

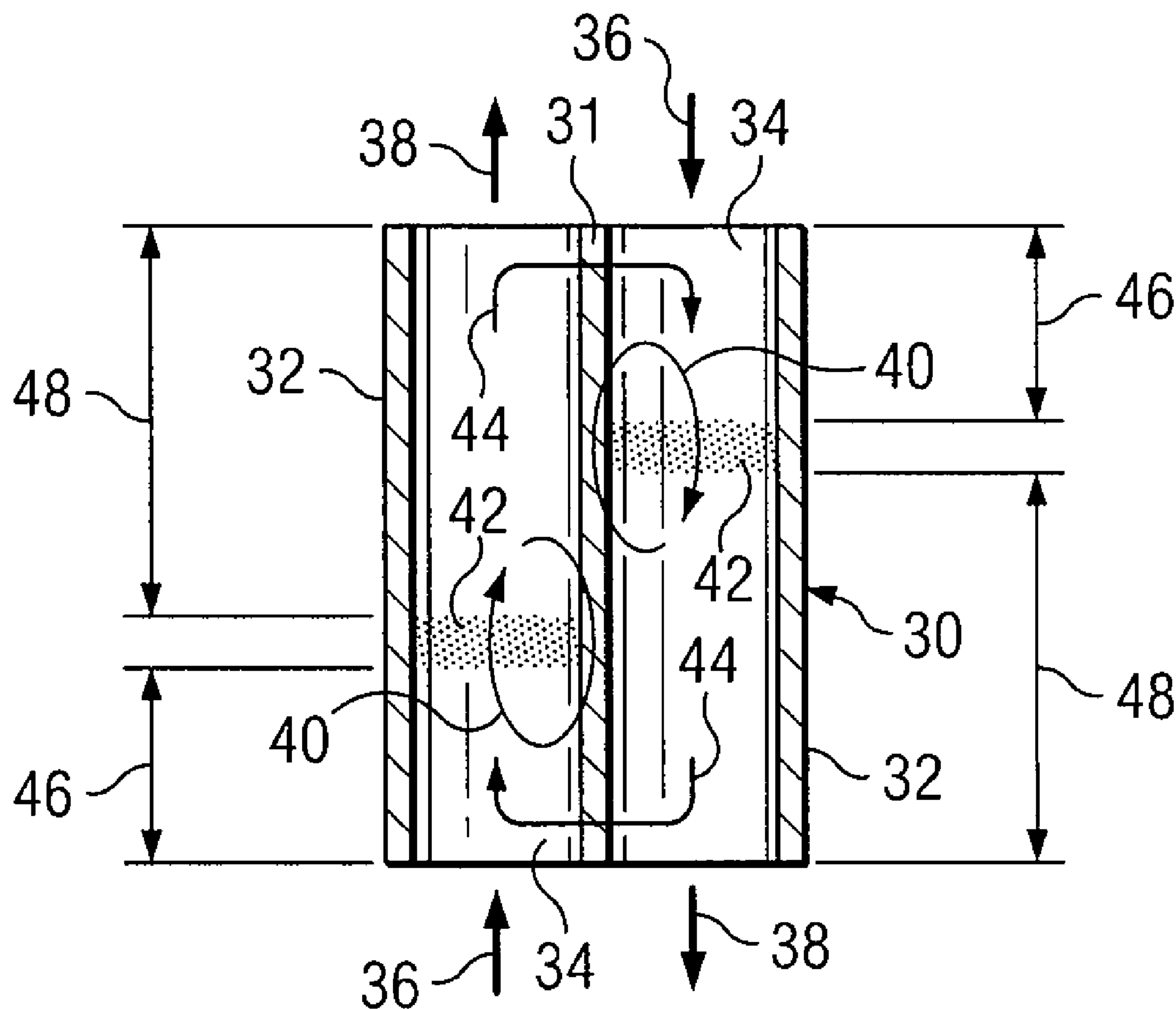
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Schoegl et al.(10) **Pub. No.: US 2009/0087801 A1**(43) **Pub. Date: Apr. 2, 2009**(54) **SYSTEM AND METHOD FOR
SUPERADIABATIC COUNTERFLOW
REACTOR****Related U.S. Application Data**

(60) Provisional application No. 60/743,439, filed on Mar. 8, 2006.

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AUSTIN, TX 78701-4039 (US)(57) **ABSTRACT**

The present disclosure may disclose a system and method for superadiabatic counterflow reactors. The system may include a first channel configured to communicate gas in a first direction, a second channel formed adjacent the first channel and configured to communicate gas in a second direction, the second direction substantially opposite the first direction, and the first channel having a first heat source positioned such that gas flowing through the first channel preheats gas in the second channel and the second channel having a second heat source positioned such that gas flowing through the second channel preheats gas in the first channel.

(21) Appl. No.: **12/282,020**(22) PCT Filed: **Mar. 8, 2007**(86) PCT No.: **PCT/US2007/063605**§ 371 (c)(1),
(2), (4) Date: **Sep. 8, 2008**

