an apex connecting two legs at different angles may have alternate embodiments in which the surface feature legs may not be connected at the apex.

[0224] An advantage of the inventive process, at least in one embodiment, is that the gap distances between the process microchannels, optional reactant stream channels, and heat exchange channels may be the same whether the process is intended for laboratory or pilot plant scale or for full production scale. As a result, the dispersion of the hydrogen reactant into the reaction mixture used in the inventive process may be substantially the same whether the microchannel reactor is built on a laboratory, pilot plant scale or as a full scale plant unit.

[0225] The catalyst may be segregated into separate reaction zones in the process microchannels in the direction of flow through the process microchannels. The same or different catalyst or catalyst composition may be used in each reaction zone. In each reaction zone the length of one or more adjacent heat exchange zone(s) may vary in their dimensions. For example, in one embodiment, the length of the one or more adjacent heat exchange zones may be less than about 50% of the length of each reaction zone. Alternatively, the one or more heat exchange zones may have lengths that are more than about 50% of the length of each reaction zone up to about 100% of the length of each reaction zone.

[0226] The catalyst may be in the form of a catalyst bed that is graded in composition or graded with a thermally conductive inert material. The thermally conductive inert material may be interspersed with the active catalyst. Examples of thermally conductive inert materials that may be used include diamond powder, silicon carbide, aluminum, alumina, copper, graphite, and the like. The bed fraction may range from 100% by weight active catalyst to less than about 10% by weight active catalyst. In an alternate embodiment the thermally conductive inert material may be deployed at the center or within the catalyst particles. The active catalyst may be deposited on the outside, inside or intermittent within a composite structure that includes the thermally conductive inert. The resulting catalyst composite structure may have an effective thermal conductivity when placed in a process microchannel that is at least about 0.5 W/m/K, and in one embodiment at least about 1 W/m/K, and in one embodiment at least about 2 W/m/K.

[0227] The catalyst may be in the form of a catalyst bed that is graded only locally within the reactor. For example, a process microchannel may contain a catalyst bed with a first reaction zone and a second reaction zone. The top or bottom (or front or back) of the catalyst bed may be graded in composition whereby a more or less active catalyst is employed in all or part of the first or second reaction zone. The composition that is reduced in one reaction zone may generate less heat per unit volume and thus reduce the hot spot and potential for the production of undesirable by-products. The catalyst may be graded with an inert material in the first and/or second reaction zone, in full or in part. The first reaction zone may contain a first composition of catalyst or inert material, while the second reaction zone may contain a second composition of catalyst or inert material.

[0228] In one embodiment, different particle sizes may be used in different axial length regions of the process microchannels to provide for graded catalyst beds. For example, very small particles may be used in a first reaction zone while larger particles may be used in a second reaction zone. The average particle diameters may be less than half the height or gap of the process microchannels. The very small particles may be less than one-fourth of the process microchannel height or gap. Larger particles may cause lower pressure drops per unit length of the process microchannels and may also reduce the catalyst effectiveness. The effective thermal conductivity of the catalyst bed may be lower for larger size particles. Smaller particles may be used in regions where improved heat transfer is sought throughout the catalyst bed or alternatively larger particles may be used to reduce the local rate of heat generation.

[0229] In one embodiment, relatively short contact times, high selectivity to the desired product and relatively low rates of deactivation of the catalyst may be achieved by limiting the diffusion path required for the catalyst. This may be achieved when the catalyst is in the form of a thin layer on an engineered support such as a metallic foam or on the wall of the process microchannel. This allows for increased space velocities. In one embodiment, the thin layer of catalyst may be produced using chemical vapor deposition or by a chemical reaction in a solution, for example, electroless plating. This thin layer may have a thickness in the range up to about 5 microns, and in one embodiment from about 0.1 to about 5 microns, and in one embodiment from about 0.5 to about 3 microns, and in one embodiment from about 1 to about 3 microns, and in one embodiment about 2.5 microns. These thin layers may reduce the time the reactants are within the active catalyst structure by reducing the diffusional path. This decreases the time the reactants spend in the active portion of the catalyst. The result may be increased selectivity to the product and reduced unwanted by-products. An advantage of this mode of catalyst deployment is that, unlike conventional catalysts in which the active portion of the catalyst may be bound up in an inert low thermal conductivity binder, the active catalyst film may be in intimate contact with either the engineered structure or the wall of the process microchannel. This may leverage high heat transfer rates attainable in the microchannel reactor and allow for close control of temperature. This may result in the ability to operate at increased temperature (faster kinetics) without promoting the formation of undesired by-products, thus producing higher productivity and yield and prolonging catalyst life.

[0230] The microchannel reactor configuration may be tailored to match the reaction kinetics. For example, near the entrance or top of a first reaction zone of the reactor, the microchannel height or gap may be smaller than in a second reaction zone near the exit or bottom of the reactor. Alternatively, the zones may be much smaller than half the reactor length. For example, a first process microchannel height or gap may be used for the first 25%, 50%, 75%, or 90% of the length of the process microchannel, while a larger second height or gap may be used in a second reaction zone downstream from the first reaction zone. Alternatively, different configurations may be used. For example, a larger process microchannel height or gap may be used near the entrance of the process microchannels and a smaller process microchannel height or gap may be used near the reactor exit. In one embodiment, other gradations in the process microchannel height or gap may be used. For example, a first height or gap may be used near the entrance of the microchannel to provide a first reaction zone, a second height or gap downstream from the first reaction zone may be used to provide a second reaction zone, and a third height or gap may be used to provide a third reaction zone near the exit of the microchannel. The first and third heights or gaps may be the same or different. The first and third heights or gaps may be larger or smaller than the second height or gap. The third height or gap may be smaller or larger than the second height or gap. The second height or gap may be larger or smaller than the third height or gap.

