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Xu et al.

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(54) **FUEL REFORMER COOLER**

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See application file for complete search history.

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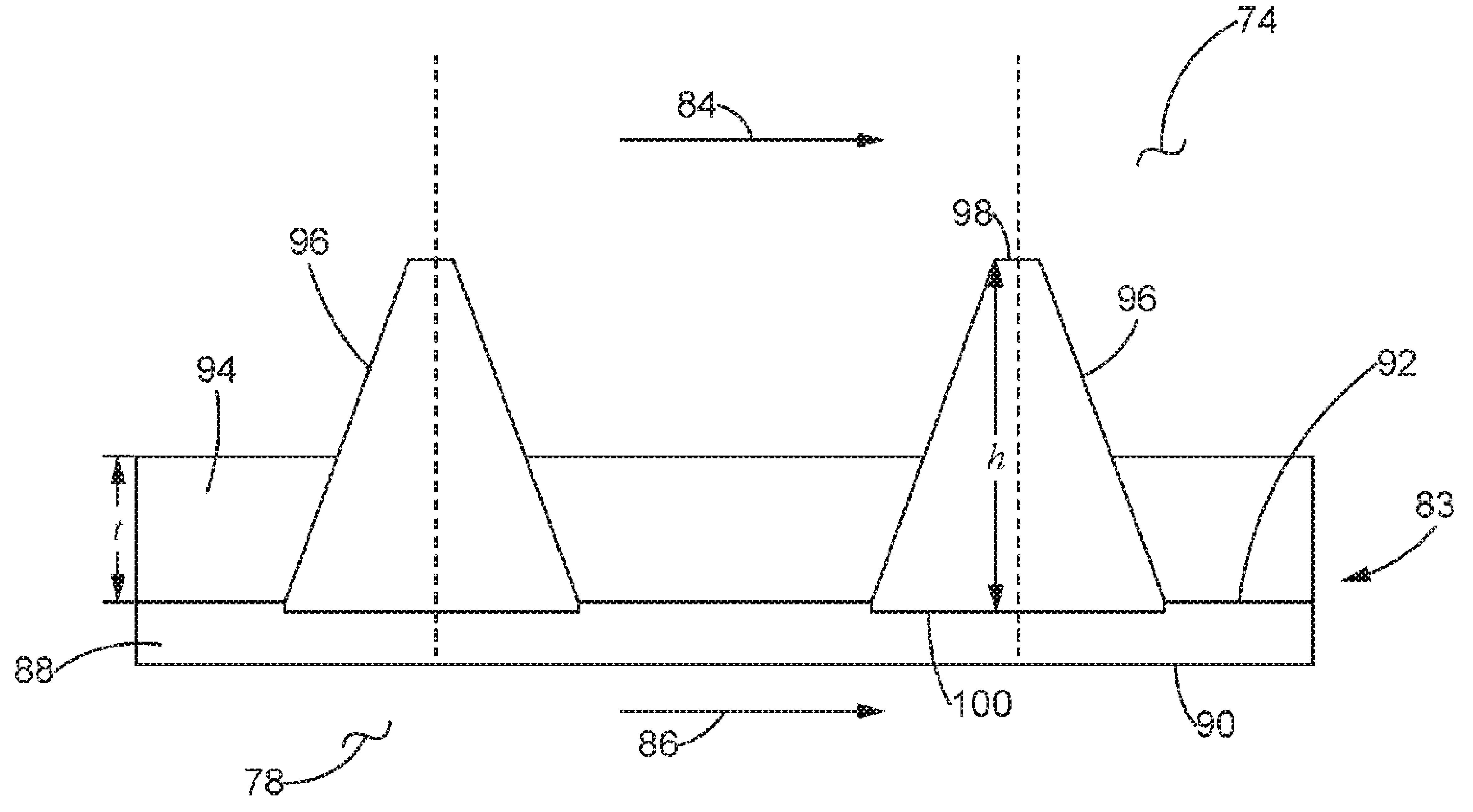
(57) **ABSTRACT**

A fuel reformer cooler for cooling a hydrogen-containing effluent released from a fuel reformer is disclosed. The fuel reformer cooler may comprise a heat transfer wall separating an effluent conduit from a coolant conduit and permitting heat transfer from the effluent in the effluent conduit to a coolant in the coolant conduit therethrough. The heat transfer wall may be formed from a base that includes a first surface facing the coolant conduit and a second surface facing the effluent conduit. The cooler may further comprise an anti-hydrogen embrittlement layer applied to the second surface of the base to shield the base from exposure to the effluent, and a plurality of symmetrical fins each extending through the anti-hydrogen embrittlement layer and contacting the second surface of the base. The plurality of symmetrical fins may project into the effluent conduit.

20 Claims, 4 Drawing Sheets



(51) **Int. Cl.**

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C01B 3/38	(2006.01)
F28D 7/16	(2006.01)
F28D 21/00	(2006.01)

(52) **U.S. Cl.**

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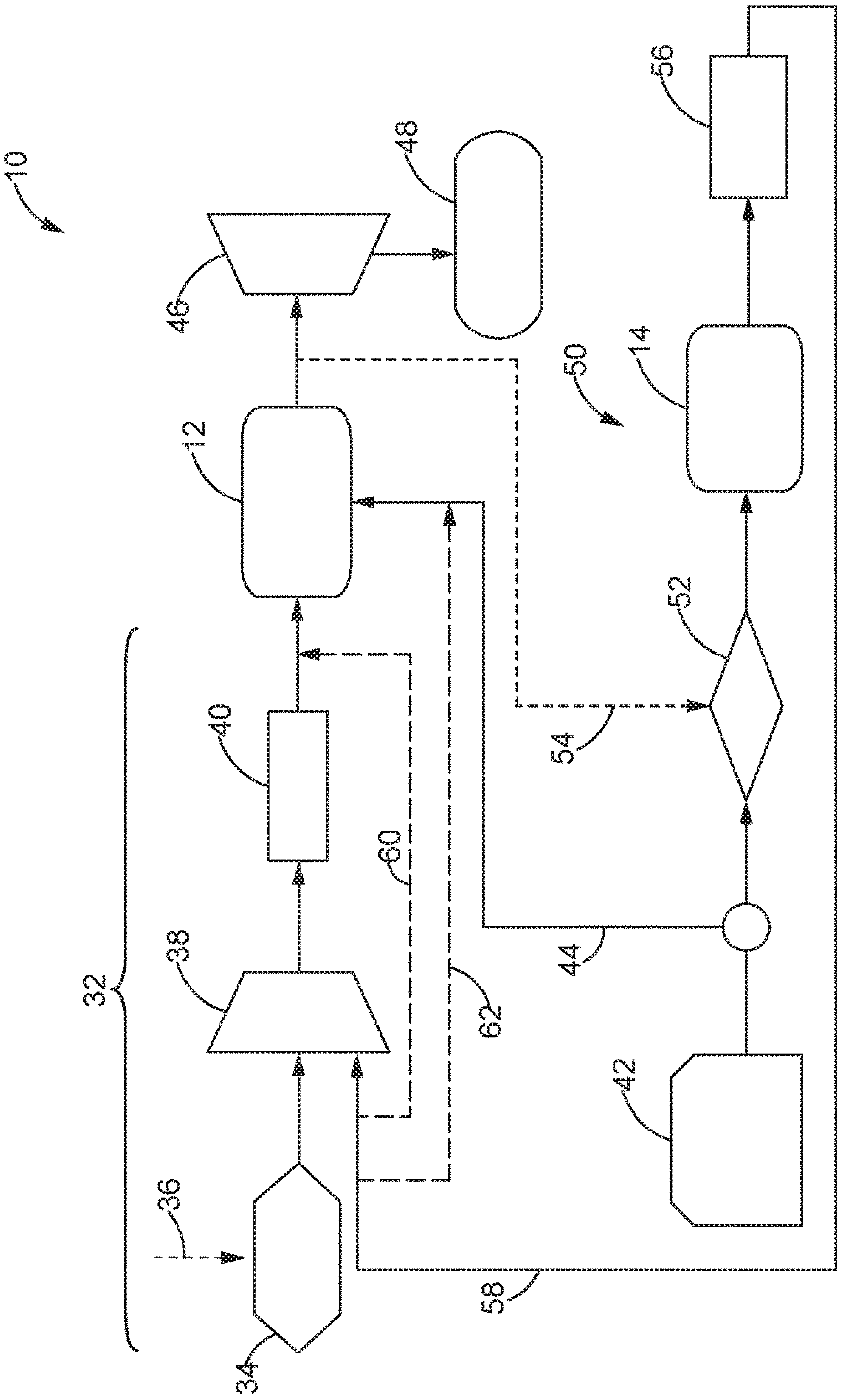
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FIG. 1