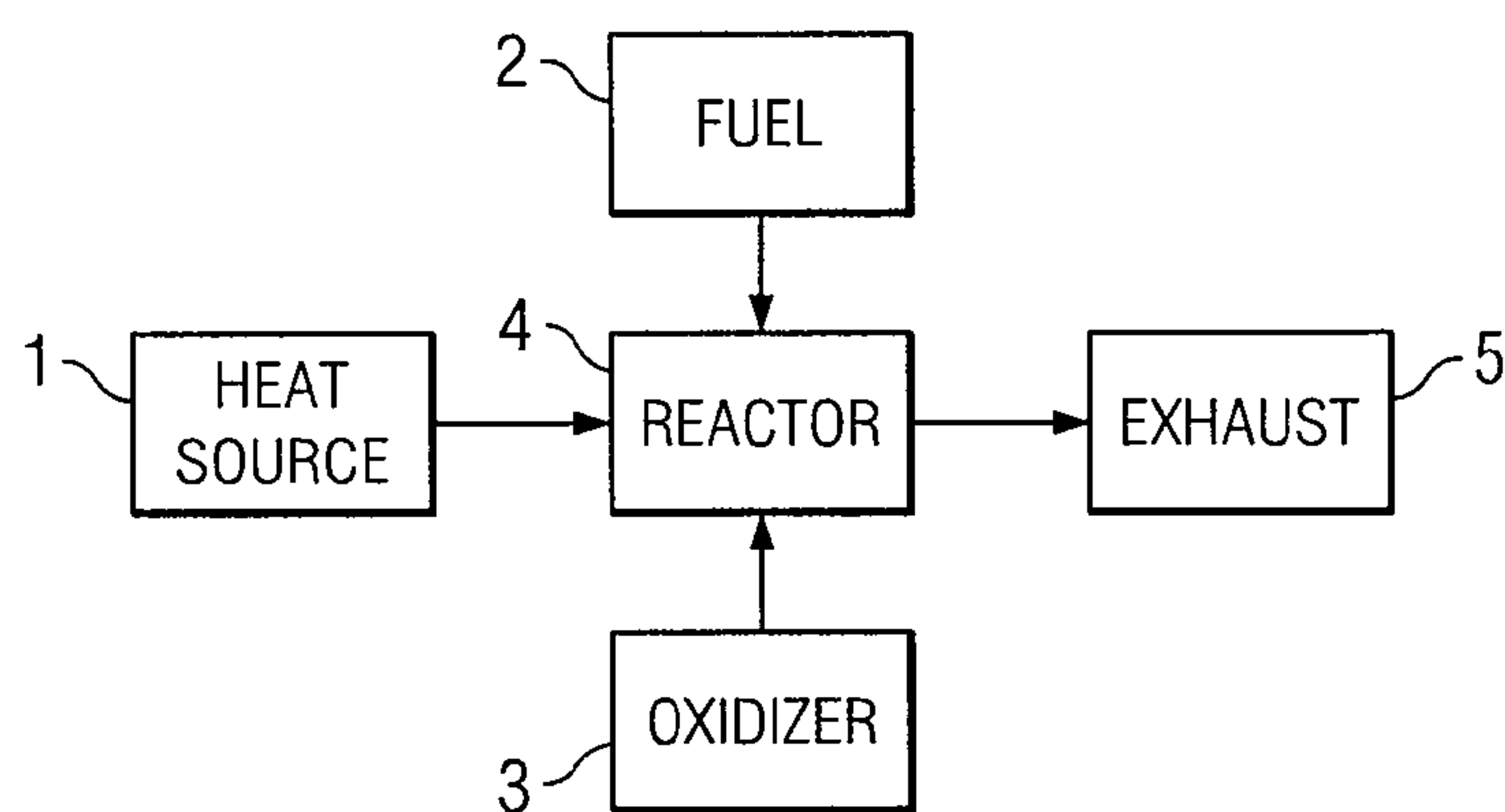


FIG. 1

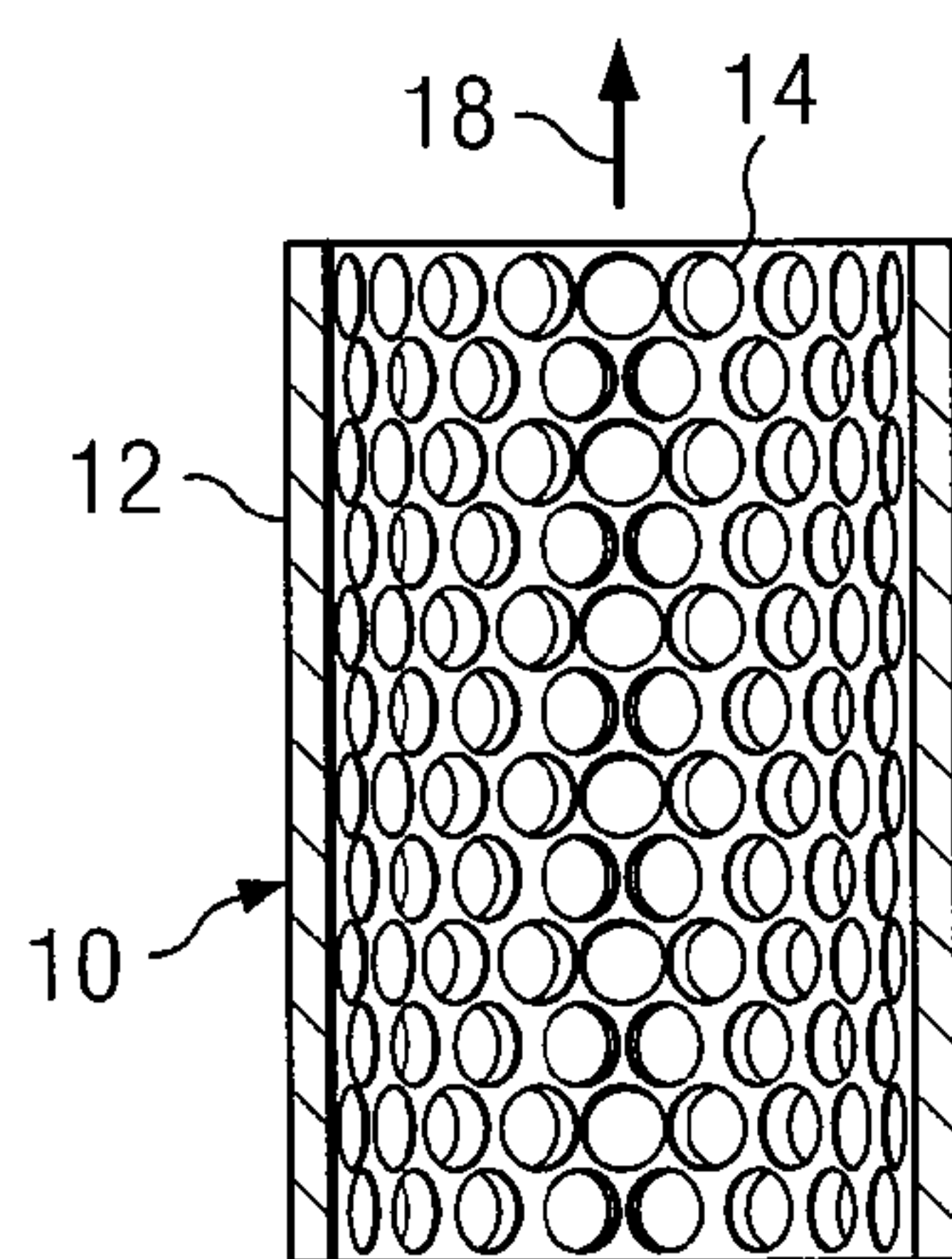


FIG. 2A

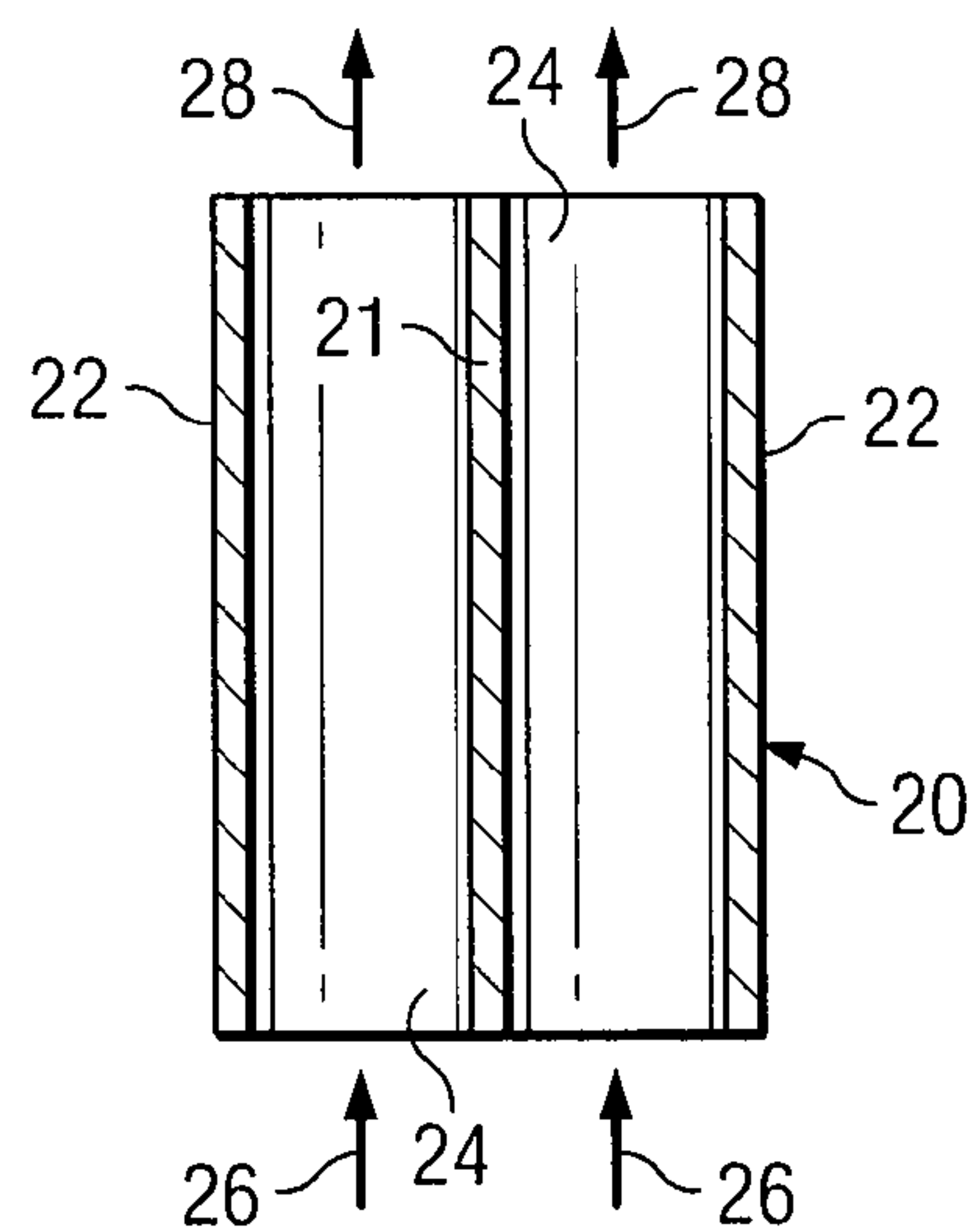


FIG. 2B

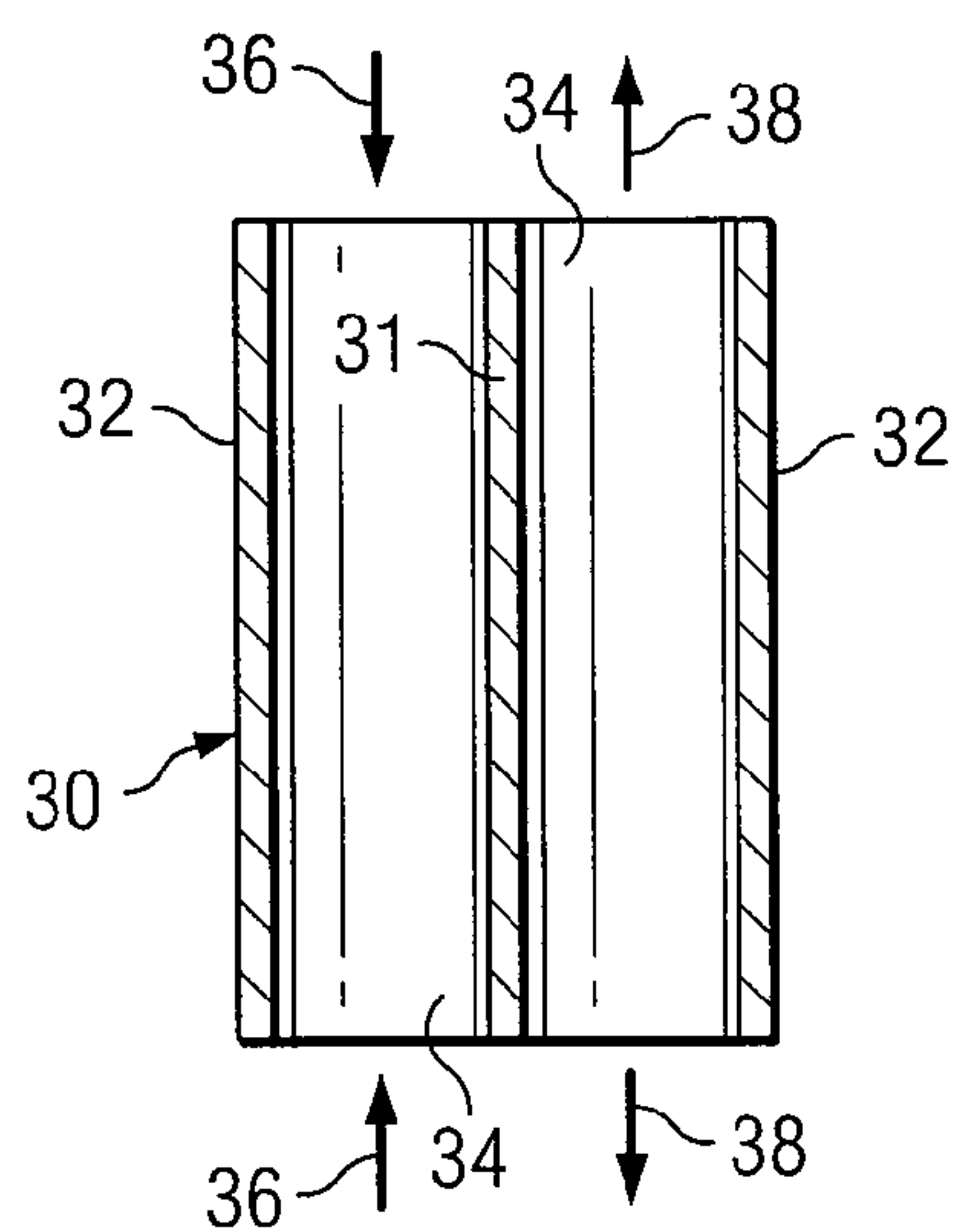


FIG. 2C

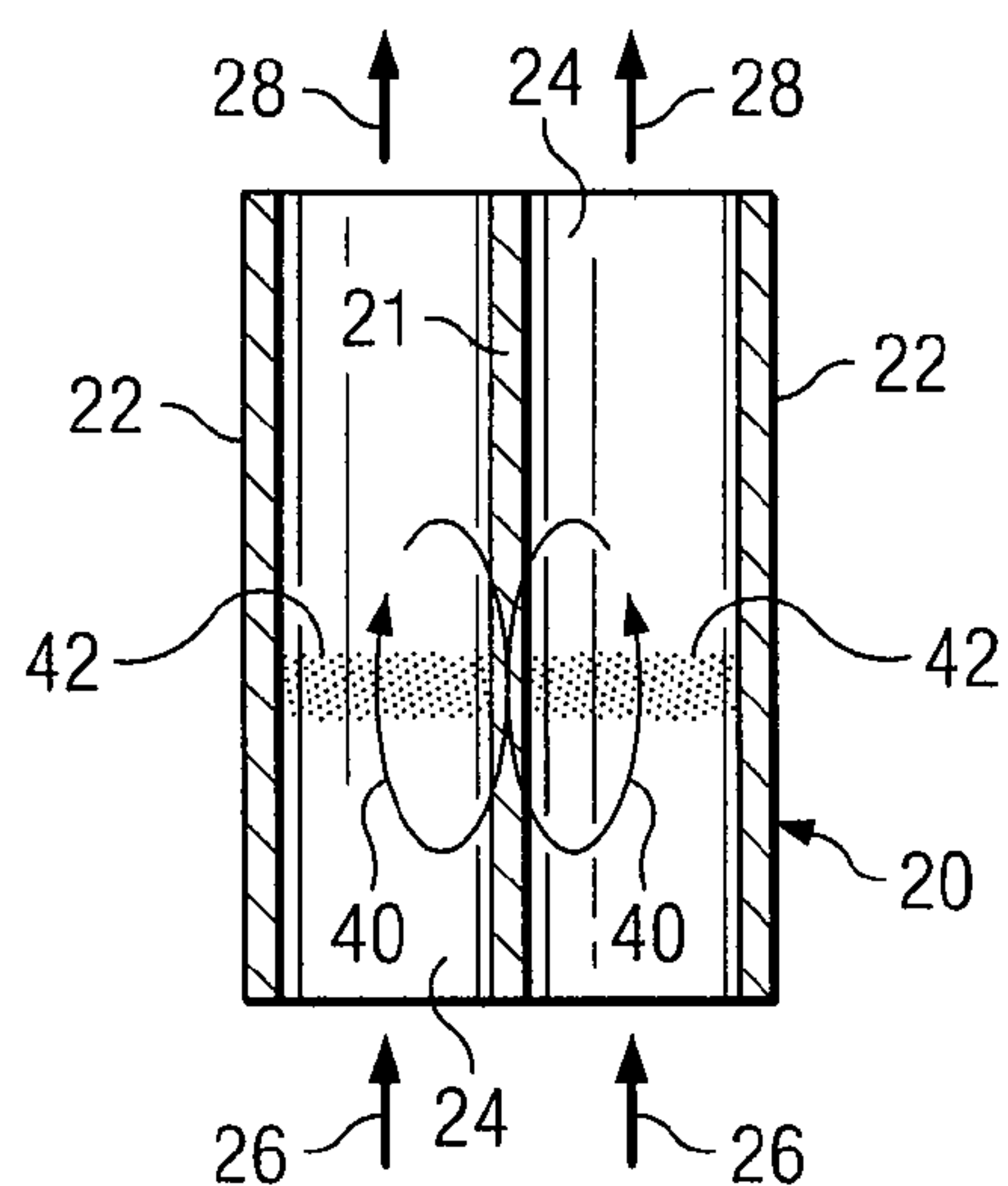


FIG. 3A

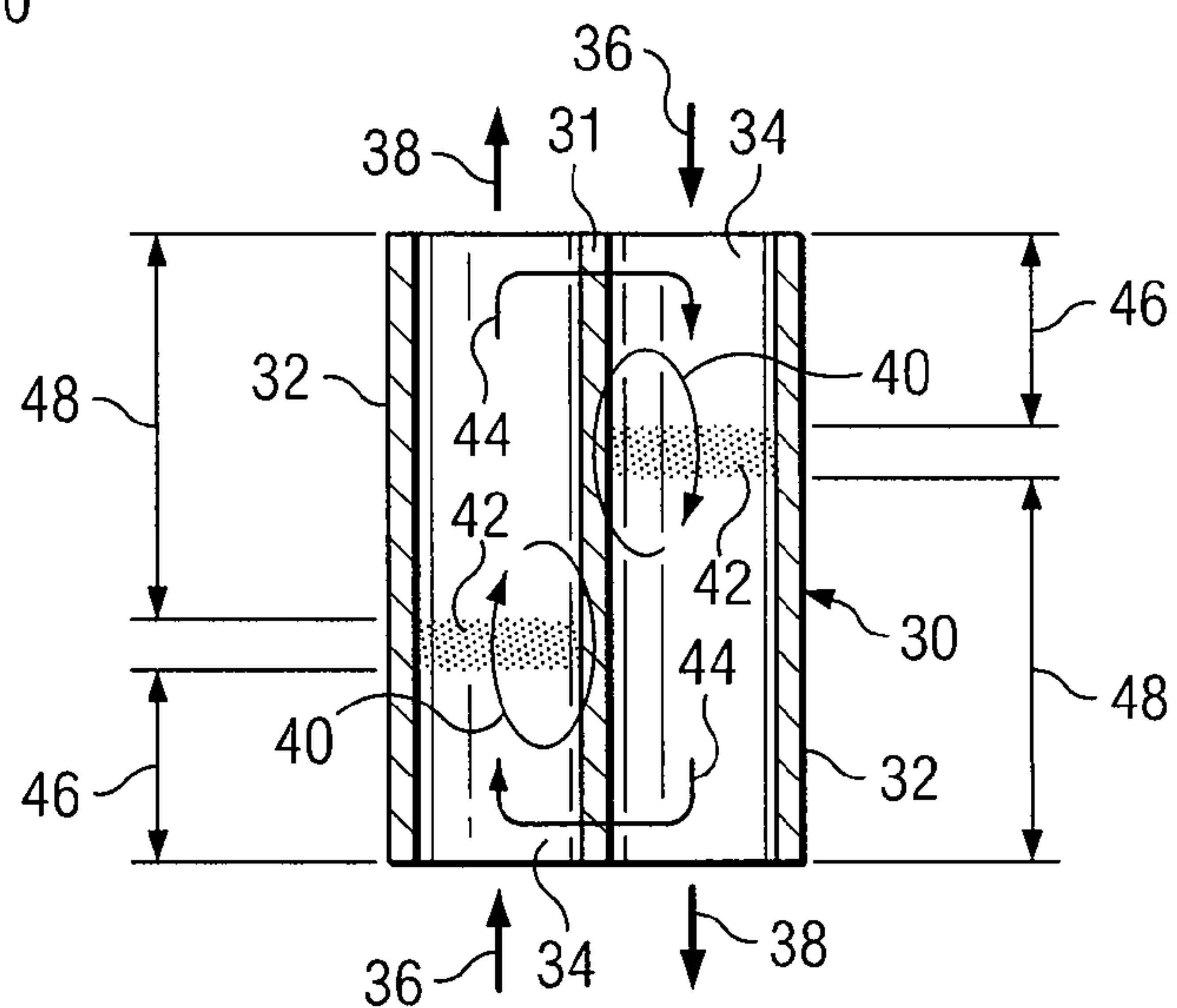


FIG. 3B

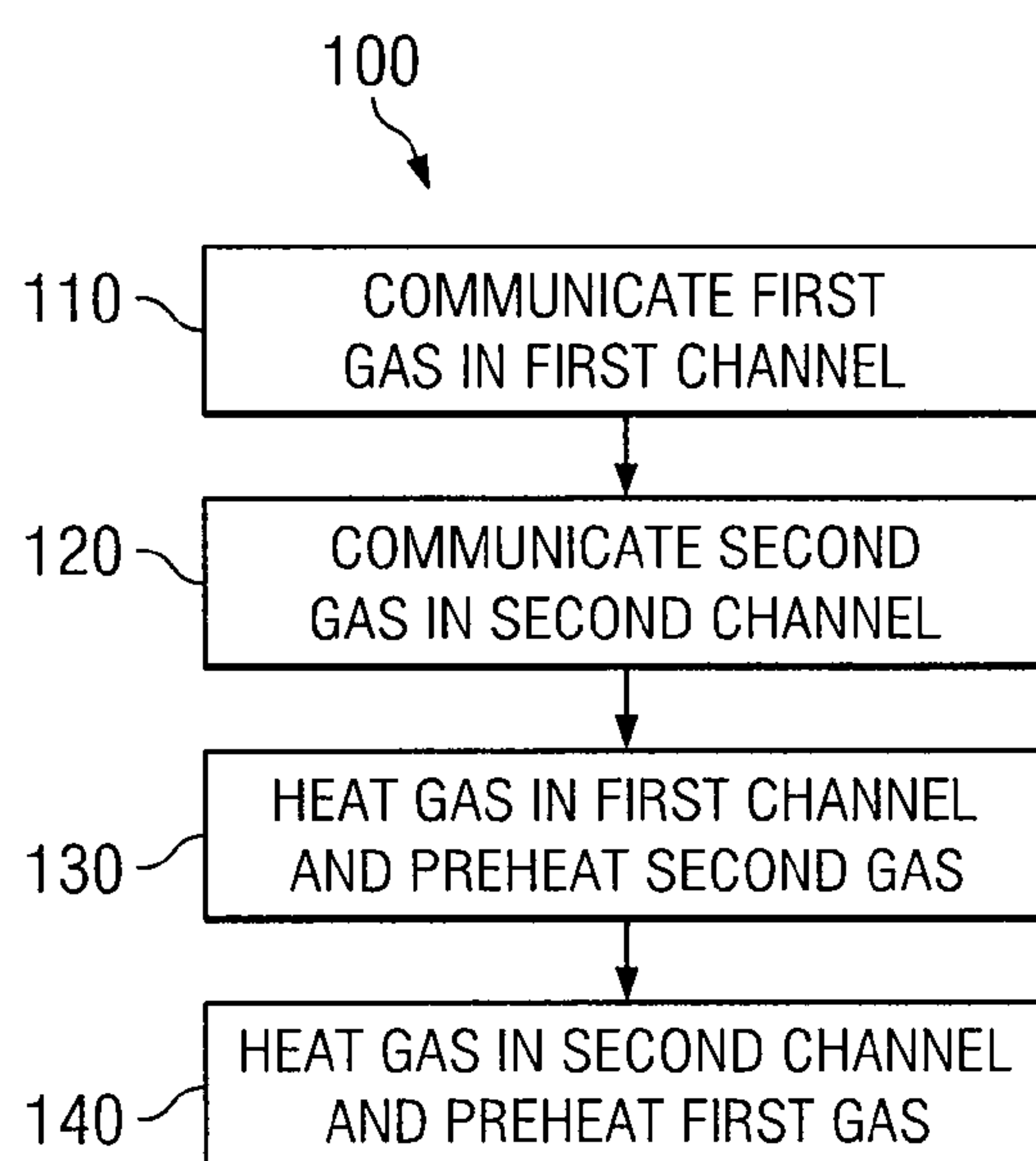


FIG. 4

SYSTEM AND METHOD FOR SUPERADIABATIC COUNTERFLOW REACTOR

RELATED APPLICATIONS

[0001] This application claims the benefit of provisional patent application entitled "System and Method for Supera-diabatic Counterflow Reactor," Application Ser. No. 60/743, 439 filed 8 Mar. 2006.

TECHNICAL FIELD

[0002] The present disclosure relates in general to combustion processes, and more particularly to a system and method for superadiabatic counterflow reactors.

BACKGROUND

[0003] Classic theories of combustion assume the validity of the principle that the maximum temperature attainable in a reaction is that predicted by equilibrium for an adiabatic process, i.e., the adiabatic flame temperature. Under certain circumstances, however, the maximum temperature may exceed this value locally due to internal and/or external heat recirculation. Weinberg originally proposed a theory of energy concentration in combustion zones. Weinberg's theory has been verified in experiments using external heat recirculation in a swiss-roll combustor. Energy concentration may also result from filtration combustion in which a gaseous mixture is fed into a porous media or packed bed.

[0004] Recirculation of heat concentrates the energy such that local temperatures can exceed the adiabatic flame temperature by a significant amount. Such temperature may be called superadiabatic combustion. Superadiabatic combustion may significantly broaden conventional flammability limits. Without such recirculation, operation outside of the conventional flammability limits (e.g., ultra-lean or ultra-rich mixtures) often fails because the energy content of the reactants is not sufficient to sustain a free flame.

SUMMARY OF THE DISCLOSURE

[0005] In accordance with the teachings of the present disclosure, various systems and methods may provide supera-diabatic combustion in a counterflow reactor. In one particular embodiment, fuel/oxidizer mixtures may be reacted in channels in a counterflow arrangement so that heat from one channel preheats the gas in the neighboring channel.

[0006] In accordance with one embodiment of the present disclosure, a system for reacting fuel and oxidizer mixtures may be provided. The system may include a first channel configured to communicate gas in a first direction, a second channel configured to communicate gas in a second direction substantially opposite the first direction, a first heat source positioned such that gas flowing through the first channel preheats gas in the second channel, and a second heat source positioned such that gas flowing through the second channel preheats gas in the first channel.

[0007] In accordance with one embodiment of the present disclosure, a method for reacting a fuel and oxidizer mixture may be provided. The method may include communicating gas to a first channel in a first direction, simultaneously communicating gas to a second channel in a second direction substantially opposite the first direction, heating the gas in the first channel with a first heat source positioned such that gas flowing through the first channel preheats gas in the second

channel and heating the gas in the second channel with a second heat source positioned such that the gas flowing through the second channel preheats gas in the first channel.