[0231] The openings or apertures **254** (FIGS. **9-13**) may be of sufficient size to permit the flow of the hydrogen reactant through the apertured sections. The openings **254** may be referred to as pores. The apertured section **258** may have thicknesses in the range from about 0.01 to about 50 mm, and in one embodiment about 0.05 to about 10 mm, and in one embodiment about 0.1 to about 2 mm. The openings **254** may have average diameters in the range up to about 1000 microns, and in one embodiment up to about 250 microns, and in one embodiment up to about 50 microns, and in one embodiment in the range from about 0.001 to about 50 microns, and in one embodiment from about 0.05 to about 50 microns, and in one embodiment from about 0.1 to about 50 microns. In one embodiment, the openings **254** may have average diameters in the range from about 0.5 to about 10 nanometers (nm), and in one embodiment about 1 to about 10 nm, and in one embodiment about 5 to about 10 nm. The number of openings **254** in the apertured section **258** may be in the range from about 1 to about 5×10^8 openings per square centimeter, and in one embodiment about 1 to about 1×10^6 openings per square centimeter. The openings **254** may or may not be isolated from each other. A portion or all of the openings **254** may be in fluid communication with other openings **254** within the apertured section **258**; that is, a fluid may flow from one opening to another opening. The ratio of the thickness of the apertured section **258** to the length of the apertured section along the flow path of the fluids flowing through the process microchannels **210** may be in the range from about 0.001 to about 1, and in one embodiment about 0.01 to about 1, and in one embodiment about 0.03 to about 1, and in one embodiment about 0.05 to about 1, and in one embodiment about 0.08 to about 1, and in one embodiment about 0.1 to about 1.

[0232] The apertured section **258** may be constructed of any material that provides sufficient strength and dimensional stability to permit the operation of the inventive process. These materials include: steel (e.g., stainless steel, carbon steel, and the like); monel; inconel; brass; aluminum; titanium; nickel; copper; chromium; alloys of any of the foregoing metals; polymers (e.g., thermoset resins); ceramics; glass; composites comprising one or more polymers (e.g., thermoset resins) and fiberglass; quartz; silicon; microporous carbon, including carbon nanotubes or carbon molecular sieves; zeolites; or a combination of two or more thereof. The openings **254** may be formed using known techniques such as laser drilling, microelectro machining system (MEMS), lithography electrodeposition and molding (LIGA), electrical sparkling, or electrochemical or photochemical etching. The openings **254** may be formed using techniques used for making structured plastics, such as extrusion, or membranes, such as aligned carbon nanotube (CNT) membranes. The openings **254** may be formed using techniques such as sintering or compressing metallic powder or particles to form tortuous interconnected capillary channels and the techniques of membrane fabrication. The openings **254** may be reduced in size from the size provided by any of these methods by the application of coatings over the apertures internal side walls to partially fill the apertures. The selective coatings may also form a thin layer exterior to the porous body that provides the smallest pore size adjacent to the continuous flow path. The smallest average pore opening may be in the range from about one nanometer to about several hundred microns depending upon the desired droplet size for the emulsion. The apertures may be reduced in size by heat treating as well as by methods that form an oxide scale or coating on the internal side walls of the apertures. These techniques may be used to partially occlude the apertures to reduce the size of the openings for flow.

[0233] The apertured section **258** may be made from a metallic or nonmetallic porous material having interconnected channels or pores of an average pore size in the range from about 0.01 to about 200 microns. These pores may function as the openings **254**. The porous material may be made from powder or particulates so that the average inter-pore distance is similar to the average pore size. When very small pore sizes are used, the inter-pore distance may also be very small. The porous material may be tailored by oxidization at a high temperature in the range from about 300° C. to about 1000° C. for a duration of about 1 hour to about 20 days, or by coating a thin layer of another material such as alumina by sol coating or nickel using chemical vapor deposition over the surface and the inside of pores to block the smaller pores, decrease pore size of larger pores, and in turn increase the inter-pore distance.

[0234] The cooling of the process microchannels during the inventive process, in one embodiment, is advantageous for reducing the formation of undesired coke. As a result of this cooling, in one embodiment, the temperature of the feed streams entering the entrance to the process microchannels may be within about 200° C., and in one embodiment within about 100° C., and in one embodiment within about 50° C., and in one embodiment within about 20° C., of the temperature of the product exiting the process microchannels.

[0235] The hydrotreating catalyst may be any hydrotreating catalyst. The hydrotreating catalyst may comprise Ni, Mo, Co, W, or combinations of two or more thereof. These may be supported on alumina. The catalyst may comprise Mo-W/Al_2O_3.

[0236] The hydrocracking catalyst may be any hydrocracking catalyst. These catalysts may include zeolite catalysts including beta zeolite, omega zeolite, L-zeolite, ZSM-5 zeolites and Y-type zeolites. The hydrocracking catalyst may comprise one or more pillared clays, MCM-41, MCM-48, HMS, or a combination of two or more thereof. The hydrocracking catalyst may comprise Pt, Pd, Ni, Co, Mo, W, or a combination of two or more thereof. The hydrocracking catalyst may include a refractory inorganic oxide such as alumina, magnesia, silica, titania, zirconia and silica-alumina. The hydrocracking catalyst may comprise a hydrogenation component. Examples of suitable hydrogenation components include metals of Group IVB and Group VIII of the Periodic Table and compounds of such metals. Molybdenum, tungsten, chromium, iron, cobalt, nickel, platinum, palladium, iridium, osmium, rhodium and ruthenium may be used as the hydrogenation component. These catalysts are described in U.S. Pat. No. 6,312,586 B1, which is incorporated herein by reference.

[0237] The hydrotreating and hydrocracking catalysts that are used in the microchannel reactor may have any size and geometric configuration that fits within the process microchannels. The catalyst may be in the form of particulate solids (e.g., pellets, powder, fibers, and the like) having a median particle diameter of about 1 to about 1000 μm (microns), and in one embodiment from about 10 to about 500 μm, and in one embodiment from about 25 to about 300 μm, and in one embodiment from about 80 to about 300 μm.

[0238] The catalyst may be in the form of a bed of particulate solids. The median particle diameter may be in the range from about 1 to about 1000 μm, and in one embodiment from about 10 to about 500 μm. This is shown in FIG. **16** wherein a bed of particulate solids **400** is packed in process microchannel **402**. Reactants flow into the process microchannel as indicated by arrow **404** and product flows out of the process microchannel as indicated by arrow **406**. Microfibers (e.g. within a catalyst bed or catalyst bale and/or coated with catalyst) to promote good liquid distribution across a catalyst may be used.

[0239] Foams for retaining catalyst particles and/or coated foams, including graphite foams, silicon carbide, metal (e.g., Fecralloy), ceramic, and/or internal coatings of grapheme for high thermal conductivity coating may be used.