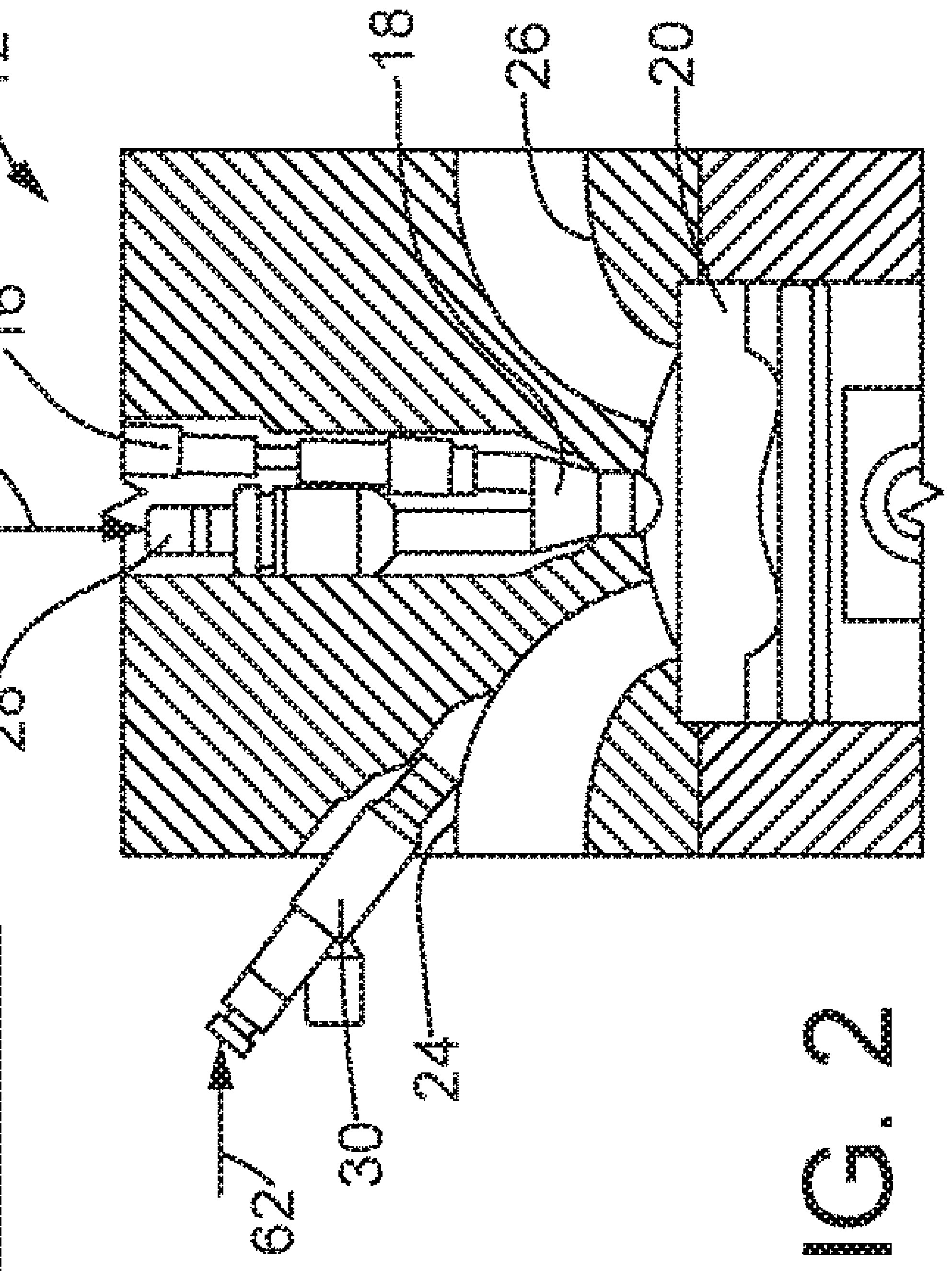
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FIG. 2