[0008] In accordance with one embodiment of the present disclosure, a system for reacting a fuel and oxidizer mixture may be provided. The system may include a means for communicating first gas in a first direction, a means for communicating a second gas in a second direction substantially opposite the first direction, a means for heating the first gas positioned such that the first gas preheats the second gas, and a means for heating the second gas positioned such that the second gas preheats the first gas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] A more complete understanding of the present embodiments and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

[0010] FIG. 1 illustrates a block diagram of a reaction system for a mixture of fuel and oxidizer in accordance with teachings of the present disclosure;

[0011] FIG. 2A illustrates an example porous burner for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure;

[0012] FIG. 2B illustrates an example co-flow burner for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure;

[0013] FIG. 2C illustrates an example counter-flow burner for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure;

[0014] FIG. 3A illustrates an example system for use in the combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure;

[0015] FIG. 3B illustrates an example system for use in the combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure; and

[0016] FIG. 4 illustrates a flowchart of a method for use in for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure.

DETAILED DESCRIPTION OF THE DRAWINGS

[0017] Preferred embodiments and their advantages are best understood by reference to FIGS. 1 through 4, wherein like numbers are used to indicate like and corresponding parts.

[0018] In general, combustion is described as a series of reactions between a fuel and an oxidant producing energy (e.g., heat and/or light). A typical example of combustion is a fire. A mixture of a liquid fuel with an oxidant normally will not result in combustion unless the temperature of the mixture exceeds its flash point. From the other point of view, the flash point may be described as the minimum temperature at which enough of the fuel will evaporate to form a combustible mixture. A combustion process preferably results in the conversion of a large portion of the chemical energy of the fuel into thermal energy (e.g., heat).

[0019] FIG. 1 illustrates a block diagram of a reaction system for a mixture of fuel and oxidizer in accordance with teachings of the present disclosure. In FIG. 1, reactor 4 may receive input from heat source 1, fuel 2, and oxidizer 3. As a result of the reaction, reactor 4 may produce exhaust 5. Reactor 4 may include any system or apparatus configured to

accept heat source **1**, fuel **2**, and oxidizer **3** and combine them in an appropriate manner. Reactor **4** may include any system or apparatus configured to communicate exhaust **5** away from reactor **4**. For example, reactor **4** may include burners, fluid channels, a combustion chamber, or other features and/or components.

[0020] Heat source **1** may include any source of thermal energy configured to communicate thermal energy to reactor **4** or any components therein. For example, heat source **1** may include flame. In other embodiments, heat source **1** may include an electric spark, and/or any other appropriate source of thermal energy operable to raise the temperature of fuel **2** and oxidizer **3** to the flash point (and/or above the flash point) of fuel **2**.

[0021] Fuel **2** may include any material that is capable of releasing energy when its chemical or physical structure is altered through combustion. For example, fuel **2** may include hydrocarbons (e.g., gasoline, diesel, petroleum, natural gas, and/or combinations or mixtures including hydrocarbons).

[0022] Oxidizer **3** may include any oxidizing agent (e.g., oxidant and/or oxidizer). For example, oxidizer **3** may include room air or ambient air. In other embodiments, oxidizer **3** may include a more specific combination or mixture configured to provide an oxidizing agent to a combustion process (e.g., ozone, sulfoxides, nitrous oxide, and/or any other oxidizing agent).

[0023] Exhaust **5** may include any material resulting from use of the reaction system depicted in FIG. 1. For example, in a process resulting in complete combustion of fuel **2** consisting of a hydrocarbon in oxidizer **3** consisting of an oxygen atmosphere, exhaust **5** may include water vapor and carbon dioxide. In other combustion processes which may include fuel **2** including a hydrocarbon and additional elements in oxidizer **3** including oxygen and additional elements, exhaust **5** may include any combustion product, byproduct, excess oxidizer **3** and/or incompletely oxidized fuel **2**.

[0024] Complete combustion, although not achieved in typical practice, refers to the conceptual complete oxidation of fuel **2**. That is, fuel **2** may be completely converted to its constituent products and its entire reserve of chemical energy may be converted into thermal energy. Any deviation from complete combustion may result in an increase in byproducts and incompletely oxidized fuel **2**. A suboptimal mixture of fuel **2** and oxidizer **3** may result in deviation from complete combustion. In extreme cases, a mixture of fuel **2** and oxidizer **3** in some proportions may not result in combustion at all. Operation outside of the conventional flammability limits (e.g., ultra-lean (too little fuel **2**) or ultra-rich (too much fuel **2**) mixtures) often fails because the energy content of fuel **2** and oxidizer **3** is not sufficient to sustain a free flame.

[0025] One process of stripping hydrogen from a fuel-rich hydrocarbon/air mixture is referred to as fuel reforming. Some methods for accomplishing fuel reforming include the use of catalysts to enhance the reaction rates. Catalysts, however, are subject to poisoning by sulfur compounds occurring in many fuels (e.g., catalyst ageing). In addition to problems with catalyst ageing, catalytic surfaces add substantially to the cost of the reactor. Another approach may include use of a porous reactor including a porous matrix without a catalytic surface. In such a porous reactor, gas phase reactions dominate the chemistry and, therefore, surface poisoning is not an issue. A conventional inert reactor may consist of a single tube of porous media.

[0026] Some fuel reforming techniques without catalysts include the propagation of rich combustion waves (filtration waves) in the direction of the exit of the porous channel. Such propagation may inhibit continuous operation of the combustor. One technique to overcome such an inhibition may include cyclical reversal of the fuel flow direction. This technique may successfully hold the combustion zone inside the reactor but, however, significantly complicates the reactor design. Another technique includes establishment of a stationary combustion front at the interface between an upstream small pore section and a downstream large pore section. Although the latter technique may address the propagation problem previously discussed, reactors embodying this technique have been observed to limit the peak temperatures in the reaction zone close to the adiabatic flame temperature previously discussed.

[0027] Environmental concerns as well as the necessity for the efficient usage of available energy resources have spurred research considering alternative forms of power generation. Fuel cell systems are considered likely to be appropriate for transportation purposes and small-scale power generation devices. Conversion efficiencies of fuel cells are not limited by the Carnot cycle and thus promise higher energy efficiencies than conventional combustion engines. Current fuel cell technologies are highly specific to a small variety of fuel types, with hydrogen representing the most common energy source. Inside a fuel cell, hydrogen and atmospheric oxygen react to form water in an electrochemical process and thus generate electricity without potentially polluting emissions. While substances containing hydrogen are extremely abundant, hydrogen itself is not naturally available in molecular form and thus has to be extracted from water, ammonia, fossil hydrocarbon fuels or renewable energy sources (e.g. ethanol and biodiesel).

[0028] Some of the unresolved issues of hydrogen-based technologies arise in the context of transportation and storage of hydrogen. Gaseous hydrogen is extremely volatile and has a comparatively low volumetric energy density. Efficient storage of hydrogen gas is only possible under relatively high pressure and/or low temperature. In another storage concept, hydrogen remains bound in form of the primary fuel, which is reformed in situ and provides hydrogen on demand. In addition to avoiding the high pressure/low temperature requirements, this approach provides the advantage that the required distribution network can be built upon existing infrastructure for hydrocarbon fuels such as natural gas and petroleum derivatives.

[0029] Current reforming technologies typically involve four different paths for reforming: thermal decomposition (TD), steam reforming (SR), partial oxidation and autothermal reforming (ATR). While TD and SR are endothermic processes and require external energy sources, pox is exothermic and thus a self-sustaining process. ATR uses the reactions of SR and can be performed nearly thermoneutral in a single reactor design (e.g., Christensen and Primdahl, 1994), or a counterflow reactor design (e.g., Frauhammer et al., 1999). Most current reforming technologies use catalysts to promote the conversion of hydrocarbons to syngas.

[0030] FIGS. 2A, 2B and 2C illustrate some embodiments of burners that may be used to react fuel and oxidizer mixtures in accordance with teachings of the present disclosure. In each embodiment, a mixture of fuel and oxidizer may flow through a channel or channels in the direction shown by arrows. A reactor including burners in accord with the depic-

tions in FIGS. 2A, 2B, and 2C may include additional features or components (not expressly shown) to deliver and/or pre-mix fuel and oxidizer, to provide a heat source to the mixture of fluid and oxidizer, or perform any other functions appropriate to facilitate combustion of the mixture.

[0031] FIG. 2A depicts a conventional porous burner 10 in section which may be used in an inert reactor to avoid problems associated with catalysts, as described above. Burner 10 may be generally configured to facilitate combustion of fuel 2 and oxidizer 3. For example, in embodiments such as that shown in FIG. 2A, burner 10 may include outer wall 12 for containing inlet mixture 16 of fuel 2 and oxidizer 3, and porous matrix 14 for maintaining the mixture of fuel 2 and oxidizer 3 in a largely gaseous phase. Burner 10 may be configured to accept inlet mixture 16 and reject exhaust 18. In other embodiments, burner 10 may include multiple outer walls 12 and porous matrices 14 arranged in series and/or in parallel.

[0032] Outer wall 12 may include any device or feature of burner 10 configured to contain mixture 16 of fuel 2 and oxidizer 3 and/or channel mixture 16 from one end of burner 10 to the other. In some embodiments, outer wall 12 may define a fluid channel configured to channel mixture 16 from one end of burner 10 to the other. For example, outer wall 12 may define a round tube, a square tube, an array of fluid channels and/or any combination of the above. Outer wall 12 may have any surface features appropriate for channeling mixture 16, including a smooth wall and/or selected textures. Outer wall 12 may be formed of any material appropriate for channeling mixture 16. In some embodiments, outer wall 12 may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process).

[0033] Porous matrix 14 may include any device or feature of burner 10 configured to provide reduced flow apertures for mixture 16. In general, porous matrix 14 may be configured to result in atomization of mixture 16. The conversion of liquid fuel into a spray or mist (e.g., by atomization) may increase the efficiency of a combustion process (e.g., by reducing the flash point, by better mixing fuel 2 and oxidizer 3 and/or other physical or chemical effects).

[0034] Inlet mixture 16 may include any mixture of fuel 2 and oxidizer 3 configured to react or combust as desired in reactor 4 as previously discussed in relation to FIG. 1. For instance, inlet mixture 16 may include hydrocarbons contained in fuel 2 and oxygen contained in room air or oxidizer 3. Exhaust 18 may include any combustion product, byproduct, excess oxidizer 3 and/or incompletely oxidized fuel 2.

[0035] Porous burners, such as that depicted in FIG. 2A, are characterized by a stationary reaction zone inside porous matrix 14. The portion of porous matrix 14 upstream of the reaction zone may be heated by radiation between its surfaces as well as conduction from the hot region downstream of the reaction zone. Thus incoming mixture 16 may be preheated by both convection and radiation from porous matrix 14 as mixture 16 travels through the interstitial spaces of porous matrix 14. Such preheating may result in local heat recirculation and increased firing rates.

[0036] In reactors including such porous burners, operation requires stabilization of the flame inside porous matrix 14. While stationary combustion zones without stabilization can be realized, they are properly considered a special case of a filtration combustion wave with zero wave velocity. Such a case has been obtained for particular combinations of equivalence ratios and inlet velocities. Small deviations, however, of

the inlet conditions lead to a transient combustion zone moving towards the burner inlet (flashback) or burner exit (blow-off). In addition, since the peak temperature provided in such a burner remains close to the adiabatic flame temperature, such a design does not allow combustion outside of the conventional flammability limits.

[0037] For combustion of inlet mixtures 16 close to the conventional flammability limits, it may be possible to stabilize a reaction zone using a two-layer design in which the flame is held close to the interface between a small-pore upstream section and a large pore downstream section of porous matrix 14. This solution may take advantage of the fact that flashback for the small pore section occurs at lower velocities than for the large pore section. This makes stable operation possible for the velocity range between blow-off of the small pore media and flashback of the large pore media. Another concept based on changing flow conditions uses a widening porous channel, where the reaction zone is anchored at the location where the flow velocity matches the local flame speed. In general, however, neither of the above designs is capable of significantly increasing the peak temperatures of the reaction zone, although the firing rates may be significantly increased.