[0240] The catalyst may be supported on a porous support structure such as a foam, felt, wad or a combination thereof. The term "foam" is used herein to refer to a structure with continuous walls that include pores positioned along the length or the structure or throughout the structure. The pores may be on the surface of the continuous walls and used for adhering catalyst material (e.g., catalyst metal particles) to the walls of the foam structure. The term "felt" is used herein to refer to a structure of fibers with interstitial spaces there between. The term "wad" is used herein to refer to a structure of tangled strands, like steel wool. The catalyst may be supported on a monolith or honeycomb structure.

[0241] The catalyst may be supported on a flow-by support structure such as a felt with an adjacent gap, a foam with an adjacent gap, a fin structure with gaps, a washcoat on any inserted substrate, or a gauze that is parallel to the flow direction with a corresponding gap for flow. An example of a flow-by structure is illustrated in FIG. **17**. In FIG. **17**, the catalyst **410** is contained within process microchannel **412**. An open passage way **414** permits the flow of fluid through the process microchannel **412** in contact with the catalyst **410** as indicated by arrows **416** and **418**.

[0242] The catalyst may be supported on a flow-through support structure such as a foam, wad, pellet, powder, or gauze. An example of a flow-through structure is illustrated in FIG. **18**. In FIG. **18**, the flow-through catalyst **420** is contained within process microchannel **422** and the fluid flows through the catalyst **420** as indicated by arrows **424** and **426**.

[0243] The support structure for a flow-through catalyst may be formed from a material comprising silica gel, foamed copper, sintered stainless steel fiber, steel wool, alumina, poly(methyl methacrylate), polysulfonate, poly(tetrafluoroethylene), iron, nickel sponge, nylon, polyvinylidene difluoride, polypropylene, polyethylene, polyethylene ethylketone, polyvinyl alcohol, polyvinyl acetate, polyacrylate, polymethylmethacrylate, polystyrene, polyphenylene sulfide, polysulfone, polybutylene, or a combination of two or more thereof. In one embodiment, the support structure may be made of a heat conducting material, such as a metal, to enhance the transfer of heat away from the catalyst.

[0244] The catalyst may be directly washcoated on the interior walls of the process microchannels, grown on the walls from solution, or coated in situ on a fin structure or other support structure. The catalyst may be in the form of one or more pieces of porous contiguous material. In one embodiment, the catalyst may be comprised of a contiguous material and has a contiguous porosity such that molecules can diffuse through the catalyst. In this embodiment, the fluids flow through the catalyst rather than around it. In one embodiment, the cross-sectional area of the catalyst occupies about 1 to about 99%, and in one embodiment about 10 to about 95% of the cross-sectional area of the process microchannels. The catalyst may have a surface area, as measured by BET, of greater than about 0.5 m^2/g, and in one embodiment greater than about 2 m^2/g.

[0245] The catalyst may comprise a porous support, an interfacial layer on the porous support, and a catalyst material deposited on or mixed with the interfacial layer. In one embodiment, a buffer layer may be positioned between the porous support and the interfacial layer. The buffer layer may be grown or deposited on the porous structure. For example, the porous support may be made of an alumina forming material such as Fecralloy (an alloy of Fe, Cr. Al and Y), and the porous structure may be heat treated in air to form an alumina layer on the surface of the porous support. This alumina layer would be a buffer layer. The interfacial layer may be coated or solution deposited on the surface of the porous support or it may be deposited by chemical vapor deposition or physical vapor deposition. Any of the foregoing layers may be continuous or discontinuous as in the form of spots or dots, or in the form of a layer with gaps or holes.

[0246] The porous support may have a porosity of at least about 5% as measured by mercury porosimetry. The porous support may have an opening or gap with a height or width normal to the bulk flow direction of reactants flowing through the catalyst in the range from about 1 to about 2000 μm, and in one embodiment from about 1 to about 1500 μm. The reactants flowing through the opening or gap may contact catalyst on the walls of the porous support. The porous support may be a ceramic or a metal support. Other porous supports that may be used include carbides, nitrides, and composite materials. The porous support may have a porosity of about 30% to about 99%, and in one embodiment about 60% to about 98%. The porous support may be in the form of a foam, felt, wad, or a combination thereof. The foam may have a porous construction on the surface of its walls with about 20 pores per inch (ppi) to about 3000 ppi, and in one embodiment about 20 to about 1000 ppi, and in one embodiment about 40 to about 120 ppi. The term "ppi" refers to the largest number of pores per inch (in isotropic materials the direction of the measurement is irrelevant; however, in anisotropic materials, the measurement is done in the direction that maximizes pore number).

[0247] The buffer layer, when present, may have a different composition and/or density than both the porous support and the interfacial layers, and in one embodiment has a coefficient of thermal expansion that is intermediate the thermal expansion coefficients of the porous support and the interfacial layer. The buffer layer may be a metal oxide or metal carbide. The buffer layer may be comprised of Al_2O_3, TiO_2, SiO_2, ZrO_2, or combination thereof. The Al_2O_3 may be α-Al_2O_3, γ-Al_2O_3 or a combination thereof. α-Al_2O_3 provides the advantage of excellent resistance to oxygen diffusion. When the porous support is made of an alumina forming material such as Fecralloy (an alloy of Fe, Cr, Al and Y), the buffer layer may be Al_2O_3 on the surface of the porous support formed by heating the porous support in air.

[0248] The buffer layer may comprise two or more compositionally different sublayers. For example, when the porous support is metal, for example a stainless steel foam, a buffer layer formed of two compositionally different sub-layers may be used. The first sublayer (in contact with the porous support) may be TiO_2. The second sublayer may be α-Al_2O_3 which is placed upon the TiO_2. In one embodiment, the α-Al_2O_3 sublayer is a dense layer that provides protection of the underlying metal surface. A less dense, high surface area interfacial layer such as alumina may then be deposited as support for a catalytically active layer.

[0249] The porous support may have a thermal coefficient of expansion different from that of the interfacial layer. In such a case a buffer layer may be needed to transition between the two coefficients of thermal expansion. The thermal expansion coefficient of the buffer layer can be tailored by controlling its composition to obtain an expansion coefficient that is compatible with the expansion coefficients of the porous support and interfacial layers. The buffer layer should be free of openings and pin holes to provide superior protection of the underlying support. The buffer layer may be nonporous. The buffer layer may have a thickness that is less than one half of the average pore size of the porous support. The buffer layer may have a thickness of about 0.05 to about 10 μm, and in one embodiment about 0.05 to about 5 μm.