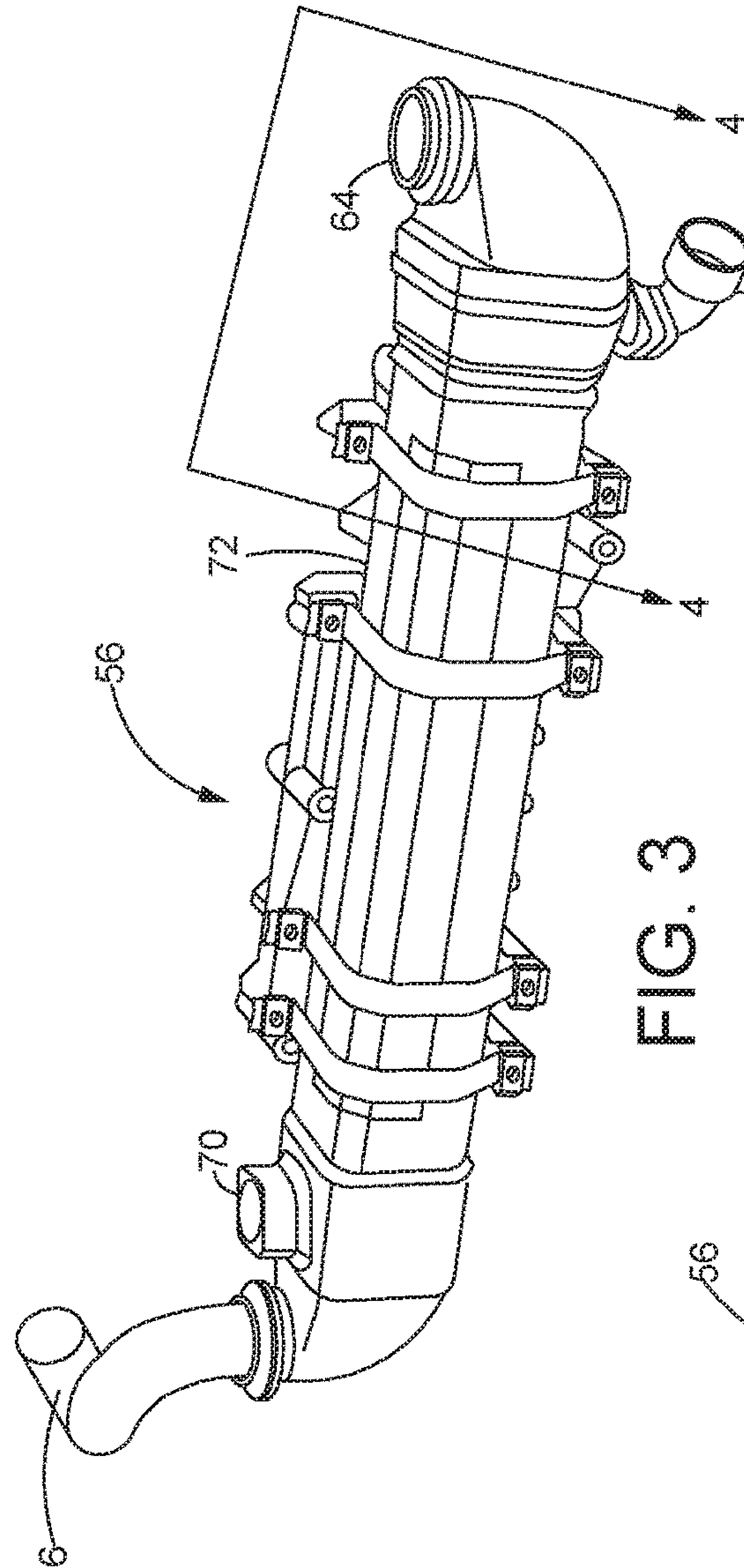

FIG. 3

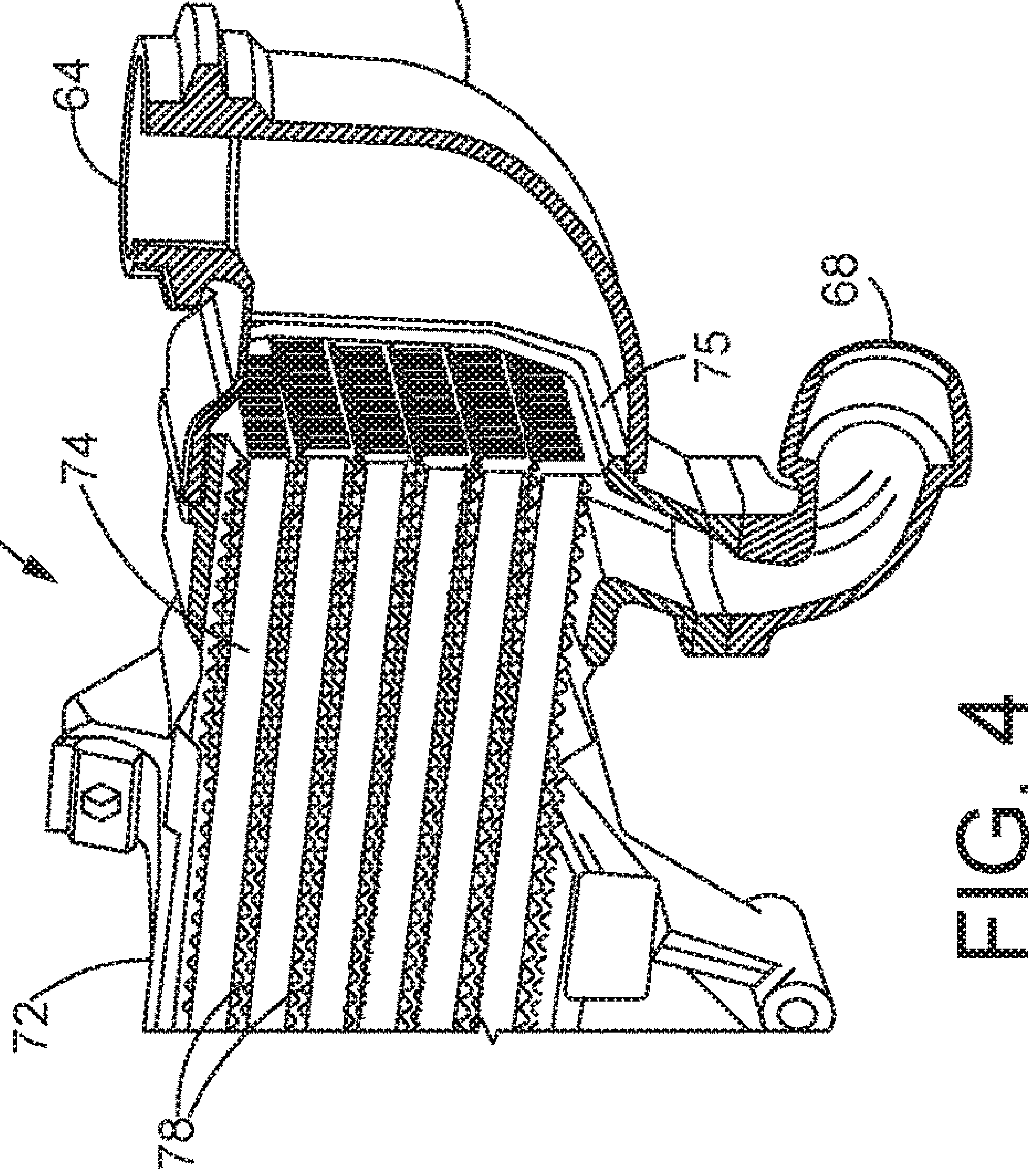

FIG. 4

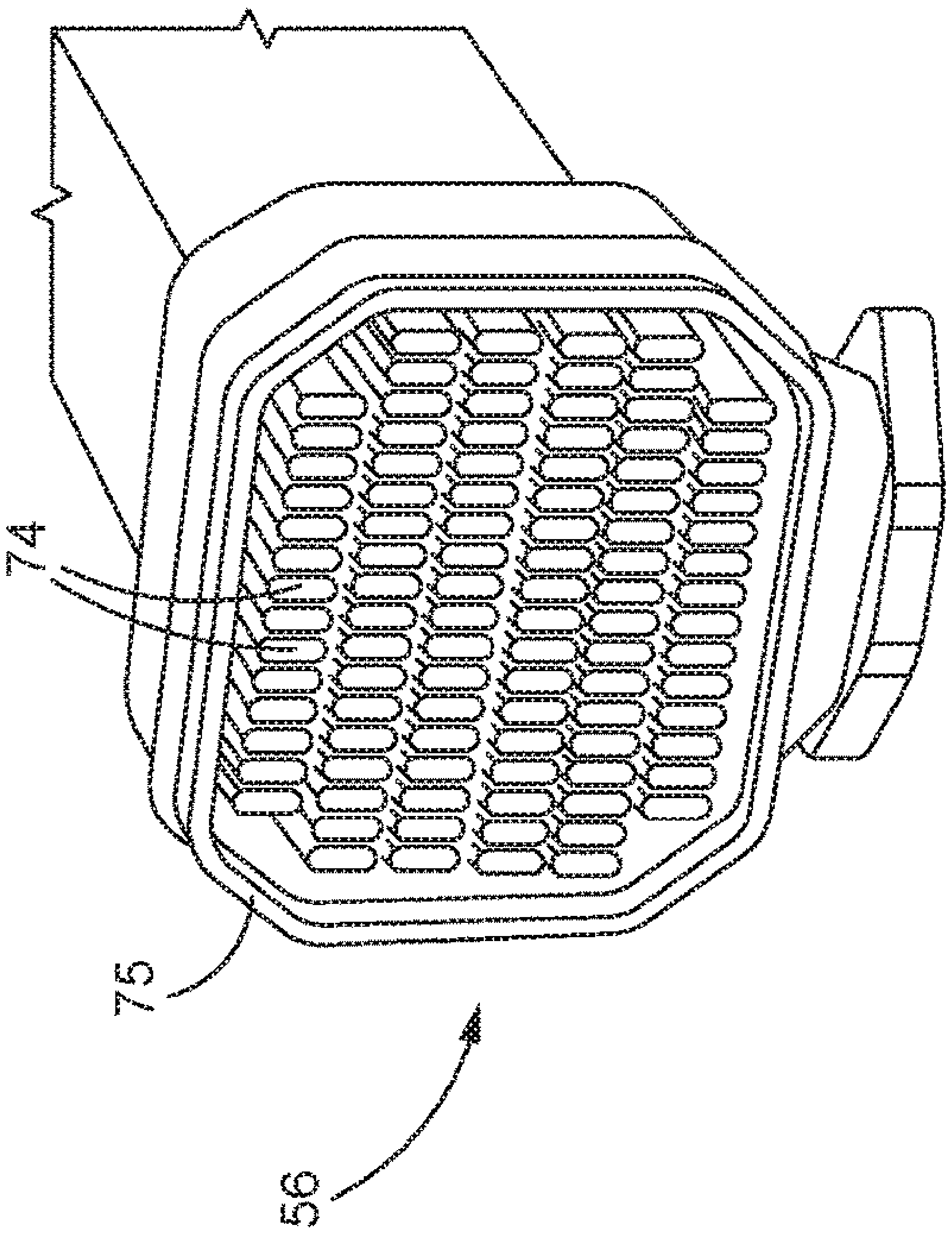

FIG. 5

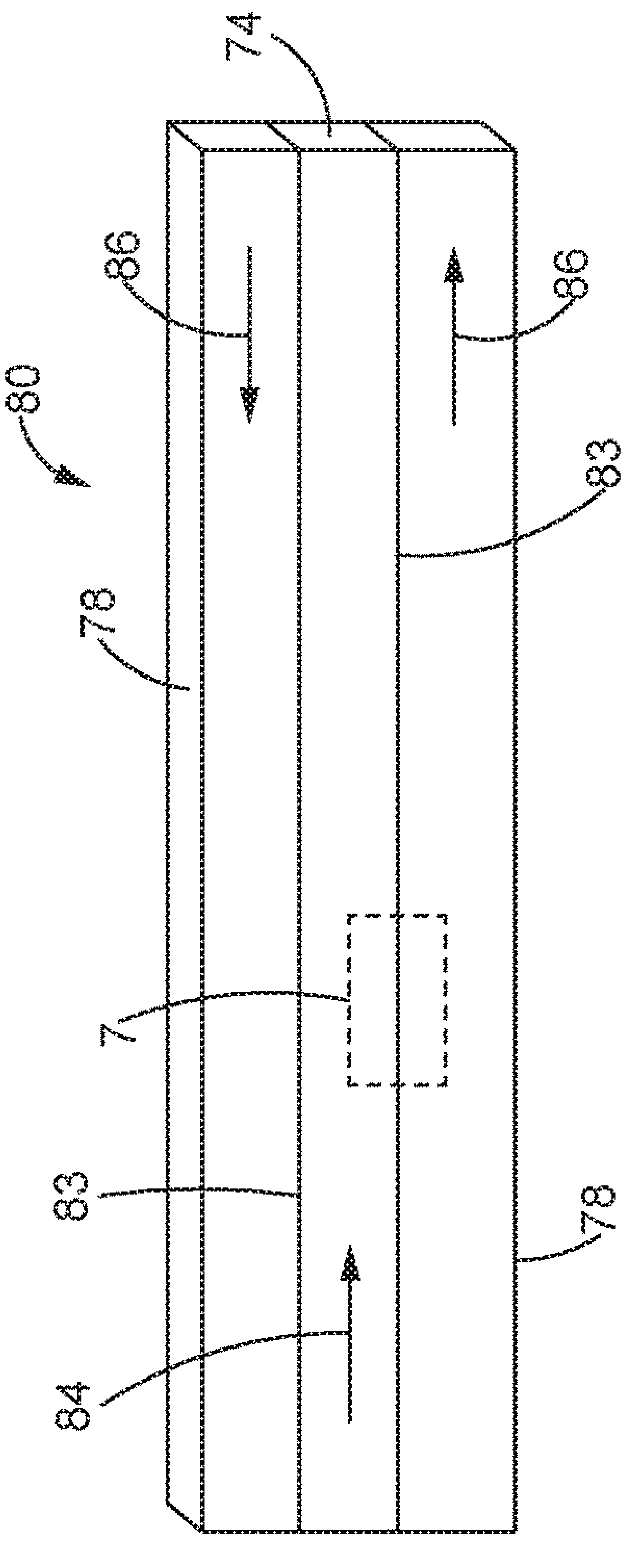

FIG. 6

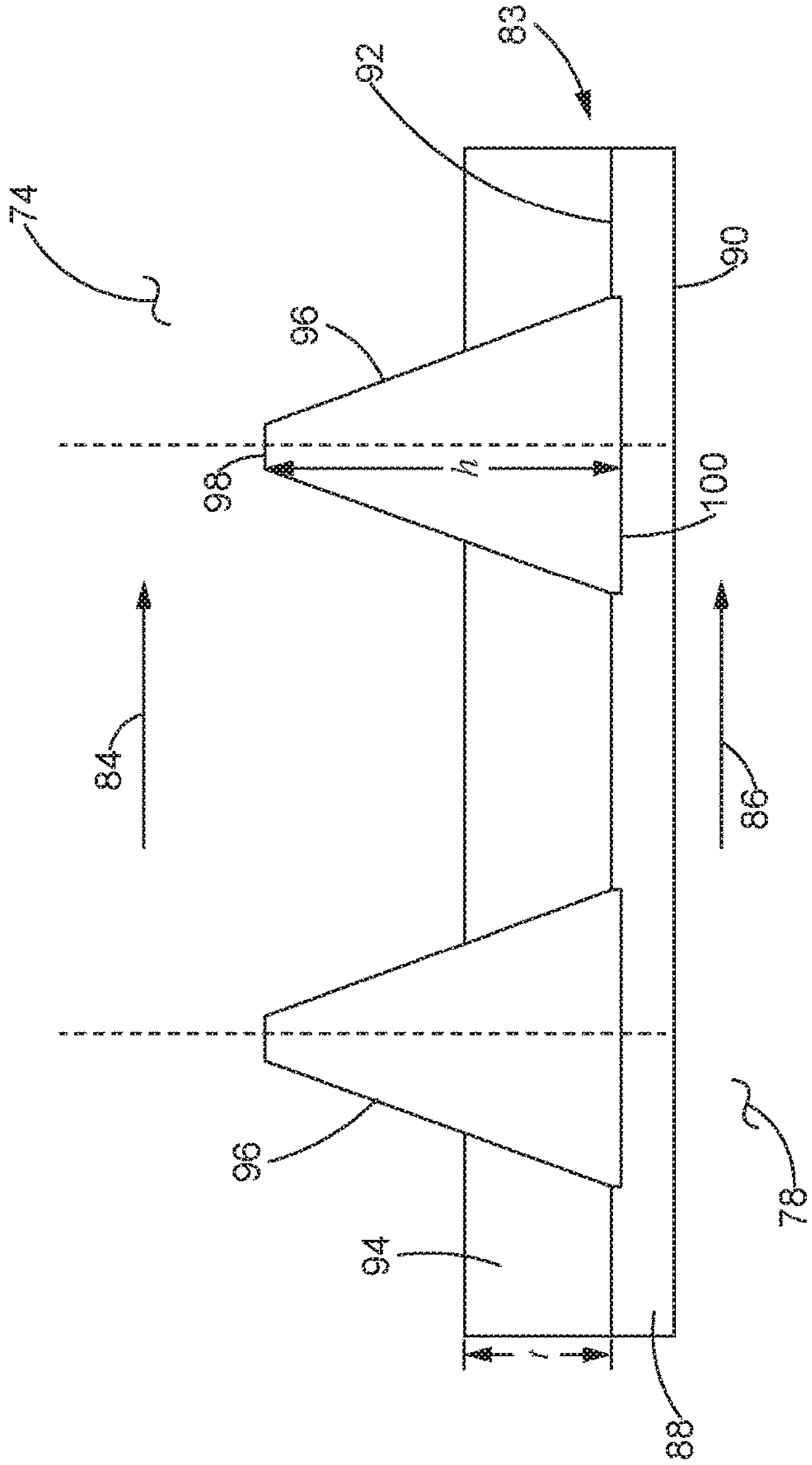

FIG. 7

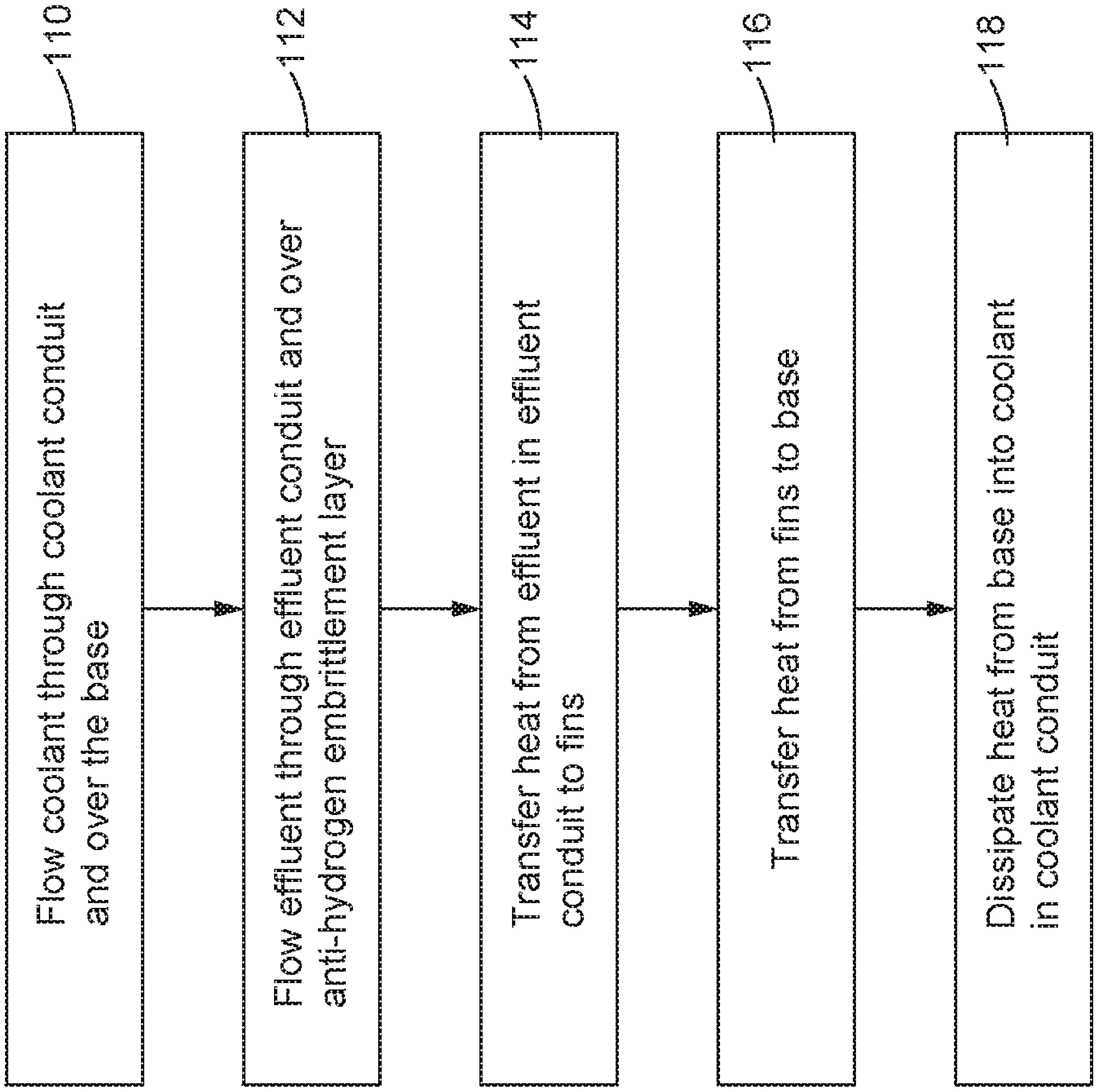
110
Flow coolant through coolant conduit and over the base
112
Flow effluent through effluent conduit and over anti-hydrogen embrittlement layer
114
Transfer heat from effluent in effluent conduit to fins
116
Transfer heat from fins to base
118
Dissipate heat from base into coolant in coolant conduit

FIG. 8

FUEL REFORMER COOLER

TECHNICAL FIELD

The present disclosure generally relates to coolers for hydrogen-containing fluids and, more specifically, to coolers for cooling hydrogen-containing effluents released by fuel reformers.

BACKGROUND

A fuel reformer is a device that transforms one type of fuel into another type of fuel. A common type of fuel reformer is a hydrogen fuel reformer which transforms fuel (e.g., natural gas, methane, liquid petroleum gas, etc.) into hydrogen. In a hydrogen fuel reformer, methane (CH_4) or natural gas may react with water and oxygen at high temperatures (e.g., about 700° C. to about 1100° C.) to produce hydrogen (H_2), carbon monoxide (CO), and other products. Fuel reformers may be used to produce hydrogen for fuel cell applications, or to provide a reducing atmosphere for catalyst regeneration in exhaust aftertreatment systems. In another