[0038] FIG. 2B depicts in cross-section an example co-flow burner 20 for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure. Co-flow burner 20 may be generally configured to facilitate combustion of fuel 2 and oxidizer 3. For example, in embodiments such as that shown in FIG. 2B, co-flow burner 20 may include inner wall 21 for separating two or more gas flows, outer walls 22, and fluid channels 24 for containing inlet mixture 26 of fuel 2 and oxidizer 3. Co-flow burner 20 may be configured to accept inlet mixture 26 and reject exhaust 28. In other embodiments, co-flow burner 20 may include multiple outer walls 22 and fluid channels 24 arranged in series and/or in parallel.

[0039] Inner wall 21 may include any device or feature of co-flow burner 20 configured to separate two or more gas flows. For example, inner wall 21 may be configured to separate inlet mixture 26 into two or more streams. In embodiments including inner wall 21, inner wall 21 may be configured to separate inlet mixture 26 into substantially equal streams (e.g., equal volume flow rate, mass flow rate, and/or equal volume) or may be configured to separate inlet mixture 26 without regard to the amount of inlet mixture 26 in each stream. For example, inner wall 21 may define part of a round tube, a square tube, an array of fluid channels and/or any combination of the above. Inner wall 21 may have any surface features appropriate for channeling mixture 26, including a smooth wall and/or selected textures. Inner wall 21 may be formed of any material appropriate for channeling mixture 26. In some embodiments, inner wall 21 may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process). In other embodiments, inner wall 21 may be configured to serve as the separator for more than two fluid streams.

[0040] Outer wall 22 may include any device or feature of co-flow burner 20 configured to contain mixture 26 of fuel 2 and oxidizer 3 and/or channel mixture 26 from one end of co-flow burner 20 to the other. In some embodiments, outer wall 22 may, in part, define fluid channel 24 configured to channel mixture 26 from one end of co-flow burner 20 to the other. For example, outer wall 22 may define a round tube, a square tube, an array of fluid channels and/or any combina-

tion of the above. Outer wall **22** may have any surface features appropriate for channeling mixture **26**, including a smooth wall and/or selected textures. Outer wall **22** may be formed of any material appropriate for channeling mixture **26**. In some embodiments, outer wall **22** may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process).

[0041] Fluid channels **24** may include any device or feature of co-flow burner **20** configured to channel inlet mixture **26** through co-flow burner **20** from one end to the other. In some embodiments, such as that shown in FIG. 2B, fluid channels **24** may be formed between inner walls **21** and outer walls **22**. Although pictured as a straight path in FIG. 2B, fluid channels **24** may include any path, whether straight or tortuous. In some embodiments, fluid channels **24** may include varying cross-sectional shapes and/or areas.

[0042] Inlet mixture **26** may include any mixture of fuel **2** and oxidizer **3** configured to react or combust as desired in reactor **4** as previously discussed in relation to FIG. 1. For instance, inlet mixture **26** may include hydrocarbons contained in fuel **2** and oxygen contained in room air or oxidizer **3**. Exhaust **28** may include any combustion product, byproduct, excess oxidizer **3** and/or incompletely oxidized fuel **2**.

[0043] FIG. 2C depicts an example counter-flow burner **30** for combustion of a mixture of fuel and oxidizer in cross-section in accordance with teachings of the present disclosure. Counter-flow burner **30** may be generally configured to facilitate combustion of fuel **2** and oxidizer **3**. For example, in embodiments such as that shown in FIG. 2C, counter-flow burner **30** may include inner wall **31** for separating two or more gas flows, outer walls **32**, and fluid channels **34** for containing inlet mixture **36** of fuel **2** and oxidizer **3**. Counter-flow burner **30** may be configured to accept inlet mixture **36** and reject exhaust **38**. In other embodiments, counter-flow burner **30** may include multiple outer walls **32** and fluid channels **34** arranged in series and/or in parallel.

[0044] Inner wall **31** may include any device or feature of counter-flow burner **30** configured to separate two or more gas flows and communicate the two or more flows in substantially opposing directions. For example, inner wall **31** may define part of a round tube, a square tube, an array of fluid channels and/or any combination of the above. Inner wall **31** may have any surface features appropriate for channeling mixture **36**, including a smooth wall and/or selected textures. Inner wall **31** may be formed of any material appropriate for channeling mixture **36**. In some embodiments, inner wall **31** may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process). In other embodiments, inner wall **31** may be configured to serve as the separator for more than two fluid streams.

[0045] Outer wall **32** may include any device or feature of counter-flow burner **30** configured to contain mixture **36** of fuel **2** and oxidizer **3** and/or channel mixture **36** from one end of co-flow burner **30** to the other. In some embodiments, outer wall **32** may, in part, define fluid channels **34** configured to channel mixture **36** from one end of counter-flow burner **30** to the other. For example, outer wall **32** may define one or more round tubes, square tubes, an array of fluid channels and/or any combination of the above. Outer wall **32** may have any surface features appropriate for channeling mixture **36**, including a smooth wall and/or selected textures. Outer wall **32** may be formed of any material appropriate for channeling mixture **36**. In some embodiments, outer wall **32** may be

formed of an inert material (e.g., formed of some material unaffected by the desired combustion process).

[0046] Fluid channels **34** may include any device or feature of counter-flow burner **30** configured to channel inlet mixture **36** through counter-flow burner **30** from one end to the other. In some embodiments, such as that shown in FIG. 2C, fluid channels **34** may be configured to communicate inlet mixture **36** in at least two streams. In such embodiments, the at least two streams of inlet mixture **36** may be disposed to flow in substantially opposite directions. When two streams are so disposed, they may be described as counter-flow. Fluid channels **34** may be formed between inner walls **31** and outer walls **32**. Although pictured as a straight path in FIG. 2C, fluid channels **34** may include any path, whether straight or tortuous. In some embodiments, fluid channels **34** may include varying cross-sectional shapes and/or areas.

[0047] Inlet mixture **36** may include any mixture of fuel **2** and oxidizer **3** configured to react or combust as desired in reactor **4** as previously discussed in relation to FIG. 1. For instance, inlet mixture **36** may include hydrocarbons contained in fuel **2** and oxygen contained in room air or oxidizer **3**. Exhaust **38** may include any combustion product, byproduct, excess oxidizer **3** and/or incompletely oxidized fuel **2**.

[0048] FIGS. 3A and 3B depict cross-sectional views of some embodiments of burner configurations that may be used to react fuel and oxidizer mixtures in accordance with teachings of the present disclosure. In each embodiment, a mixture of fuel and oxidizer may flow through a channel or channels in the direction shown by arrows. A reactor including burners in accord with the depictions in FIGS. 3A and 3B may include additional features or components (not expressly shown) to deliver and/or premix fuel and oxidizer, to provide a heat source to the mixture of fluid and oxidizer, or perform any other functions appropriate to facilitate combustion of the mixture.

[0049] As previously discussed, one process of stripping hydrogen from a fuel-rich hydrocarbon/air mixture is referred to as fuel reforming. Traditional methods of fuel reforming may include application of a catalyst to the combustion process or addition of a porous matrix to the combustion chamber. In accordance with teachings of the present disclosure, however, a process of fuel reforming may include recirculation of heat generated during the combustion process. Recirculation of heat concentrates the energy such that local temperatures can exceed the adiabatic flame temperature by a significant amount. Such temperature may be called superadiabatic combustion. Superadiabatic combustion may significantly broaden conventional flammability limits (e.g., allow combustion when the mixture of fuel **2** and oxidizer **3** includes too much or too little fuel **2** for conventional combustion).

[0050] Internal and/or external heat recirculation may be used to raise the temperature level of the reaction to a level that is sufficient for a self sustained reaction. If the mixture of fuel **2** and oxidizer **3** includes too little fuel **2** (i.e., ultra-lean), superadiabatic combustors may be used as a thermal oxidizer, where high temperatures facilitate the combustion of mixtures with sparse amounts of fuel **2**. If the mixture of fuel **2** and oxidizer **3** includes too much fuel **2** (i.e., ultra-rich), the high temperatures inside reactor **4** promote the conversion of a rich hydrocarbon fuel/air mixture into H₂, CO, CO₂, H₂O and other hydrocarbon species. Application of the teachings of the present disclosure may allow thermal oxidation to destroy pollutants in the gaseous stream (e.g., volatile organic

compounds (VOCs)) and/or converting rich fuel/oxidizer mixtures to “syngas” or a mixture of other gases.

[0051] FIG. 3A illustrates in cross-section an example system for use in the combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure including co-flow burner 20. Co-flow burner 20 may be generally configured to facilitate combustion of fuel 2 and oxidizer 3. For example, in embodiments such as that shown in FIG. 3A, co-flow burner 20 may include inner wall 21 for separating two or more gas flows, outer walls 22, and fluid channels 24 for containing inlet mixture 26 of fuel 2 and oxidizer 3. Co-flow burner 20 may be configured to accept inlet mixture 26 and reject exhaust 28. In other embodiments, co-flow burner 20 may include multiple outer walls 22 and fluid channels 24 arranged in series and/or in parallel.

[0052] Inner wall 21 may include any device or feature of co-flow burner 20 configured to separate two or more gas flows. For example, inner wall 21 may be configured to separate inlet mixture 26 into two or more streams. In embodiments including inner wall 21, inner wall 21 may be configured to separate inlet mixture 26 into substantially equal streams (e.g., equal volume flow rate, mass flow rate, and/or equal volume) or may be configured to separate inlet mixture 26 without regard to the amount of inlet mixture 26 in each stream. For example, inner wall 21 may define part of a round tube, a square tube, an array of fluid channels and/or any combination of the above. Inner wall 21 may have any surface features appropriate for channeling mixture 26, including a smooth wall and/or selected textures. Inner wall 21 may be formed of any material appropriate for channeling mixture 26. In some embodiments, inner wall 21 may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process). In other embodiments, inner wall 21 may be configured to serve as the separator for more than two fluid streams. Persons having ordinary skill in the art will appreciate that the specific features and characteristics of inner wall 21 (e.g., thermal conductivity and thickness) may serve to facilitate or restrict heat conduction between adjoining fluid channels 24.

[0053] Outer wall 22 may include any device or feature of co-flow burner 20 configured to contain mixture 26 of fuel 2 and oxidizer 3 and/or channel mixture 26 from one end of co-flow burner 20 to the other. In some embodiments, outer wall 22 may, in part, define fluid channel 24 configured to channel mixture 26 from one end of co-flow burner 20 to the other. For example, outer wall 22 may define a round tube, a square tube, an array of fluid channels and/or any combination of the above. Outer wall 22 may have any surface features appropriate for channeling mixture 26, including a smooth wall and/or selected textures. Outer wall 22 may be formed of any material appropriate for channeling mixture 26. In some embodiments, outer wall 22 may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process).

[0054] Fluid channels 24 may include any device or feature of co-flow burner 20 configured to channel inlet mixture 26 through co-flow burner 20 from one end to the other. In some embodiments, such as that shown in FIG. 3A, fluid channels 24 may be formed between inner walls 21 and outer walls 22. Although pictured as a straight path in FIG. 3A, fluid channels 24 may include any path, whether straight or tortuous. In some embodiments, fluid channels 24 may include varying cross-sectional shapes and/or areas.

[0055] Inlet mixture 26 may include any mixture of fuel 2 and oxidizer 3 configured to react or combust as desired in reactor 4 as previously discussed in relation to FIG. 1. For instance, inlet mixture 26 may include hydrocarbons contained in fuel 2 and oxygen contained in room air or oxidizer 3. Exhaust 28 may include any combustion product, byproduct, excess oxidizer 3 and/or incompletely oxidized fuel 2.