[0250] The buffer layer may be used to increase the adhesion of the interfacial layer to the surface of the porous support. However, in one embodiment of the invention, adequate adhesion and chemical stability may be obtained without a buffer layer and, consequently, in this embodiment the buffer layer may be omitted.

[0251] The interfacial layer may comprise nitrides, carbides, sulfides, halides, metal oxides, carbon, or a combination thereof. The interfacial layer provides high surface area and/or provides a desirable catalyst-support interaction for supported catalysts.

[0252] The interfacial layer may be comprised of any material that is conventionally used as a catalyst support. The interfacial layer may be comprised of a metal oxide. Examples of metal oxides that may be used include Al_2O_3, SiO_2, ZrO_2, TiO_2, tungsten oxide, magnesium oxide, vanadium oxide, chromium oxide, manganese oxide, iron oxide, nickel oxide, cobalt oxide, copper oxide, zinc oxide, molybdenum oxide, tin oxide, calcium oxide, aluminum oxide, lanthanum series oxide(s), zeolite(s) and combinations thereof. The interfacial layer may serve as a catalytically active layer without any further catalytically active material deposited thereon. Usually, however, the interfacial layer is used in combination with a catalytically active layer. The interfacial layer may also be formed of two or more compositionally different sublayers. The interfacial layer may have a thickness that is less than one half of the average pore size of the porous support. The interfacial layer thickness may range from about 0.5 to about 100 μm, and in one embodiment from about 1 to about 50 μm. The interfacial layer may be either crystalline or amorphous. The interfacial layer may have a BET surface area of at least about 1 m^2/g.

[0253] The catalyst may be deposited on the interfacial layer. Alternatively, the catalyst material may be simultaneously deposited with the interfacial layer. The catalyst layer may be intimately dispersed on the interfacial layer. That the catalyst layer is "dispersed on" or "deposited on" the interfacial layer includes the conventional understanding that microscopic catalyst particles are dispersed: on the support layer (i.e., interfacial layer) surface, in crevices in the support layer, and in open pores in the support layer.

[0254] The catalyst may be in the form of a bed of particulate solids positioned in a reaction zone wherein one or more interior walls of the reaction zone includes additional catalyst washcoated and/or grown thereon. The catalyst in the bed of particulate solids may be the same as the catalyst washcoated and/or grown on the interior walls of the reaction zone, or it may be different.

[0255] The catalyst may be supported on an assembly of one or more fins or other structures positioned within the process microchannels. Examples are illustrated in FIGS. **19-21**. Referring to FIG. **19**, fin assembly **430** includes fins **432** which are mounted on fin support **434** which overlies base wall **436** of process microchannel **438**. The fins **432** project from the fin support **434** into the interior of the process microchannel **438**. The fins **432** extend to and may contact the interior surface of upper wall **440** of process microchannel **438**. Fin channels **442** between the fins **432** provide passage ways for fluid to flow through the process microchannel **438** parallel to its length. Each of the fins **432** has an exterior surface on each of its sides, this exterior surface provides a support base for the catalyst. With the inventive process, the reactant composition flows through the fin channels **442**, contacts the catalyst supported on the exterior surface of the fins **432**, and reacts to form the product. The fin assembly **430***a* illustrated in FIG. **20** is similar to the fin assembly **430** illustrated in FIG. **19** except that the fins **432***a* do not extend all the way to the interior surface of the upper wall **440** of the microchannel **438**. The fin assembly **430***b* illustrated in FIG. **21** is similar to the fin assembly **430** illustrated in FIG. **20** except that the fins **432***b* in the fin assembly **430***b* have cross sectional shapes in the form of trapezoids. Each of the fins may have a height ranging from about 0.02 mm up to the height of the process microchannel **438**, and in one embodiment from about 0.02 to about 10 mm, and in one embodiment from about 0.02 to about 5 mm, and in one embodiment from about 0.02 to about 2 mm. The width of each fin may range from about 0.02 to about 5 mm, and in one embodiment from about 0.02 to about 2 mm and in one embodiment about 0.02 to about 1 mm. The length of each fin may be of any length up to the length of the process microchannel **438**, and in one embodiment up to about 10 m, and in one embodiment about 0.5 to about 10 m, and in one embodiment about 0.5 to about 6 m, and in one embodiment about 0.5 to about 3 m. The gap between each of the fins may be of any value and may range from about 0.02 to about 5 mm, and in one embodiment from about 0.02 to about 2 mm, and in one embodiment from about 0.02 to about 1 mm. The number of fins in the process microchannel **438** may range from about 1 to about 50 fins per centimeter of width of the process microchannel **438**, and in one embodiment from about 1 to about 30 fins per centimeter, and in one embodiment from about 1 to about 10 fins per centimeter, and in one embodiment from about 1 to about 5 fins per centimeter, and in one embodiment from about 1 to about 3 fins per centimeter. Each of the fins may have a cross-section in the form of a rectangle or square as illustrated in FIG. **19** or **20**, or a trapezoid as illustrated in FIG. **21**. When viewed along its length, each fin may be straight, tapered or have a serpentine configuration. The fin assembly may be made of any material that provides sufficient strength, dimensional stability and heat transfer characteristics to permit operation for which the process microchannel is intended. These materials include: steel (e.g., stainless steel, carbon steel, and the like); aluminum; titanium; nickel; platinum; rhodium; copper; chromium; alloys of any of the foregoing metals; monel; inconel; brass; polymers (e.g., thermoset resins); ceramics; glass; composites comprising one or more polymers (e.g., thermoset resins) and fiberglass; quartz; silicon; or a combination of two or more thereof. The fin assembly may be made of an Al_2O_3 forming material such as an alloy comprising Fe, Cr, Al and Y, or a Cr_2O_3 forming material such as an alloy of Ni, Cr and Fe.