use, fuel reforming may supply hydrogen gas to combustion chambers to facilitate and stabilize combustion under lean burn conditions (i.e., in an excess of air). In particular, because hydrogen ignites readily due to its high flame propagation speed, it may facilitate ignition of fuel and air in the combustion chamber.

Due to the high operating temperatures of hydrogen fuel reformers, the hydrogen-containing effluent gas leaving a hydrogen fuel reformer may be at high temperatures in a range of about 600° C. to about 800° C. or more. Prior to introduction of the reformed gas to an intake manifold and/or fuel admission valves for supporting lean burn combustion, the effluent gas should be sufficiently cooled to prevent shock issues in the combustion chamber. Ideally, the temperature of the effluent gas from a fuel reformer should be reduced to below about 120° C. prior to introduction into the combustion chamber. Coolers may be used for this purpose. However, it may be a technical challenge for a typical engine cooler or an industry cooler to withstand a hydrogen-rich environment due to hydrogen embrittlement.

Hydrogen embrittlement is caused by the diffusion of hydrogen atoms into a metal. The hydrogen atoms within the metal may recombine to form hydrogen molecules or other compounds that may create pressure within the metal. This pressure may increase to levels where the metal has reduced ductility, toughness, and tensile strength, such that the metal may eventually fracture or crack. Certain metals, such as steel, titanium, and aluminum alloys, are particularly vulnerable to hydrogen embrittlement compared to other types of metals and materials. As many coolers may include a steel framework, such coolers are vulnerable to hydrogen embrittlement. This problem may be further exacerbated by the high temperature of the effluent gas, as hydrogen diffusion into materials occurs more rapidly at higher temperatures. Hydrogen diffusion into the framework of the cooler may be further assisted by a hydrogen concentration gradient between the framework of the cooler and the effluent gas. Some coolers do not purge the gaseous mixture in the cooler at shutdown, such that hydrogen diffusion into the metal framework may occur at even lower temperatures due to significantly more hydrogen outside the metal than inside. Accordingly, coolers may be susceptible to early failure due to hydrogen embrittlement when used to cool hydrogen-containing effluent gas from fuel reformers.

U.S. Pat. No. 8,852,820 discloses a hydrogen fuel cell module having heat exchangers that heat fuel and air inlet streams, wherein the housing of the module is coated with an anti-hydrogen embrittlement material that protects the module from hydrogen embrittlement. While effective, the patent does relate to coolers for cooling effluent gas from fuel reformers. Thus, there is a need for improved cooler designs for cooling hydrogen-containing effluent gas from fuel reformers.