[0056] When the system of FIG. 3A is operated in accordance with teachings of the present disclosure, combustion of inlet mixture 26 occurs at combustion zone 42 in each fluid channel 24. Combustion zone 42 for each fluid channel 24 may be defined as the location along the length of fluid channel 24 within which combustion of inlet mixture 26 begins and is completed. The location of combustion zone 42 may further serve to define upstream portion 46 (before inlet mixture 26 has reached combustion zone 42) and downstream portion 48 (as exhaust 28 leaves combustion zone 42 and travels out of burner 20). Persons having ordinary skill in the art will recognize that the precise location of combustion zone 42 in each fluid channel 24 may depend on a variety of conditions (e.g., the configuration of fluid channel 24, the mass or volume flow rate of inlet mixture 26, the fuel/oxidizer ratio in inlet mixture 26, the inlet temperature of inlet mixture 26, the amount of heat energy added to inlet mixture 26, and/or any other relevant data). In some embodiments, such as that shown in FIG. 3A, combustion zone 42 in each fluid channel 24 may be aligned along the length of fluid channel 24 so as to be located at substantially the same position along the length of fluid channel 24.

[0057] In embodiments such as that shown in FIG. 3A, when operated in accord with teachings of the present disclosure, downstream portion 48 of each fluid channel 24 may be at a significantly higher temperature than upstream portion 46. When such conditions exist, heat transfer effects may conduct heat from downstream portion 48 to upstream portion 46 through inner wall 21. These potential heat transfer effects are represented by arrows 40 in FIG. 3A. As shown therein, heat from downstream portion 48 may serve to preheat upstream portion 46. This preheating may serve to allow the superadiabatic combustion discussed herein.

[0058] FIG. 3B depicts in cross-section an example counter-flow burner 30 for combustion of a mixture of fuel and oxidizer in accordance with teachings of the present disclosure. Counter-flow burner 30 may be generally configured to facilitate combustion of fuel 2 and oxidizer 3. For example, in embodiments such as that shown in FIG. 3B, counter-flow burner 30 may include inner wall 31 for separating two or more gas flows, outer walls 32, and fluid channels 34 for containing inlet mixture 36 of fuel 2 and oxidizer 3. Counter-flow burner 30 may be configured to accept inlet mixture 36 and reject exhaust 38. In other embodiments, counter-flow burner 30 may include multiple outer walls 32 and fluid channels 34 arranged in series and/or in parallel.

[0059] Inner wall 31 may include any device or feature of counter-flow burner 30 configured to separate two or more gas flows and communicate the two or more flows in substantially opposing directions. For example, inner wall 31 may define part of a round tube, a square tube, an array of fluid channels and/or any combination of the above. Inner wall 31 may have any surface features appropriate for channeling mixture 36, including a smooth wall and/or selected textures. Inner wall 31 may be formed of any material appropriate for channeling mixture 36. In some embodiments, inner wall 31 may be formed of an inert material (e.g., formed of some

material unaffected by the desired combustion process). In some embodiments, inner wall **31** may be configured to serve as the separator for more than two fluid streams. Persons having ordinary skill in the art will appreciate that the specific features and characteristics of inner wall **31** (e.g., thermal conductivity and thickness) may serve to facilitate or restrict heat conduction between adjoining fluid channels **34a** and **34b**.

[0060] Outer wall **32** may include any device or feature of counter-flow burner **30** configured to contain mixture **36** of fuel **2** and oxidizer **3** and/or channel mixture **36** from one end of co-flow burner **30** to the other. In some embodiments, outer wall **32** may, in part, define fluid channels **34** configured to channel mixture **36** from one end of counter-flow burner **30** to the other. For example, outer wall **32** may define one or more round tubes, square tubes, an array of fluid channels and/or any combination of the above. Outer wall **32** may have any surface features appropriate for channeling mixture **36**, including a smooth wall and/or selected textures. Outer wall **32** may be formed of any material appropriate for channeling mixture **36**. In some embodiments, outer wall **32** may be formed of an inert material (e.g., formed of some material unaffected by the desired combustion process).

[0061] Fluid channels **34** may include any device or feature of counter-flow burner **30** configured to channel inlet mixture **36** through counter-flow burner **30** from one end to the other. In some embodiments, such as that shown in FIG. 3B, fluid channels **34** may be configured to communicate inlet mixture **36** in at least two streams. In such embodiments, the at least two streams of inlet mixture **36** may be disposed to flow in substantially opposite directions. When two streams are so disposed, they may be described as counter-flow. Fluid channels **34** may be formed between inner walls **31** and outer walls **32**. Although pictured as a straight path in FIG. 3B, fluid channels **34** may include any path, whether straight or tortuous. In some embodiments, fluid channels **34** may include varying cross-sectional shapes and/or areas.

[0062] Inlet mixture **36** may include any mixture of fuel **2** and oxidizer **3** configured to react or combust as desired in reactor **4** as previously discussed in relation to FIG. 1. For instance, inlet mixture **36** may include hydrocarbons contained in fuel **2** and oxygen contained in room air or oxidizer **3**. Exhaust **38** may include any combustion product, byproduct, excess oxidizer **3** and/or incompletely oxidized fuel **2**.

[0063] When the system of FIG. 3B is operated in accordance with teachings of the present disclosure, combustion of inlet mixture **36** occurs at combustion zone **42** in each fluid channel **34**. Combustion zone **42** for each fluid channel **34** may be defined as the location along the length of fluid channel **34** within which combustion of inlet mixture **36** begins and is completed. The location of combustion zone **42** may further serve to define upstream portion **46** (before inlet mixture **36** has reached combustion zone **42**) and downstream portion **48** (as exhaust **38** leaves combustion zone **42** and travels out of burner **30**). Persons having ordinary skill in the art will recognize that the precise location of combustion zone **42** in each fluid channel **34** may depend on a variety of conditions (e.g., the configuration of fluid channel **34**, the mass or volume flow rate of inlet mixture **36**, the fuel/oxidizer ratio in inlet mixture **36**, the inlet temperature of inlet mixture **36**, the amount of heat energy added to inlet mixture **36**, and/or any other relevant data). In some embodiments, such as that shown in FIG. 3B, combustion zone **42** in each fluid channel **34** may be aligned along the length of fluid channel

34 so as to be located at some distance from one another along the length of fluid channels **34**.

[0064] In embodiments such as that shown in FIG. 3B, when operated in accord with teachings of the present disclosure, downstream portion **48** of each fluid channel **34** may be at a significantly higher temperature than upstream portion **46**. When such conditions exist, heat transfer effects may conduct heat from downstream portion **48** to upstream portion **46** through inner wall **31**. As discussed in relation to FIG. 3A, this effect may include conduction from downstream portion **46** of fluid channel **34** to upstream portion **46** of fluid channel **34**. These potential heat transfer effects are represented by first arrows **40**. In addition to this mechanism, however, operation of a counter-flow reactor in accordance with the present teachings may also provide that heat from downstream portion **48** of first fluid channel **34a** may conduct through inner wall **31** to upstream portion of second fluid channel **34b**. These potential heat transfer effects are represented by second arrows **44**. As shown in FIG. 3B, the effect of heat transfer at first arrows **40** and second arrows **44** may serve to allow the superadiabatic combustion discussed herein.

[0065] The burner configurations depicted in FIGS. 3A and 3B are only representative of the embodiments that may be useful in practicing the teachings of the present disclosure and persons having ordinary skill in the art may use the teachings of the present disclosure to design and/or operate reactors without some or all of the features disclosed herein. Application of the teachings of the present disclosure provides that otherwise inflammable mixtures may be preheated to sufficiently high temperature levels that promote self-sustaining chemical reaction fronts without the need for a moving combustion zone.

[0066] FIG. 4 illustrates a flowchart of a method for use in for combustion of a mixture of fuel and oxidizer in a reactor **4** in accordance with teachings of the present disclosure. In general, method **100** may include steps to be completed simultaneously, or ongoing steps that may be performed in any sequence as long as the relevant durations overlap.

[0067] At step **110**, a user may communicate a first gas in a first channel. The first gas may include any appropriate combination of fuel **2** and oxidizer **3**. At step **120**, a user may communicate a second gas in a second channel. The second gas may include any appropriate combination of fuel **2** and oxidizer **3**. At step **130**, a user may heat the gas in the first channel and preheat the second gas. The process of heating the gas in the first channel may include heating the gas above its flash point to facilitate combustion. At step **140**, a user may heat the gas in the second channel and preheat the first gas. The process of heating the gas in the second channel may include heating the gas above its flash point to facilitate combustion.

[0068] It will be appreciated that while the disclosure is particularly described in the context of counter-flow combustion systems, the apparatuses, techniques, and methods disclosed herein may be similarly applied in other contexts. Additionally, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the disclosure as illustrated by the following claims.

Technical Discussion

[0069] The conceptual framework for the understanding of the heat transfer processes is built on a simplified mathematical model of the reactor, which is developed below.

[0070] By separating the overall model into a generic heat transfer problem built around a combustion problem, it is possible to obtain a direct solution of the heat transfer problem. However, only a solution by singular perturbation illuminates the physics of the heat transfer problem in the proximity of the combustion front, which is critical for the understanding of the boundary conditions of the combustion problem. The combustion problem itself may be subsequently solved by activation energy asymptotics.

Concept Summary

[0071] The working principle of superadiabatic combustion relies on convective heating of an otherwise inflammable fuel/air mixture to temperature levels at which self-sustained chemical reaction zones become feasible. In the embodiments including porous material in the fluid channels, the overall system can be understood as filtration waves in opposing flow channels that interact over a dividing wall. Additionally, the porous matrix may enhance the heat transfer between the channels. The combustion zones **42** in the individual fluid channels act as heat sources. As the gas in fluid channel **34a** passes from the inlet to combustion zone **42** it is preheated by the combustion products in adjoining fluid channel **34b**. Once reacted, exhaust **38** in fluid channel **34a** passes through a high temperature zone that is defined by the locations of combustion zones **42** in fluid channels **34a** and **34b**. While exiting, the excess enthalpy carried by exhaust **38** in first channel **34a** is transferred to the inlet mixture in second fluid channel **34b**. Since the gases in fluid channel **34b** are flowing in the opposite direction, they undergo the same process. The continuous process of heat recirculation between fluid channels **34a** and **34b** concentrates the energy such that local temperatures can exceed the adiabatic flame temperature by a significant amount.

Summary of Analytical Discussion

[0072] Full asymptotic solutions of gas temperature, gas concentration and solid temperature have been developed for filtration waves in a packed bed (e.g., Gort and Brouwers, 2001), as well as for a flame propagating in a narrow channel (e.g., Ju and Xu, 2005). In stationary combustors, simultaneous analytical solutions for gas and porous media have been discussed for cases where the flame is stabilized close to the exit face of the burner (e.g., McIntosh and Prothero, 1991; and Golombok et al., 1991).

[0073] Due to the simplifications inherent to the approach, however, solutions using activation energy asymptotics are incapable of resolving the flame structure. In order to account for characteristic chemical reactions describing different layers inside of the reaction zone, rate-ratio asymptotics have been applied (e.g., Buckmaster et al., 2005). At least one case investigated the asymptotic flame structure of a fuel rich flame (e.g., Seshadri et al., 2001).