[0256] The catalyst may be supported by a microgrooved support strip. Examples of these support strips are illustrated in FIGS. **22** and **23**. Referring to FIG. **23**, process microchannel **450** includes support strip **452** mounted on interior wall **454** of the process microchannel **450**. Bulk flow region **456** is defined by the space within the process microchannel **450** between the support strip **452** and the top channel wall **457**. Process fluid flows through the process microchannel **450** as indicated by arrows **458** and **460**. In flowing through the process microchannel **450**, the process fluid flows through the bulk flow region **456** in contact with the catalyst support strip **452**. The catalyst may be in the form of microsized particulates positioned in the microgrooves **462**. The support strip **452** is a flow-by support strip. However, some of the process fluid may flow in the microgrooves **462** in contact with the catalyst. The flow of the process fluid through the microgrooves **462** may be in the general direction from the front edge **463** and the first side edge **464** toward the second side edge **466** and the back edge **468**. The process microchannel illustrated in FIG. **23** is similar to the process microchannel illustrated in FIG. **22** with the exception that the process microchannel **450** illustrated in FIG. **23** contains opposite interior walls **454** and **457** and a catalyst supporting support strip **452** mounted on each of the opposite interior walls. Additional details concerning the construction and use of the microgrooved support strip **452** can be found in US Patent Publication No. U.S. 2007-0225532A1, which is incorporated herein by reference.

[0257] Surface features can be used in combination with a supported catalyst to enhance contact between the reactants and the catalyst. This is shown in FIG. **24**. Referring to FIG. **24**, process microchannel **450** which has support strip **452** mounted on interior wall **454** and surface features **470** formed in the opposite interior wall **457**. Process fluid flows through the process microchannel **450** as indicated by arrows **472**. The flow of the process fluid is modified as the process fluid flows through surface features **470**. The surface features **470** illustrated in FIG. **24** are in the form of hemispherical depressions in the microchannel wall **457**. The modification of the flow of the process fluids by the surface features **470** enhances contact between the process fluid and the catalyst supported by the support strip **452**.

[0258] A sintered ceramic or metal material (e.g., one micron, Inconel sintered metal) may be used to contact the catalyst or to support the catalyst in the microchannel reactor. The sintered material may be contained or attached to interior walls of solid metal "sleeves" to form a unit, which may serve as individual pressure vessels and may be added for capacity/replacement. The sintered metal and/or metal sleeves may comprise a high thermal conductivity metal such as copper, aluminum or titanium. Catalyst particles may be loaded into the subassemblies. The catalyst may be coated using solution coating, slurry coating, sol-gel coating, physical vapor deposition, chemical vapor deposition or electroless plating onto the sintered metal.

[0259] The catalyst may be regenerated. This may be done by flowing a regenerating fluid through the process microchannels in contact with the catalyst. The regenerating fluid may comprise hydrogen or a diluted hydrogen stream, hydrogen sulphide (or other sulphur containing compound) or a diluted hydrogen sulphide (or other sulphur containing compound) stream, oxygen or an oxygen containing stream, or a stream containing a halogen containing gas or a mixture of oxygen and a halogen containing gas. Halogen compounds may include metal halides and organic halides. The diluent may comprise nitrogen, argon, helium, methane, ethylene, carbon dioxide, steam, or a mixture of two or more thereof. The regenerating fluid may flow from the header through the process microchannels and to the footer, or in the opposite direction from the footer through the process microchannels to the header. The temperature of the regenerating fluid may be from about 20 to about 600° C., and in one embodiment about 150 to about 400° C. The pressure within the process microchannels during this regeneration step may range from about 0.1 to about 4 MPa, and in one embodiment about 0.1 to about 2 MPa, and in one embodiment about 0.1 to about 0.5 MPa. The residence time for the regenerating fluid in the process microchannels may range from about 0.01 second to about 3 hours, and in one embodiment about 0.1 second to about 100 seconds.

[0260] The catalyst may be regenerated in-situ in the process microchannels by oxidizing a carbonaceous material on the surface of the catalyst or by removing carbonaceous materials via hydrogenation. The catalysts may be regenerated via sulphiding. The regeneration process may also occur ex situ, whereby the feed is bypassed from the reactor, the temperature is dropped to ambient, and a liquid or gaseous fluid is used to remove carbonaceous materials. In one embodiment, the regeneration process utilizes a dissolution process to remove the carbonaceous material. The pressure drop through the reactor may be lower after regeneration than before by about 10% or more

[0261] The plant facility used for conducting the inventive process may comprise a plurality of process microchannels, microchannel reactors, or reaction vessels containing one or more microchannel reactors. The catalyst in one or more of the process microchannels, microchannel reactors or reaction vessels may be regenerated, while the inventive process may be carried out simultaneously in other process microchannels, microchannel reactors or reaction vessels in the plant facility.

[0262] The inventive process may be conducted using a regenerated catalyst at relatively high liquid hourly space velocities (LHSV), for example, at about 5 hr^{-1} or above, or about 10 hr^{-1} or above. The process may be conducted under stable operating conditions using the regenerated catalyst for extended periods of time, for example, periods in excess of about 1000 hours.

[0263] The process microchannels may be characterized by having a bulk flow path. The term "bulk flow path" refers to an open path (contiguous bulk flow region) within the process microchannels. A contiguous bulk flow region allows rapid fluid flow through the microchannels without large pressure drops. In one embodiment, the flow of fluid in the bulk flow region is laminar. Bulk flow regions within each process microchannel may have a cross-sectional area of about 0.05 to about 10,000 mm^2, and in one embodiment about 0.05 to about 5000 mm^2, and in one embodiment about 0.1 to about 2500 mm^2. The bulk flow regions may comprise from about 5% to about 95%, and in one embodiment about 30% to about 80% of the cross-section of the process microchannels.

[0264] The heat exchange fluid may be any fluid. These may include air, steam, liquid water, steam, gaseous nitrogen, other gases including inert gases, carbon monoxide, molten salt, oils such as mineral oil, a gaseous hydrocarbon, a liquid hydrocarbon, heat exchange fluids such as Dowtherm A and Therminol which are available from Dow-Union Carbide, or a mixture of two or more thereof. "Dowtherm" and "Therminol" are trademarks.

[0265] The heat exchange fluid may comprise a stream of one or more of the reactants and/or the product. This can provide process cooling for the process microchannels and/or pre-heat for the reactants and thereby increase the overall thermal efficiency of the process.

[0266] The heat exchange channels may comprise process channels wherein an endothermic process is conducted. These heat exchange process channels may be microchannels. Examples of endothermic processes that may be conducted in the heat exchange channels include steam reforming and dehydrogenation reactions. Steam reforming of an alcohol that occurs at a temperature in the range from about 200° C. to about 300° C. is an example of an endothermic process suited for an exothermic reaction such as an ethylene oxide synthesis reaction in the same temperature range. The incorporation of a simultaneous endothermic reaction to provide an improved heat sink may enable a typical heat flux of roughly an order of magnitude above the convective cooling heat flux.