SUMMARY

In accordance with one aspect of the present disclosure, a fuel reformer cooler for cooling a hydrogen-containing effluent released from a fuel reformer is disclosed. The fuel reformer cooler may comprise an effluent conduit configured to permit a flow of the effluent from an effluent inlet to an effluent outlet, a coolant conduit configured to permit a flow of a coolant from a coolant inlet to a coolant outlet, and a heat transfer wall separating the effluent conduit from the coolant conduit and permitting heat transfer from the effluent to the coolant therethrough. The heat transfer wall may be formed from a base that includes a first surface facing the coolant conduit and a second surface facing the effluent conduit. The fuel reformer cooler may further comprise an anti-hydrogen embrittlement layer applied to the second surface of the base to shield the base from exposure to the effluent, and a plurality of symmetrical fins each extending through the anti-hydrogen embrittlement layer and contacting the second surface of the base. The plurality of symmetrical fins may project into the effluent conduit.

In accordance with another aspect of the present disclosure, and engine system is disclosed. The engine system may comprise a combustion chamber configured to combust a mixture of fuel and air, an air intake system configured to supply the combustion chamber with the air, at least one fuel admission valve configured to supply the combustion chamber with the fuel, and a fuel reformer configured to transform the fuel into a hydrogen-containing effluent. The engine system may further comprise a fuel reformer cooler configured to cool the effluent released from the fuel reformer. The fuel reformer cooler may include a plurality of stacked heat transfer modules each having an effluent conduit, a coolant conduit, and at least one heat transfer wall separating the effluent conduit form the coolant conduit. The heat transfer wall may include a base facing the coolant conduit, an anti-hydrogen embrittlement layer facing the effluent conduit, and a plurality of symmetrical fins each contacting the base and extending through the anti-hydrogen embrittlement layer into the effluent conduit. The engine system may further comprise at least one delivery conduit configured to deliver the cooled effluent exiting the cooler to one of the air intake system and the fuel admission valve.

In accordance with another aspect of the present disclosure, a method for cooling a hydrogen-containing effluent released from a fuel reformer using a fuel reformer cooler is disclosed. The fuel reformer cooler may include a heat transfer wall separating an effluent conduit from a coolant conduit and including a base exposed to the coolant conduit and an anti-hydrogen embrittlement layer exposed to the effluent conduit. The method may comprise flowing a coolant through the coolant conduit and over the base, wherein the base is formed from steel and has a first surface facing the coolant conduit and a second surface facing the effluent conduit. The method may further comprise flowing the effluent through the effluent conduit and over the anti-hydrogen embrittlement layer, wherein the anti-hydrogen embrittlement layer is a nitride film applied to the second surface of the base. In addition, the method may further comprise transferring heat from the effluent in the effluent conduit to symmetrical fins extending from the second surface of the base into the effluent conduit, wherein the symmetrical fins are formed from copper. Furthermore, the method may comprise transferring heat from the symmetrical fins to the base, and dissipating heat from the base to the coolant in the coolant conduit.

These and other aspects and features of the present disclosure will be more readily understood when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic representation of an engine system having a fuel reformer and a fuel reformer cooler for supplying a hydrogen-containing effluent to an engine, constructed in accordance with the present disclosure.

FIG. **2** is a sectional view of a portion of the engine of the engine system, constructed in accordance with the present disclosure.

FIG. **3** is a perspective view of the fuel reformer cooler shown in isolation, constructed in accordance with the present disclosure.

FIG. **4** is a cross-sectional view through the section **4-4** of FIG. **3**, constructed in accordance with the present disclosure.

FIG. **5** is a perspective view of a coolant annulus of the fuel reformer cooler containing stacked effluent conduits, constructed in accordance with the present disclosure.

FIG. **6** is a side view of a heat transfer module of the fuel reformer cooler, constructed in accordance with the present disclosure.

FIG. **7** is an exploded view of detail **7** of FIG. **6**, illustrating a heat transfer wall of the heat transfer module, constructed in accordance with the present disclosure.

FIG. **8** is a flowchart depicting a series of steps involved in cooling the hydrogen-containing effluent using the fuel reformer cooler, in accordance with a method of the present disclosure.

DETAILED DESCRIPTION

Referring now to the drawings, and with specific reference to FIG. **1**, an engine system **10** is shown. The engine system **10** may provide power to a machine such as a mining truck, an off-road vehicle, a marine vehicle, earth-moving equipment, as well as other types of machines and equipment. In general, the engine system **10** may include an internal combustion engine **12** that combusts a fuel under lean conditions (i.e., in an excess of air) to provide mechanical energy to operate the machine, as well as a fuel reformer **14** that transforms a fuel into hydrogen (H_2) and other products (CO, CO_2, N_2, etc.) under elevated temperatures (e.g., about 700° C. to about 1100° C.) and in the presence of a catalyst as will be understood by those with ordinary skill in the art. The hydrogen produced by the fuel reformer **14** may be subsequently delivered to the engine **12** to support and stabilize lean burn combustion as described in further detail below.

As shown in FIG. **2**, the engine **12** may be a spark-ignited engine that includes a spark plug **16** to initiate combustion in a pre-combustion chamber **18** that is in fluid communication with a main combustion chamber **20**. The combustion in the pre-combustion chamber **18** may create jets that serve as an ignition source in the main combustion chamber **20**. An intake manifold **24** may supply the main combustion chamber **20** with a mixture of fuel and air for combustion, and an exhaust manifold **26** may provide a passage to evacuate exhaust gases from the main combustion chamber **20**. In addition, the engine **12** may have a first fuel admission valve **28** and a second fuel admission valve **30** for controlling a flow of fuel to the pre-combustion chamber **18** and the intake manifold **24**, respectively. In other arrangements, the engine **12** may be a dual fuel engine in which combustion is initiated by ignition of a pilot fuel as will be understood by those with ordinary skill in the art.

Turning back to FIG. **1**, the engine system **10** may include an air intake system **32** that provides air to the intake manifold **24**. Included in the air intake system **32** may be an air cleaner **34** that purifies incoming ambient air **36**, as well as a compressor **38** and an after cooler **40** downstream of the air cleaner **34**. The compressor **38** may compress and increase the pressure of the ambient air, while the after cooler **40** may reduce the temperature of the air caused by compression prior to delivery to the engine **12** through the intake manifold **24**. In addition, the engine system **10** may have one or more fuel sources **42** to supply one or more types of fuel (e.g., natural gas, methane, etc.) to the first and second fuel admission valves **28** and **30** via conduits **44**. A turbine **46** may receive a flow of the exhaust gas via the exhaust manifold **26** and may extract mechanical work from the exhaust gas by expansion of the exhaust gas therethrough. Subsequently, the exhaust gases may be treated at one or more aftertreatment stations **48** to reduce the levels of NO_x and/or particulate matter in the exhaust gas prior to emission.

The fuel source **42** may also supply fuel (e.g., natural gas, methane, etc.) to a fuel reforming station **50** that includes the fuel reformer **14**. For instance, the fuel source **42** may supply the same type of fuel (e.g., natural gas, methane, etc.) to the engine **12** for combustion and to the fuel reforming station **50** for production of hydrogen. In other arrangements, the engine **12** and the fuel reformer **14** may use different types of fuel derived from different fuel sources. At an upstream end of the fuel reforming station **50** may be a mixer **52** that mixes the fuel from the fuel source **42** with exhaust gas derived from the engine **12** via one or more conduits **54**. Mixing of the fuel with the exhaust gas in this way increases the temperature of the fuel to enhance chemical transformation of the fuel at the downstream fuel reformer **14**. Following mixing with the exhaust gas at the mixer **52**, the fuel reformer **14** may transform the fuel to produce a high temperature (about 600° C. to about 800° C.) effluent containing hydrogen.