[0074] While known equilibrium calculations are based on idealized conditions and thus have practical limitations, they still can be used to gain insight into the prerequisites for efficient non-catalytic reforming concepts. The known results show that optimum conversion can be expected for equivalence ratios ≈ 3.5 , where both preheating and steam addition increase the hydrogen yield. Moreover, the calculations show that for these cases, the net temperature increases lie in the range of $\Delta T = 300 \dots 600$ [K], and thus are insufficient to sustain a free flame. The practical implications are that an

efficient non-catalytic fuel reformer requires significant preheating, which is tantamount to superadiabatic conditions with large excess enthalpies.

[0075] One of the principal questions regarding the counter-current fuel reformer concept depends on flow rates. Since the fuel reforming occurs in a thin combustion zone, it is governed by local reaction-diffusion processes. Similar to the case of conventional flames, the reaction rate determines the flow rate through the burner. The laminar flame speed of a free premixed flame is a function of equivalence ratio and temperature. The flame speed is evaluated at different equivalence ratios and levels of preheating. The known results have shown that the flame speed drops as the equivalence ratio increases, where low flame speeds (< 5 cm/s) indicate flame extinction due to heat losses in a practical burner. By preheating the inlet, however, it is possible to increase the flame speeds of mixtures with high equivalence ratios to levels that indicate viable flames.

[0076] In the counter-flow design discussed herein, filtration waves are initiated at the fluid channel inlets. This section considers fluid channels that include porous media therein. Initially, exhaust **38** heats the porous media downstream of combustion zone **42**, and the propagation of each front will be similar to a normal filtration wave. As the filtration waves travel downstream, the high temperature zones approach each other, and the two filtration waves start to interact. Once the tails of the high temperature zones have moved past combustion zones **42**, heat is transferred from exhaust **38** to unreacted inlet mixture **36**. Due to the heat transfer across inner wall **31**, the direction of wave propagation is reversed and the reaction zones move towards the channel inlets. The regions between channel inlet and respective combustion zone **42** form a balanced counterflow heat exchanger. Steady state conditions are reached whenever the temperature profile is fully established and the preheating increases the local flame speed to a level that balances the incoming flow.

[0077] The fully established temperature profile shows a plateau-like temperature distribution between the reaction zones, which is beneficial for fuel reforming applications. Kinetic simulations reveal that conversion of methane to hydrogen occurs in a two-stage process of partial oxidation followed by steam reforming. In the partial oxidation zone, the reaction is exothermic and methane is converted to hydrogen. In the steam reforming zone, the reaction is endothermic. Hydrogen is produced through the reaction $\text{CH}_4 + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO}$ in which water produced in the exothermic reaction reacts with unburned methane.

[0078] A non-dimensional form of the governing equations for combustion in counter-flow heat exchangers has been developed. The coupling of gas temperature and species concentration appears only in the forcing term, which vanishes outside the immediate surroundings of the flame. Thus it is possible to split the overall problem in two parts, which in general have to be solved iteratively. On a macroscopic level, the flame can be replaced by a generic point source of unknown strength, and the heat transfer process inside the heat exchanger can be examined independent from the gas concentrations. The microscopic problem computes the strength of the generic point source, where the boundary conditions follow from the results of the macroscopic problem.

[0079] The direct analytical solution of the macroscopic heat transfer problem is developed below.

Development of the Mathematical Model

[0080] The mathematical model is developed for two channels in counter-flow configuration with external heat losses. Heat source **1** is located in channel **34a** and heat source **2** is located in channel **34b**. As inlet mixture **36** passes towards the heat source in channel **34a**, its temperature increases. After passing the location of heat source in channel **34b**, heat is transferred to the inner wall **31** and subsequently to inlet mixture **36** in channel **34b**. Inlet mixture **36** in channel **34b** is flowing in the opposite direction and undergoes the same processes.

[0081] Governing Equations

[0082] The transient equations describing the distributions of gas temperature T_i and the concentration of a limiting species y_i in each of the channels are given by:

$$\rho_g c_g \left(\frac{\partial T_i}{\partial \tilde{t}} + \tilde{U}_i \frac{\partial T_i}{\partial \tilde{x}} \right) = k_g \frac{\partial^2 T_i}{\partial \tilde{x}^2} - \frac{h_g}{d_g} (T_i - T_w) - QW'(\tilde{T}_i, \tilde{y}_i) \quad (1)$$

$$\rho_g \left(\frac{\partial \tilde{y}_i}{\partial \tilde{t}} + \tilde{U}_i \frac{\partial \tilde{y}_i}{\partial \tilde{x}} \right) = \rho_g D_g \frac{\partial^2 \tilde{y}_i}{\partial \tilde{x}^2} + \tilde{W}'(T_i, \tilde{y}_i) \quad (2)$$

where $i=1, 2$ identifies the channel and the flow velocities for balanced flow conditions are given as $\tilde{U}=\tilde{U}_1=-\tilde{U}_2$. While the coupling between gas temperature T_i and gas concentrations y_i within the channels is determined by the chemical reaction rate $W'(T_i, y_i)$ the gas temperatures of the individual channels interact through the dividing wall. The wall temperature T_w is the solution of

$$\rho_w c_w \frac{\partial T_w}{\partial \tilde{t}} = k_w \frac{\partial^2 T_w}{\partial \tilde{x}^2} + \frac{h_w}{d_w} (T_1 + T_2 - 2T_w) + \frac{h_\infty}{d_w} (T_\infty - T_w). \quad (3)$$

The subscripts g/w used in Equations (1) through (3) denote gas and wall, respectively. The parameters in the equation describe channel height d_g , wall thickness d_w , conductivities for gas k_g and solid wall k_w , densities for gas ρ_g and wall ρ_w , specific heat for gas c_g and solid c_w , as well as flow velocity \tilde{U} , heat addition Q , convective heat transfer coefficients to wall and environment, h_w and h_∞ as well as molecular gas diffusivity D_g .

[0083] The exothermic chemical reaction is modeled by single-step, first order, irreversible Arrhenius kinetics so that:

$$\tilde{W}'(T_i, \tilde{y}_i) = Z \rho_g \tilde{y}_i \exp\left(-\frac{E_\alpha}{RT_i}\right) \quad (4)$$

where Z is the pre-exponential factor, E_α is the activation energy or the reaction and R is the universal gas constant (e.g., Matkowsky and Sivashinsky, 1979).

Non-Dimensional Equations

[0084] Starting with Eqs. (1) through (3), the axial coordinate of the channel x is rescaled to the interval $[-1,1]$. Furthermore, the time t is non-dimensionalized by half of the residence time of the gas in the channels, the temperature T is

normalized by the adiabatic heat addition and the concentration y is scaled to the initial concentration of the limiting species. Thus, the scaled variables become:

$$x = \frac{2\tilde{x}}{L}, t = \frac{2U}{L}\tilde{t}, \quad (5)$$

$$\theta_i = \frac{c_g}{\tilde{y}_0 Q} (T_i - T_\infty), y = \frac{\tilde{y}}{\tilde{y}_0}$$

Using the non-dimensional parameters $Pe=d_g U/\alpha_g$ (Peclet Number), $a=L/2d_g$ (channel aspect ratio), $b=d_g/d_w$ (wall thickness ratio), $k=k_g/k_w$ (conductivity ratio), $Nu=h_w d_g/k_g$ and $Nu_\infty=h_\infty d_g/k_g$ (Nusselt numbers for internal and external heat transfer), $\alpha=a_g/a_w$ (ratio of thermal diffusivities) and $l=D_g/\alpha_g$ (Lewis Number), as well as introducing additional non-dimensional parameters, the equation system can be rewritten as

$$\frac{1}{\alpha} \frac{\partial \theta_w}{\partial t} = \textcircled{?} \frac{\partial^2 \theta_w}{\partial x^2} - \frac{\kappa}{\mu} \left[(1 + \chi) \theta_w - \frac{1}{2} (\theta_1 + \theta_2) \right] \quad (6)$$

$$\frac{\partial \theta_i}{\partial t} = \textcircled{?} \frac{\partial^2 \theta_i}{\partial x^2} \mp \frac{\partial \theta_i}{\partial x} - \frac{1}{\mu} (\theta_i - \theta_w) + \frac{1}{\textcircled{?}} \frac{W'}{V^2} \quad (7)$$

$$\frac{\partial y_i}{\partial t} = \frac{\textcircled{?}}{l} \frac{\partial^2 y_i}{\partial x^2} \mp \frac{\partial y_i}{\partial x} + \frac{1}{\textcircled{?}} \frac{W'}{V^2} \quad (8)$$

$$x = \frac{2\tilde{x}}{L}, t = \frac{2U}{L}\tilde{t}, \quad (5)$$

$$\theta_i = \frac{c_g}{\tilde{y}_0 Q} (T_i - T_\infty), y = \frac{\tilde{y}}{\tilde{y}_0}$$

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Using the non-dimensional parameters $Pe=d_g U/\alpha_g$ (Peclet Number), $a=L/2d_g$ (channel aspect ratio), $b=d_g/d_w$ (wall thickness ratio), $k=k_g/k_w$ (conductivity ratio), $Nu=h_w d_g/k_g$ and $Nu_\infty=h_\infty d_g/k_g$ (Nusselt numbers for internal and external heat transfer), $\alpha=a_g/a_w$ (ratio of thermal diffusivities) and $l=D_g/\alpha_g$ (Lewis Number), as well as introducing additional non-dimensional parameters, the equation system can be rewritten as

$$\frac{1}{\alpha} \frac{\partial \theta_w}{\partial t} = \textcircled{?} \frac{\partial^2 \theta_w}{\partial x^2} - \frac{\kappa}{\mu} \left[(1 + \chi) \theta_w - \frac{1}{2} (\theta_1 + \theta_2) \right] \quad (6)$$

$$\frac{\partial \theta_i}{\partial t} = \textcircled{?} \frac{\partial^2 \theta_i}{\partial x^2} \mp \frac{\partial \theta_i}{\partial x} - \frac{1}{\mu} (\theta_i - \theta_w) + \frac{1}{\textcircled{?}} \frac{W'}{V^2} \quad (7)$$

$$\frac{\partial y_i}{\partial t} = \frac{\textcircled{?}}{l} \frac{\partial^2 y_i}{\partial x^2} \mp \frac{\partial y_i}{\partial x} + \frac{1}{\textcircled{?}} \frac{W'}{V^2} \quad (8)$$

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The definition of the non-dimensional reaction term W' as:

$$W' = \frac{k_g \tilde{W}'}{c_g m^2 \tilde{y}_0} = \Lambda y_i \exp\left(-\frac{E_\alpha}{R} \left(\frac{1}{T_i} - \frac{1}{T_b}\right)\right), \text{ with } m = \rho U_b$$

is used to relate the source term to the classical solution of the adiabatic flame speed (e.g., Bush and Fendell, 1970), where external heat losses are assumed to be zero and the flame speed is determined from the solution of the eigenvalue:

$$\Lambda = \frac{Z\rho_g k_g}{c_g m^2} \exp\left(-\frac{E_a}{RT_b}\right) = \frac{Z\rho_g^2}{\alpha_g} \exp\left(-\frac{E_a}{RT_b}\right),$$

where $l_o = k_g/(c_g m)$ and T_b is the adiabatic flame temperature. Note that the eigenvalue Λ is a Damköhler number (ratio of reaction rate to heat-conduction rate (e.g., Law, 1984).