[0267] The heat exchange fluid may undergo a partial or full phase change as it flows through the heat exchange channels. This phase change may provide additional heat removal from the process microchannels beyond that provided by convective cooling. For a liquid heat exchange fluid being vaporized, the additional heat being transferred from the process microchannels would result from the latent heat of vaporization required by the heat exchange fluid. An example of such a phase change would be a heat exchange fluid such as oil or water that undergoes partial boiling. In one embodiment, up to about 50% by weight of the heat exchange fluid may be vaporized.

[0268] The gaseous fraction of reactants and products may flow in the reaction zone in contact with the catalyst to produce a Reynolds number up to about 100000, and in one embodiment up to about 10000, and in one embodiment up to about 100, and in one embodiment in the range from about 10 to about 100, and in another in the range from about 0.01 to about 10, and in one embodiment in the range from about 0.1 to about 5.

[0269] The heat flux for heat exchange in the microchannel reactor may range from about 0.01 to about 500 watts per square centimeter of surface area of the heat transfer walls (W/cm^2) in the microchannel reactor, and in one embodiment from about 0.1 to about 350 W/cm^2, and in one embodiment from about 1 to about 250 W/cm^2, and in one embodiment from about 1 to about 100 W/cm^2, and in one embodiment from about 1 to about 50 W/cm^2, and in one embodiment from about 1 to about 25 W/cm^2, and in one embodiment from about 1 to about 10 W/cm^2.

[0270] The cooling of the process microchannels during the inventive process, in one embodiment, is advantageous for controlling selectivity towards the main or desired product due to the fact that such added cooling reduces or eliminates the formation of undesired by-products from undesired parallel reactions with higher activation energies. As a result of this cooling, in one embodiment, the temperature of the reactants at the entrance to the process microchannels may be within about 20° C., and in one embodiment within about 10° C., and in one embodiment within about 5° C., and in one embodiment within about 3° C., and in one embodiment within about 2° C., and in one embodiment within about 1° C., of the temperature of the product (or mixture of product and unreacted reactants) at the outlet of the process microchannels. In one embodiment, the process microchannels may be operated with an isothermal or substantially isothermal temperature profile.

[0271] The contact time of the reactants with the catalyst in the process microchannels may range from about 1 to about 2000 milliseconds (ms), and in one embodiment from about 10 to about 1000 ms, and in one embodiment from about 100 to about 500 ms.

[0272] The liquid hourly space velocity (LHSV) for the flow of liquid reactant in the process microchannels may be at least about 0.1 liters of liquid reactant per hour per liter of volume in the process microchannel (hr^{-1}), and in one embodiment at least about 1 hr^{-1}, and in one embodiment at least about 5 hr^{-1}, and in one embodiment at least about 10 hr^{-1}, and in one embodiment at least about 20 hr^{-1}, and in one embodiment at least about 30 hr^{-1}, and in one embodiment at least about 35 hr^{-1}, and in one embodiment at least about 40 hr^{-1}, and in one embodiment from about 0.1 to about 40 hr^{-1}, and in one embodiment from about 1 to about 40 hr^{-1}. The LHSV may be in the range from about 0.1 to about 200 hr^{-1}, and in one embodiment from about 1 to about 100 hr^{-1}, and in one embodiment from about 2 to about 100 hr^{-1}.

[0273] The gas hourly space velocity (GHSV) for the flow of gases (e.g., vapor, H_2) in the process microchannels may be in the range from about 500 to about 500,000 hr^{-1}.

[0274] In the hydrotreating and hydrocracking processes, the conversion of hydrocarbon fractions with boiling points above about 350° C. to hydrocarbons with boiling points below about 350° C. may be at least about 50% by weight, and in one embodiment at least about 55% by weight, and in one embodiment at least about 60% by weight, and in one embodiment at least about 65% by weight, and in one embodiment at least about 70% by weight, and in one embodiment at least about 75% by weight, and in one embodiment at least about 80% by weight, and in one embodiment at least about 85% by weight, and in one embodiment at least about 90% by weight.

[0275] The pressure drop for the process fluids as they flow in the process microchannels may range up to about 50 bars per foot of length of the process microchannel (bars/ft) (0.16 MPa/cm), and in one embodiment up to about 10 bars/ft (0.032 MPa/cm), and in one embodiment up to about 1.5 bars/ft (0.005 MPa/cm), and in one embodiment up to 1 bar/ft (0.0033 MPa/cm), and in one embodiment up to about 0.5 bar/ft (0.0016 MPa/cm).

[0276] The flow of the process fluids in the process microchannels may be laminar or in transition, and in one embodiment it is laminar. The Reynolds Number for the flow of process fluids in the process microchannels may be up to about 10,000, and in one embodiment up to about 4000, and in one embodiment up to about 2300, and in one embodiment in the range of about 1 to about 2000, and in one embodiment in the range from about 100 to about 1500.

[0277] The superficial velocity for process gas flowing in the process microchannels may be at least about 0.01 meters per second (m/s), and in one embodiment in the range from about 0.01 to about 5 m/s, and in one embodiment in the range from about 0.01 to about 2 m/s, and in one embodiment in the range from about 0.01 to about 1 m/s, and in one embodiment in the range from about 0.05 to about 0.5 m/s.

[0278] The heat exchange fluid in the heat exchange channels may have a temperature in the range from about 100° C. to about 800° C., and in one embodiment from about 250° C. to about 500° C. The difference in temperature between the heat exchange fluid and the process fluids in the process microchannel may be up to about 50° C., and in one embodiment up to about 30° C., and in one embodiment up to about 10° C. The residence time of the heat exchange fluid in the heat exchange channels may range from about 1 to about 1000 ms, and in one embodiment about 1 to about 500 ms, and in one embodiment from 1 to about 100 ms. The pressure drop for the heat exchange fluid as it flows in the heat exchange channels may be up to about 3 bar/ft, and in one embodiment up to about 1 bar/ft. The flow of the heat exchange fluid in the heat exchange channels may be laminar or in transition, and in one embodiment it is laminar. The Reynolds Number for the flow of heat exchange fluid in the heat exchange channels may be up to about 50,000, and in one embodiment up to about 10,000, and in one embodiment up to about 2300, and in one embodiment in the range of about 10 to about 2000, and in one embodiment about 10 to about 1500.