The hydrogen-containing effluent produced by the fuel reformer **14** may be subsequently cooled at a fuel reformer cooler **56** prior to delivery of the effluent to the engine **12**. Specifically, the fuel reformer cooler **56** may lower the temperature of the effluent to a range between about 40° C. to about 120° C. In other arrangements, the effluent may be reduced to temperatures near or below ambient temperature at the cooler **56**. Once cooled, the hydrogen-containing effluent may be supplied to the air intake system **32** or one or both of the fuel admission valves **28** and **30** for delivery to the pre-combustion chamber **18** and/or the main combustion chamber **20**. For instance, the cooled effluent may be introduced upstream of the compressor **38** via one or more delivery conduits **58**. Alternatively, or in combination with this, the cooled effluent gas may be delivered downstream of the after-cooler **40** through one or more delivery conduits **60** and/or into one or both of the first and second fuel admission valves **28** and **30** through one or more delivery conduits **62**.

Turning now to FIGS. **3**-**5**, the fuel reformer cooler **56** is shown in isolation. The fuel reformer cooler **56** may have an effluent inlet **64** through which the high temperature effluent from the fuel reformer **14** enters the cooler **56**, as well as an effluent outlet **66** through which the cooled effluent exits the cooler **56** for delivery to the air intake system **32** and/or the fuel admission valves **28** and **30**. In addition, the cooler **56** may have a coolant inlet **68** through which a coolant enters the cooler **56** for heat exchange with the effluent, and a coolant outlet **70** through which the coolant exits the cooler **56**. The coolant may be water, although other types of coolants such as ethylene glycol or propylene glycol may also be used.

The cooler **56** may have a housing **72** containing one or more effluent conduits **74** through which the effluent flows from the inlet **64** to the outlet **66** while transferring heat to the coolant (see FIGS. **4**-**5**). To handle high mass flow conditions, the cooler **56** may have a plurality of effluent conduits **74** stacked in repeating rows and columns, or other arrangements. The incoming effluent may be spread to the multiple effluent conduits **74** with a diffuser **76** at the inlet **64** (see FIG. **4**). Surrounding the effluent conduits **74** in the housing **72** may be a coolant annulus **75** through which the coolant flows between the effluent conduits **74**.

A single heat transfer module **80** of the cooler **56** is shown in FIG. **6**. A plurality of the heat transfer modules **80** may be stacked or otherwise arranged to handle high mass flow rates of effluent (see FIGS. **4**-**5**). However, under low mass flow rate conditions, the cooler **56** may have only one or a few heat transfer modules **80**. Each heat transfer module **80** may include one of the effluent conduits **74** and one or more coolant conduits **78** through which coolant flows in heat exchange relation to the effluent conduit **74**. Each heat transfer module **80** may have at least one heat transfer wall **83** separating the effluent conduit **74** from the coolant conduit **78** and permitting heat transfer from the effluent **84** to the coolant **86** therethrough. In one arrangement, the heat transfer module **80** may include two heat transfer walls **83** separating the effluent **84** from coolant **86** on two opposing sides of the effluent conduit **74**, as shown in FIG. **6**.

Turning now to FIG. **7**, the heat transfer wall **83** of a heat transfer module **80** is shown in isolation. The heat transfer wall **83** may include a base **88** that is formed partly or entirely from a material, such as steel, that has a good thermal conductivity (about 50 Watts/meter·Kelvin (W/m·K)) but is susceptible to hydrogen embrittlement. The base **88** may include a first surface **90** facing the coolant conduit **78** so that it is exposed to the coolant **86** flowing through the coolant conduit **78**, as well as a second surface **92** facing the effluent conduit **74**. An anti-hydrogen embrittlement layer **94** may be applied or otherwise formed on the second surface **92** of the base **88** to shield the base **88** from attack by hydrogen in the effluent **84**. For instance, the anti-hydrogen embrittlement layer **94** may be a coating or other surface modification of the base **88** that is resistant to hydrogen embrittlement. As used herein, an "anti-hydrogen embrittlement layer" is a layer of a material that has a hydrogen diffusion coefficient that is at least two orders of magnitude less than the hydrogen diffusion coefficient of iron at a given temperature (e.g., less than about 1.66×10^{-9} cm^2/s at 100° C.). For instance, the anti-hydrogen embrittlement layer **94** may be a nitride film, such as a silicon nitride film, or it may be a layer or coating of a nickel-based alloy. Thus, the surface **92** of the base **88** facing the hydrogen-containing effluent **84** may be protected from hydrogen embrittlement by the anti-hydrogen embrittlement layer **94**.

The anti-hydrogen embrittlement layer **94** may have a low thermal conductivity (about 30 Watts/meter·Kelvin (W/m·K) or less) and, therefore, may play a minor to negligible role in transferring heat from the effluent **84** to the coolant **86** across the wall **83**. To compensate for reductions in heat transfer across the wall **83** caused by the insulating behavior of the anti-hydrogen embrittlement layer **94**, the wall **83** may further include a plurality of heat-conducting fins **96** that extend from the second surface **92** of the base **88** and project into the effluent conduit **74**. The fins **96** may extend through a thickness (t) of the anti-hydrogen embrittlement layer **94** to make direct contact with both the effluent gas **84** in the conduit **74** on one side and the base **88** on the other. As such, heat may be effectively transferred across the wall **83** from the effluent **84** to the coolant **86** through the fins **96** and the base **88** which have good to high thermal conductivity. In addition, the fins **96** may promote heat transfer by increasing the surface area of contact between the effluent **84** and highly conductive portions of the heat transfer wall **83**, thereby compensating for the loss in conductive surface area caused by the insulating layer **94**.

The fins **96** may be formed from a material having a high thermal conductivity of at least about 300 W/m·K or more. For instance, the fins **96** may be formed partly or entirely from copper. In addition, each of the fins **96** may have a height (h) extending from a top **98**, that is exposed to the effluent **84**, to a bottom **100**, that is in contact with the base **88**. The bottom **100** of each of the fins **96** may have a larger cross-sectional area than the top **98** to provide a large contact surface area between the fins **96** and the base **88**, thereby promoting heat transfer therebetween. Each of the fins **96** may also have a symmetrical shape so that the fins **96** are resistant to mechanical stress under high pressures. In one arrangement, the fins **96** may have a conical shape as shown in FIG. **6**. The conical shape of the fins **96** may provide a robust structure. In alternative designs, the fins **96** may have various other types of shapes such as rectangular, spherical, polygonal, or even asymmetrical shapes.

The anti-hydrogen embrittlement layer **94** may have a pliable consistency such that the fins **96** may be press fit or pushed through the layer **94** for installation, with the anti-embrittlement layer **94** holding the fins **96** in place on the wall **83**. More specifically, the fins **96** may be installed on the heat transfer wall **83** by inserting the fins **96** through the anti-hydrogen embrittlement layer **94** until the bottoms **100** of the fins **96** contact the second surface **92** of the base **88**, without a chemical bond or mechanical connection between the fins **96** and the base **88**. Thus, the fins **96** may be readily removed and replaced as needed when damaged to increase the useful life of the cooler **56**. The cooler **56** may also remanufactured at the end of the useful life. In addition, to ensure that the fins **96** are retained in place on the wall **83** while allowing sufficient contact between the fins **96** and the effluent **84**, the thickness (t) of the anti-hydrogen embrittlement layer **94** may be about one-third the height (h) of the fins **96**.

INDUSTRIAL APPLICABILITY

In general, the teachings of the present disclosure may find applicability in many industries including, but not limited to, industries using coolers for hydrogen-containing fluids. As disclosed herein, the fuel reformer cooler design may be used to supply hydrogen to internal combustion engines to support lean burn combustion in various types of machines, such as mining trucks, off-road vehicles, marine vehicles, and earth-moving equipment. However, the cooler configuration disclosed herein may also be applicable to any type of cooler that cools a hydrogen-enriched or hydrogen-containing fluid.