Steady-State Equations

[0085] The steady state equations for temperatures and concentration are given by

$$\textcircled{?} \frac{\mu}{\kappa} \frac{d^2 \theta_w}{dx^2} = (1 + \lambda) \theta_w \rightarrow \frac{1}{2} (\theta_1 + \theta_2) \quad (10)$$

$$\textcircled{?} \frac{d^2 \theta_1}{dx^2} = -\frac{d\theta_1}{dx} + \frac{1}{\mu} (\theta_1 - \theta_w) - \frac{1}{\textcircled{?} V^2} W' \quad (11)$$

$$\textcircled{?} \frac{d^2 \theta_2}{dx^2} = \frac{d\theta_2}{dx} + \frac{1}{\mu} (\theta_2 - \theta_w) - \frac{1}{\textcircled{?} V^2} W' \quad (12)$$

$$\textcircled{?} \frac{1}{l} \frac{d^2 y_1}{dx^2} = +\frac{dy_1}{dx} - \frac{1}{\textcircled{?} V^2} W' \quad (13)$$

$$\textcircled{?} \frac{1}{l} \frac{d^2 y_2}{dx^2} = -\frac{dy_2}{dx} - \frac{1}{\textcircled{?} V^2} W' \quad (14)$$

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[0086] Equations (10) through (14) form a system of 5 nonlinear 2nd-order equations, which require 10 boundary conditions. Exploiting the symmetry of the problem (i.e., the conditions in the second half of channel 1 are symmetric to the first half of channel 2), the equations can be solved for the half-length of the channels. Using convective boundary conditions at the channel inlet, vanishing gradients at the channel outlet and wall boundaries as well as matching the conditions at the mid-section, the boundary conditions are:

$$\frac{d\theta_1}{dx} = \frac{L}{2\alpha_g} \theta_1, \quad \frac{d\theta_2}{dx} = 0, \quad \frac{d\theta_w}{dx} = 0 \quad (15)$$

$$\frac{dy_1}{dx} = \frac{L}{2D_g} y_1, \quad \frac{dy_2}{dx} = 0$$

$$\theta_2 = \theta_1, \quad \frac{d\theta_2}{dx} = -\frac{d\theta_1}{dx}, \quad \frac{d\theta_w}{dx} = 0 \quad (16)$$

$$y_2 = y_1, \quad \frac{dy_2}{dx} = -\frac{dy_1}{dx},$$

Point Source Model

[0087] For large activation energies E_a , the source terms W' can be neglected outside an infinitesimally thin flame-sheet and thus can be replaced by point sources with a strength related to the energy content of the incoming flow. Earlier studies on channels in counterflow configuration (e.g.,

Fursenko et al., 2001; and Ju and Choi, 2003) examine the problem on a length-scale based on gas diffusion and give the strength as:

$$W'(\theta_i, y_i) \approx \textcircled{?} V H \delta(x - x_f), \quad \text{with } H = \exp\left(\beta \frac{T_f - T_b}{2T_b}\right) \quad (17)$$

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where T_f is the (maximum) flame temperature at the flame front and x_f is the location of the flame front. The validity of the approximation is limited to small deviations from the adiabatic case, $\beta \gg 1$ and $(T_f - T_b)/T_b \ll 1$.

[0088] The approximation of the reaction rate by a concentrated source term allows for the solution of the system (10) through (14) as a set of two piecewise-linear systems linked by 10 internal boundary conditions at the location of the flame fronts $x = x_f$. While integration of Eqs. (11) and (13) yields jump conditions for the derivatives of temperature and species concentration across the flame front, the remaining internal boundary conditions follow from continuity of the function values and the remaining derivatives. Denoting the difference in function values at the flame location as $[J] = f|_{x=x_f+} - f|_{x=x_f-}$ the internal boundary conditions at $x = x_f$ become:

$$\left[\frac{d\theta_1}{dx}\right]^+ = \frac{H}{\textcircled{?} V}, \quad \left[\frac{dy_1}{dx}\right]^+ = \frac{H}{\textcircled{?} V}, \quad (18)$$

$$\left[\frac{d\theta_2}{dx}\right]^+ = \left[\frac{d\theta_w}{dx}\right]^+ = \left[\frac{dy_2}{dx}\right]^+ = 0,$$

$$[\theta_1]^+ = [\theta_2]^+ = [\theta_w]^+ = [y_1]^+ = [y_2]^+ = 0,$$

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The overall problem can be split into two coupled problems that have to be solved iteratively:

[0089] 1. Heat exchanger with point heat sources (macroscopic problem): Preheating and/or superadiabaticity is determined as a function of flow velocity and location/strength of the source. The strength of the source is treated as a parameter, and temperature and concentration distributions can be solved independently.

[0090] 2. Flame sheet (microscopic problem): The strength of the source is determined as a function of initial temperature and flow velocity.

Direct Solution of the Heat Exchanger Problem

[0091] Using the point source approach, the gas temperatures decouple from the species concentrations and the equations characterizing the temperature inside the heat exchanger can be solved independently.

Parameter Variations

[0092] One example of typical solutions of the problem includes: the incoming stream is heated up by the hot gas in the adjacent channel until it reaches the location of the heat source, where the gradient flattens and a zone of high temperatures is maintained until the gas passes the location of the heat source in the opposing channel. The remaining stretch to

the channel exit is used as a counter-flow heat exchanger to heat up the gas in the opposing channel.

[0093] The internal high temperature zone shows that the counter-flow heat exchanger concept is capable of concentrating energy in the central part of the channels. The non-dimensional temperature θ is an indicator of the enhancement or superadiabaticity of the maximum temperature. As noted above, for a single channel porous media reactor, superadiabatic temperatures are attainable only for the co-flowing case, i.e. the reaction wave is propagating downstream. In the counterflow design, temperatures above the adiabatic temperature rise are possible for stationary fronts as indicated by the fact that θ is greater than 1 for many different combinations of parameters.

[0094] In the following, the predictions of the analytical model will be illustrated using a variation of the model parameters. While the problem has been solved in terms of a minimal set of dimensionless parameters, the variation will make use the more intuitive dimensionless group $\sim \alpha$ (channel aspect ratio), Pe (Peclet number), Nu (Nusselt number for wall heat transfer), Nu_{oo} (external heat losses) as well as the products $K=2 kb$ (conductivity ratio times wall thickness ratio) and H/V (strength of the heat source).

[0095] As the results indicate, the superadiabaticity θ is directly proportional to the strength of the heat source H/V . Furthermore, an optimum Pe is observed for all locations of the heat source. For low Pe , external heat losses become dominant and decrease the local peak temperature. At high Pe , the gas flows out of the reactor before it is heated by the heat source. The aspect ratio α has a significant impact on θ particularly when the reaction front is located at the center ($x=0$). For this case, the aspect ratio should be between 25 and 50 but due to increased heat losses further increases are of no consequence. For a 2 mm channel, this means the half-length of the reactor should be 50 to 100 mm long which is reasonable in practice. As heat transfer from the wall to the gas increases $(Nu_w)^{-1}$, the enhancement of the temperature is greater. Conversely, as heat losses to the outside (Nu_{oo}) increase, the temperature enhancement diminishes. Finally, the parameter $K, =2 kb$ is an indicator for the importance of the wall. As the wall thickness decreases, b increases and enhances the superadiabatic performance, which shows a maximum for a vanishing wall thickness. As the wall conductivity decreases relative to that for the gas, k increases and augments the temperature enhancement. These non-dimensional parameters give some insight as to how porous media will enhance the performance of the multichannel reactor.

What is claimed is:

1-21. (canceled)

22. A burner for reacting mixtures comprising a fuel and an oxidizer, the burner comprising:

- a first channel configured to communicate a first mixture in a first direction with a first combustion zone defining a first channel upstream portion and a first channel downstream portion; and
- a second channel formed adjacent the first channel and configured to communicate a second mixture in a second direction with a second combustion zone defining a second channel upstream portion and a second channel downstream portion, wherein the second direction is substantially opposite the first direction,

wherein the first channel downstream portion is configured to preheat the second channel upstream portion and the

second channel downstream portion is configured to preheat the first channel upstream portion.

23. The burner of claim **22**, wherein the first channel and the second channel each comprise an inert material.

24. The burner of claim **22**, wherein the first channel further comprises a porous media disposed therein.

25. The burner of claim **22**, wherein the second channel further comprises a porous media disposed therein.

26. The burner of claim **22**, wherein the first channel and the second channel are each configured to generate superadiabatic temperatures therein.

27. The burner of claim **22**, wherein the first channel comprises a first width and a first length and the second channel comprises a second width and a second length, the first width substantially equal to the second width and the first length substantially equal to the second length.

28. The burner of claim **27** comprising a ratio between the first length and the first width between approximately 25 and approximately 50.

29. The burner of claim **22** further comprising:

a plurality of first channels;

a plurality of second channels, each second channel formed adjacent to one or more of the plurality of first channel; and

each first channel having a first heat source positioned such that gas flowing through the first channel preheats gas in the adjacent one or more second channels and each second channel having a second heat source positioned such that gas flowing through the second channel preheats gas in the one or more adjacent first channels.

30. The burner of claim **29**, wherein each first channel is formed laterally adjacent to one or more of the plurality of second channels.

31. A method for reacting mixtures comprising a fuel and an oxidizer, the method comprising:

communicating in a first direction a first mixture in a first channel with a first combustion zone defining a first channel upstream portion and a first channel downstream portion;

communicating in a second direction a second mixture in a second channel with a second combustion zone defining a second channel upstream portion and a second channel downstream portion, wherein the second channel is adjacent to the first channel and the second direction is substantially opposite the first direction;

preheating the first channel upstream portion with the second channel downstream portion; and

preheating the second channel upstream portion with the first channel downstream portion.

32. The method of claim **31** further comprising performing all of the steps simultaneously.

33. The method of claim **31**, wherein the first channel and second channel comprise an inert material.

34. The method of claim **31** further comprising communicating the fuel and oxidizer mixture in the first channel and the second channel, wherein the first channel and second channel include a porous media in each respective channel.

35. The method of claim **31** further comprising combusting the first mixture and/or the second mixture at superadiabatic temperatures.

36. The method of claim **31** further comprising communicating the mixture in the first channel and the mixture in the second channel, wherein the first channel and the second

channel have a substantially equal width and the first channel and the second channel have a substantially equal length.

37. The method of claim **36** wherein a ratio between the width and the length of the first and second channel is between approximately 25 and approximately 50.

38. A method of making a combustion reactor comprising:
providing a plurality of first channels to communicate a first gas in a first direction with a first combustion zone defining a first channel upstream portion and a first channel downstream portion; and

providing a plurality of second channels, each second channel positioned adjacent to one or more of the plurality of first channels and configured to communicate a second gas in a second direction with a second combustion zone defining a second channel upstream portion and a second channel downstream portion,

wherein at least one first channel downstream portion is operable to transfer heat to at least one of the second channel upstream portions and at least one second channel downstream portion is operable to transfer heat to at least one of the first channel upstream portions.

39. The method of claim **38** further comprising providing each of the plurality of first channels laterally adjacent one or of the plurality of second channels and providing each of the plurality of second channels laterally adjacent one or more of the plurality of first channels.

40. The method of claim **38** further comprising providing a plurality of first and second channels, wherein the plurality of first channels and the plurality of second channels all have a substantially equal width and all have a substantially equal length.

41. The method of claim **40** wherein a ratio between the width and the length of each channel of the plurality of first and second channels is between approximately 25 and approximately 50.

42. The method of claim **38**, wherein at least one of the first channels is configured to generate superadiabatic temperatures therein.

43. The method of claim **38**, wherein at least one of the second channels is configured to generate superadiabatic temperatures therein.

44. A system for reacting mixtures comprising a fuel and an oxidizer, the system comprising:

a first means for communicating a first mixture in a first direction;

a second means for communicating a second mixture in a second direction, the second direction substantially opposite the first direction;

a means for preheating the first mixture in the first channel before it reacts; and

a means for preheating the second mixture in the second channel before it reacts.

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