[0279] The control of heat exchange during the hydrotreating and hydrocracking processes may be advantageous for controlling selectivity towards the desired product due to the fact that added cooling may reduce or eliminate the formation of undesired by-products from undesired parallel reactions with higher activation energies.

[0280] The pressure within each individual heat exchange channel in the microchannel reactor may be controlled using passive structures (e.g., obstructions), orifices and/or mechanisms upstream of the heat exchange channels or in the channels. By controlling the pressure within each heat exchange channel, the temperature within each heat exchange channel can be controlled. A higher inlet pressure for each heat exchange channel may be used where the passive structures, orifices and/or mechanisms let down the pressure to the desired pressure. By controlling the temperature within each heat exchange channel, the temperature in the process microchannels may be controlled. Thus, for example, each process microchannel may be operated at a desired temperature by employing a specific pressure in the heat exchange channel adjacent to or in thermal contact with the process microchannel. This may provide the advantage of precisely controlled temperatures for each process microchannel. The use of precisely controlled temperatures for each process microchannel provides the advantage of a tailored temperature profile and an overall reduction in the energy requirements for the process.

[0281] In a scale up device, for certain applications, it may be required that the mass of the process fluid be distributed uniformly among the microchannels. Such an application may be when the process fluid is required to be cooled down with adjacent heat exchange channels. The uniform mass flow distribution may be obtained by changing the cross-sectional area from one parallel microchannel to another microchannel. The uniformity of mass flow distribution may be defined by Quality Index Factor (Q-factor) as indicated below. A Q-factor of 0% means absolute uniform distribution.

$$Q = \frac{\dot{m}_{max} - \dot{m}_{min}}{\dot{m}_{max}} \times 100$$

A change in the cross-sectional area may result in a difference in shear stress on the wall. In one embodiment, the Q-factor for the microchannel reactor **100** may be less than about 50%, and in one embodiment less than about 20%, and in one embodiment less than about 5%, and in one embodiment less than about 1%.

[0282] The free stream velocity for process fluid flowing in the process microchannels may be at least about 0.001 m/s, and in one embodiment at least about 0.01 m/s, and in one embodiment in the range from about 0.001 to about 200 m/s, and in one embodiment in the range from about 0.01 to about 100 m/s, and in one embodiment in the range from about 0.01 to about 200 m/s.

[0283] Advantages of the inventive process may include the potential for process intensification. Conventional processes of the prior art (that is, non-microchannel processes) often operate under conditions of reactant dilution to prevent runaway reactions, while the inventive process may be operated, if desired, under more intense conditions leading to greater throughput.

[0284] While the invention has been explained in relation to various embodiments, it is to be understood that various modifications thereof will become apparent to those skilled in the art upon reading the specification. Therefore, it is to be understood that the invention disclosed herein is intended to cover such modifications as fall within the scope of the appended claims.

1. A process, comprising:

flowing heavy oil and hydrogen in a reactor in contact with a hydroprocessing catalyst under process intensification conditions, the heavy oil comprising one or more heteroatoms;

reacting at least some of the heteroatoms with the hydrogen to form one or more heteroatom containing compounds; and

hydrocracking the heavy oil to form an upgraded hydrocarbon product.

2. The process of claim **1** wherein the reactor comprises a process microchannel, the heavy oil and hydrogen flowing in the process microchannel in contact with the hydroprocessing catalyst.

3. The process of claim **1** wherein the hydroprocessing catalyst comprises a hydrotreating catalyst.

4. The process of claim **1** wherein the hydroprocessing catalyst comprises a hydrocracking catalyst.

5. The process of claim **1** wherein the heteroatom containing compounds are separated from the upgraded hydrocarbon product.

6. The process of claim **1** wherein the heavy oil comprises water, the process further comprising removing water from the upgraded hydrocarbon product.

7. The process of claim **1** wherein the heavy oil is reacted in the presence of a hydrotreating catalyst to form an intermediate hydrocarbon product, and the intermediate hydrocarbon product is reacted in the presence of a hydrocracking catalyst to form the upgraded hydrocarbon product.

8. The process of claim **7** wherein the reaction with the hydrotreating catalyst is conducted in a process microchannel and the reaction with the hydrocracking catalyst is conducted in a process microchannel, the hydrotreating catalyst and the hydrocracking catalyst being in the same process microchannel.

9. The process of claim **7** wherein the reaction with the hydrotreating catalyst is conducted in a first process microchannel and the reaction with the hydrocracking catalyst is conducted in a second process microchannel.

10. The process of claim **7** wherein the reaction with the hydrotreating catalyst is conducted in a first microchannel reactor and the reaction with the hydrocracking catalyst is conducted in a second microchannel reactor.

11. The process of claim **1** wherein the heteroatoms comprise nitrogen, sulfur, oxygen, metal, ora combination of two or more thereof.

12. The process of claim **1** wherein the pressure in the reactor is in the range from about 0.5 to about 25 MPa.

13. The process of claim **1** wherein the temperature in the reactor is in the range from about 100° C. to about 500° C.

14. The process of claim **1** wherein the ratio of hydrogen to heavy oil in the reactor is in the range from about 10 to about 6000 standard cubic centimeters of hydrogen per cubic centimeter of heavy oil.

15. The process of claim **1** wherein the heavy oil entering the reactor is in the form of a liquid, a vapor, or a combination of liquid and vapor.

16. The process of claim **1** wherein the reactor comprises one or more process microchannels, the heavy oil and hydrogen being mixed with each other in the one or more process microchannels.

17. The process of claim **1** wherein the reactor comprises a process microchannel and the process microchannel is in a microchannel reactor, the microchannel reactor comprising a reactant stream channel adjacent to the process microchannel, the process microchannel and the reactant stream channel having a common wall, and a plurality of openings in the common wall, the process further comprising flowing the pyrolysis oil in the process microchannel and flowing the hydrogen from the reactant stream channel through the openings in the common wall into the process microchannel in contact with the pyrolysis oil.

18. The process of claim **1** wherein the heavy oil and hydrogen are mixed prior to entering the reactor.

19. The process of claim **1** wherein the reactor comprises a microchannel reactor comprising a plurality of process microchannels, the microchannel reactor comprising a manifold providing a flow passageway for the heavy oil and hydrogen to flow into the process microchannels.