The cooler disclosed herein includes a heat transfer wall having an anti-hydrogen embrittlement layer applied to the effluent side of a base formed from a material that is susceptible to hydrogen embrittlement. The anti-hydrogen embrittlement layer effectively shields the base material from the hydrogen-containing effluent, thereby preventing hydrogen embrittlement at the base framework of the cooler and extending the useful life of the cooler. As the anti-hydrogen embrittlement layer may weakly participate in heat transfer due to its insulating properties, fins with high thermal conductivity may be inserted through the anti-hydrogen embrittlement layer on the effluent side of the wall to promote heat transfer from the hot effluent to the base. Namely, the fins may form a direct contact with the base to allow heat conduction from the fins to the base. The portion of the fins that contacts the base may have a larger cross-sectional area to further promote heat transfer to the base. All other surfaces of the base which are exposed to the effluent may be covered by the anti-hydrogen embrittlement layer to prevent hydrogen diffusion into the base.

A series of steps that may be involved in cooling the hydrogen-containing effluent **84** using the fuel reformer cooler **56** are depicted in FIG. **8**. At a block **110**, the coolant **86** may be flowed through the coolant conduit **78** and over the base **88**. Likewise, at a block **112**, the hydrogen-containing effluent **84** may be flowed through the effluent conduit **74** and over the anti-hydrogen embrittlement layer **94**, with the anti-hydrogen embrittlement layer **94** protecting the base **88** from hydrogen attack. It will be understood that the blocks **110** and **112** may be carried out in any order or simultaneously. The temperature difference between the hot effluent **84** and the fins **96** in the effluent conduit **74** may cause heat transfer from the effluent **84** to the fins **96** by convection and conduction according to a next block **114**. The heat captured by the fins **96** may be transferred to the base **88** by conduction via the direct contact between the fins **96** and the base **88** according to a next block **116**. At the coolant side of the heat transfer wall **83**, the heat captured by the base **88** may be dissipated into the coolant **86** in the coolant conduit **78** according to a block **118**. Thus, thermal gradients created across the heat transfer wall **83** due to the large temperature difference between the hot effluent on one side and the lower temperature coolant on the other side are effectively mitigated by heat transfer across the wall. Such mitigation of the thermal gradient across the heat transfer wall **83** may enhance the useful life of the cooler by reducing thermal stress on the cooler.

It is expected that the technology disclosed herein may find wide industrial applicability in a wide range of areas such as, but not limited to, lean burn engines, exhaust aftertreatment systems, and hydrogen fuel cell applications.

What is claimed is:

1. A fuel reformer cooler, comprising:

an effluent conduit configured to permit a flow of a hydrogen-containing effluent released from a fuel reformer from an effluent inlet to an effluent outlet;

a coolant conduit configured to permit a flow of a coolant from a coolant inlet to a coolant outlet;

a heat transfer wall separating the effluent conduit from the coolant conduit and permitting heat transfer from the effluent to the coolant therethrough, the heat transfer wall being formed from a base that includes a first surface facing the coolant conduit and a second surface facing the effluent conduit;

an anti-hydrogen embrittlement layer applied to the second surface of the base; and

a plurality of symmetrical fins each extending through the anti-hydrogen embrittlement layer and contacting the second surface of the base, the plurality of symmetrical fins projecting into the effluent conduit.

2. The fuel reformer cooler of claim **1**, wherein the symmetrical fins are formed from a material having a thermal conductivity of at least about 300 Watts/meter·Kelvin (W/m·K).

3. The fuel reformer cooler of claim **2**, wherein the symmetrical fins are at least partly formed from copper.

4. The fuel reformer cooler of claim **3**, wherein the symmetrical fins are formed entirely from copper.

5. The fuel reformer cooler of claim **3**, wherein the anti-hydrogen embrittlement layer is a nitride film.

6. The fuel reformer cooler of claim **3**, wherein the anti-hydrogen embrittlement layer is composed of a nickel-based alloy.

7. The fuel reformer cooler of claim **3**, wherein each of the symmetrical fins include a height extending from a top to a bottom, wherein the top projects into the effluent conduit and the bottom contacts the base, and wherein the top has a smaller cross-sectional area than the bottom.

8. The fuel reformer cooler of claim **7**, wherein each of the symmetrical fins have a conical shape.

9. The fuel reformer cooler of claim **8**, wherein the symmetrical fins are retained on the heat transfer wall by insertion into the anti-hydrogen embrittlement layer.

10. The fuel reformer cooler of claim **8**, wherein the symmetrical fins are press fit into the anti-hydrogen embrittlement layer.

11. The fuel reformer cooler of claim **9**, wherein the anti-hydrogen embrittlement layer has a thickness that is about one-third of the height of the symmetrical fins.

12. The fuel reformer cooler of claim **9**, wherein the base is formed from steel.

13. An engine, comprising:

a combustion chamber configured to combust a mixture of air and fuel;

an air intake system configured to supply the combustion chamber with the air;

at least one fuel admission valve configured to supply the combustion chamber with the fuel;

a fuel reformer configured to transform the fuel into a hydrogen-containing effluent;

a fuel reformer cooler configured to cool the effluent released from the fuel reformer, the cooler including a plurality of stacked heat transfer modules each having an effluent conduit, a coolant conduit, and at least one heat transfer wall separating the effluent conduit from the coolant conduit, the heat transfer wall including a base facing the coolant conduit and an anti-hydrogen embrittlement layer facing the effluent conduit, the heat transfer wall further including a plurality of symmetrical fins contacting the base and extending through the anti-hydrogen embrittlement layer into the effluent conduit; and

at least one delivery conduit configured to deliver the cooled effluent exiting the cooler to one of the air intake system and the fuel admission valve.

14. The engine of claim **13**, wherein the base of the heat transfer wall includes a first surface directed toward the coolant conduit and a second surface directed toward the effluent conduit, and wherein the anti-hydrogen embrittlement layer is applied on the second surface of the base and shields the base from the effluent.

15. The engine of claim **14**, wherein the symmetrical fins are formed from a material having a thermal conductivity of at least about 300 Watts/meter·Kelvin (W/m·K).

16. The engine of claim **15**, wherein the symmetrical fins are formed from copper.

17. The engine of claim **16**, wherein the anti-hydrogen embrittlement layer is a nitride film.

18. The engine of claim **16**, wherein the anti-hydrogen embrittlement layer is composed of a nickel-based alloy.

19. The engine of claim **17**, wherein each of the symmetrical fins have a conical shape with a top having a smaller cross-sectional area than a bottom, and wherein the top of each of the fins projects into the effluent conduit and the bottom of each of the fins contacts the base.

20. A method for cooling a hydrogen-containing effluent released from a fuel reformer using a fuel reformer cooler, the fuel reformer cooler including a heat transfer wall separating an effluent conduit from a coolant conduit and including a base exposed to the coolant conduit and an anti-hydrogen embrittlement layer exposed to the effluent conduit, comprising:

flowing a coolant through the coolant conduit and over the base, the base being formed from steel and having a first surface facing the coolant conduit and a second surface facing the effluent conduit;

flowing the effluent through the effluent conduit and over the anti-hydrogen embrittlement layer, the anti-hydrogen embrittlement layer being a nitride film applied to the second surface of the base;

transferring heat from the effluent in the effluent conduit to symmetrical fins extending from the second surface of the base into effluent conduit, the symmetrical fins being formed from copper;

transferring heat from the symmetrical fins to the base; and

dissipating heat from the base to the coolant in the coolant conduit.

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