20. The process of claim **1** wherein the reactor comprises a microchannel reactor comprising a plurality of the process microchannels, the microchannel reactor comprising a first manifold providing a flow passageway for the heavy oil to flow into the process microchannels, and a second manifold providing a flow passageway for the hydrogen to flow into the process microchannels.

21. The process of claim **1** wherein heat is transferred from the reactor to a heat exchanger.

22. The process of claim **1** wherein the reactor comprises a microchannel reactor comprising a plurality of process microchannels, the microchannel reactor further comprising at least one heat exchange channel in thermal contact with the process microchannels, a heat exchange fluid being in the heat exchange channel, and heat is transferred from the process microchannels to the heat exchange fluid in the heat exchange channel.

23. The process of claim **22** wherein the heat exchange fluid undergoes a phase change in the heat exchange channel.

24. The process of claim **22** wherein reactants flow in the process microchannel in a first direction, and the heat exchange fluid flows in the heat exchange channel in a second direction, the second direction being cross current relative to the first direction.

25. The process of claim **1** wherein the reactor comprises a process microchannel and a tailored heat exchange is provided along the length of the process microchannel to maintain a substantially isothermal temperature profile along the length of the process microchannel.

26. The process of claim **1** wherein the heavy oil entering the reactor comprises heavy oil vapor, the heavy oil vapor being at least partially condensed in the reactor.

27. The process of claim **1** wherein the reactor comprises a first stage reactor, the hydroprocessing catalyst comprising a first hydrocracking catalyst, the process also employing a second stage reactor containing a second hydrocracking catalyst, the heavy oil comprising heavy oil vapor, the process comprising:

flowing the heavy oil vapor and hydrogen in the first stage reactor in contact with the first hydrocracking catalyst, condensing and hydrocracking the heavy oil vapor to form a first hydrocracked hydrocarbon product comprising a first hydrocarbon liquid product and a first hydrocarbon vapor;

separating the first hydrocarbon liquid product from the first hydrocarbon vapor;

flowing the first hydrocarbon vapor and hydrogen in the second stage reactor in contact with the second hydrocracking catalyst, condensing and hydrocracking the first hydrocarbon vapor to form a second hydrocracked hydrocarbon product comprising a second hydrocarbon liquid product and a second hydrocarbon vapor; and

separating the second hydrocarbon liquid product from the second hydrocarbon vapor.

28. The process of claim **27** wherein the first hydrocarbon liquid comprises water and the second hydrocarbon liquid comprises water, the process further comprising separating water from the first hydrocarbon liquid, and separating water from the second hydrocarbon liquid.

29. The process of claim **1** wherein the reactor comprises a first stage reactor, the hydroprocessing catalyst comprising a first hydrocracking catalyst, the process also employing a second stage reactor containing a second hydrocracking catalyst, the first stage reactor and the second stage reactor being positioned in a distillation column, the second stage reactor being positioned above and/or downstream of the first stage reactor, the distillation column having a distillate end and a bottoms end and being equipped with a distillate condenser; the heavy oil comprising heavy oil vapor, the process comprising:

flowing the heavy oil vapor and hydrogen in the first stage reactor toward the distillate end in contact with the first hydrocracking catalyst, condensing and hydrocracking the heavy oil vapor to form a first hydrocracked hydrocarbon product comprising a first liquid hydrocarbon oil product and a first hydrocarbon vapor;

separating the first liquid hydrocarbon oil product from the first hydrocarbon vapor, and flowing the first liquid hydrocarbon oil product out of the distillation column;

flowing the first hydrocarbon vapor and hydrogen in the second stage reactor toward the distillate end in contact with the second hydrocracking catalyst, condensing and hydrocracking the first hydrocarbon vapor to form a second hydrocracked hydrocarbon product comprising a second liquid hydrocarbon oil product and a second hydrocarbon vapor;

separating the second liquid hydrocarbon oil product from the second hydrocarbon vapor, and flowing the second liquid hydrocarbon oil product out of the distillation column; and

condensing at least part of the second hydrocarbon vapor in the distillate condenser to provide a liquid reflux back to the distillation column.

30. The process of claim **1** wherein the hydroprocessing catalyst is in the form of particulate solids.

31. The process of claim **1** wherein the hydroprocessing catalyst is supported on a structure which comprises a foam, felt, wad, honeycomb, monolith, fin, structured packing, or a combination of two or more thereof.

32. The process of claim **1** wherein the hydroprocessing catalyst is in the form of a bed of particulate solids positioned in a process microchannel, and additional catalyst is washcoated and/or grown on one or more interior walls of the process microchannel.

33. The process of claim **1** wherein the hydroprocessing catalyst is a hydrotreating catalyst which comprises Ni, Mo, Co, W, or a combination of two or more thereof.

34. The process of claim **1** wherein the hydroprocessing catalyst is a hydrocracking catalyst which comprises Pt, Pd, Ni, Co, Mo, W, or a combination of two or more thereof.

35. The process of claim **1** wherein the upgraded hydrocarbon product comprises a middle distillate oil, a light oil, or a mixture thereof.

36. The process of claim **1** wherein the reactor comprises a process microchannel, the channel Bond number for the process microchannel being less than about 1.

37. The process of claim **1** wherein the hydroprocessing catalyst is in a process microchannel, the hydroprocessing catalyst being regenerated in-situ in the process microchannel.

38. The process of claim **1** wherein the process is conducted in a plant facility, the plant facility comprising a plurality of process microchannels, or one or more microchannel reactors containing a plurality of process microchannels, or one or more reactor housing vessels containing one or more microchannel reactors, the hydroprocessing catalyst in one or more process microchannels, microchannel reactors or reactor housing vessels being regenerated while the process is carried out in other process microchannels, microchannel reactors or reactor housing vessels in the plant facility.

39. The process of claim **1** wherein the heavy oil is derived from the gasification, pyrolysis or liquefaction of coal, shale, tar sands, bitumen, biomass, or a combination of two or more thereof.

40. The process of claim **1** wherein the heavy oil comprises pyrolysis oil, pyrolysis oil vapor, or a mixture thereof.

41. The process of claim **1** wherein the heavy oil is formed in a plant, and the reactor is in the plant, the process comprising forming the heavy oil and transporting the heavy oil to the reactor.

42. The process of claim **26** wherein the catalyst is positioned in a distillation column, the distillation column comprising a single stage catalytic distillation hydrocracker.

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