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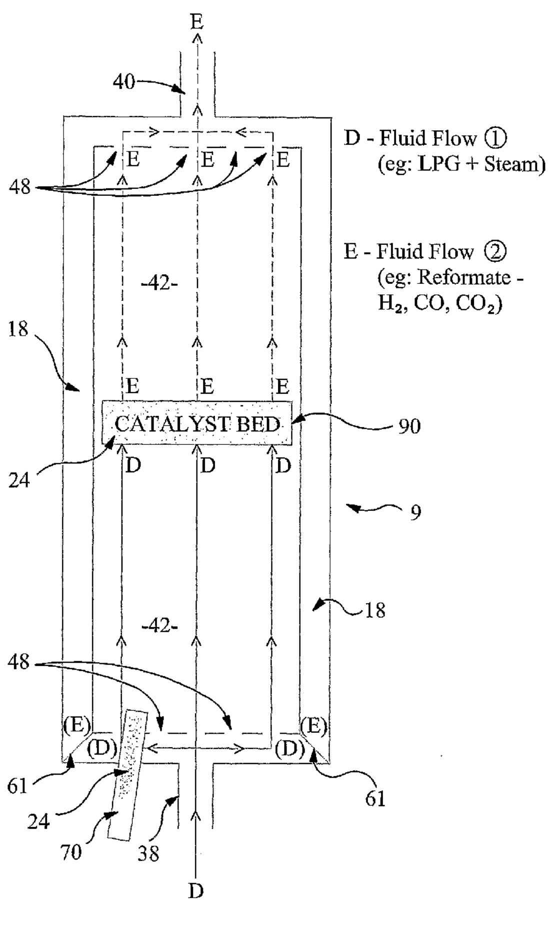
(54) **Title:** A REACTOR



(57) **Abstract:** The invention relates to a reactor for a biological or chemical reaction. The reactor comprises at least one reactor module comprising an internal cavity, which cavity is at least partly defined by an inner wall of a substantially hollow fluid conduit, which conduit comprises at least one aperture extending through a side wall and/or an outer wall thereof to allow fluid to flow into the conduit, the conduit comprising at least one further aperture extending through the inner wall thereof so that, in use, fluid flows between the hollow conduit and the internal cavity.

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A REACTOR

The present invention relates to reactors, and particularly to reactors for carrying out biological or chemical reactions. The invention extends to methods of carrying out catalysed or un-catalysed biological or chemical reactions in the reactor.

Biological and chemical reactions, and especially those carried out in industry, require a reactor that has been specifically designed and built for each specific reaction. Most reactors consist of: (i) a main reaction chamber, in which the chemical or biological reaction is carried out, and usually, (ii) an inlet through which chemical reactants or biological substrates are fed in to the reaction chamber, and (iii) an outlet through which the products of the reaction may exit the reaction chamber. The number and size of (i) to (iii) depend on the type of chemical or biological reaction being carried out in the reactor.

In addition, in order to carry out an industrial scale production with a sufficiently high product yield, the reactor needs to be specifically designed so that the many variables involved in the reaction can be correctly configured and tightly controlled during the reaction. The variables involved in a chemical reaction include a wide range of parameters, such as the flow rate of reactants, the heats of reaction, the residence time in the reactor, the catalyst activity and shape, the reaction pressure and the reaction temperature etc. The variables involved in a biological reaction include the flow rate of substrates, the temperature of the reaction, the pH of the media, the dissolved oxygen concentration in the media, and the carbon source concentration etc. Such variables need to be tightly controlled and accurately measured by appropriate means associated with the reactor, such as thermocouples, gas sensors, valves, flow meters, pressure gauges, mass flow controllers, control electronics, pumps and compressors.

Hence, in order to carry out a biological or chemical reaction, the reactor must have a suitable shape and dimensions, the required number and design of ports for feeding reactants into the reaction chamber, and for removing products away from the reaction chamber. In addition, the reactor must be made of suitable construction materials to withstand the reaction temperatures, pressures and aggressive chemical environments. The same applies to the peripheral equipment and instruments, which have to be determined according to the chemical or biological reaction being carried out.

Accordingly, industrial chemical and biological reaction processes tend to be very complicated and therefore require an elaborate system of reactant feed pipes, product outlet pipes, and peripheral equipment associated with the feed to, and product out of, the main reaction chamber. Hence, problems associated with existing process reactors are that they tend to require a very complicated network of vessels, pipes, valves, heat exchangers, heaters, tubing and wiring connected to the reaction chamber.

In addition, known reactors used for carrying out chemical reactions that involve high reaction temperatures and pressures are fabricated from special high temperature alloys which are costly and which require expensive specialised production equipment and facilities. In addition, catalysed chemical reactions carried out in catalyst coated microchannel plate reactors have the disadvantage that should the catalyst become poisoned, the complete unit has to be replaced as the catalyst is an integral component of the unit.

It is therefore an aim of embodiments of the present invention to address the problems with the prior art, and to provide a reactor, which has a simplified design, and is generally compact and allows ease of catalyst replacement, if necessary. In addition, it is an aim to provide a reactor, which exhibits improved running characteristics, and which can be operated for extended periods of time without mechanical failure.

According to a first aspect of the present invention, there is provided a reactor for a biological or chemical reaction, the reactor comprising at least one reactor module comprising an internal cavity, which cavity is at least partly defined by an inner wall of a substantially hollow fluid conduit, which conduit comprises at least one aperture extending through a side wall and/or an outer wall thereof to allow fluid to flow into the conduit, the conduit comprising at least one further aperture extending through the inner wall thereof so that, in use, fluid flows between the hollow conduit and the internal cavity.

Preferably, the hollow conduit is adapted, in use, to act as a conduit for fluids required in, or produced by, the biological or chemical reaction. Hence, the hollow conduit may be referred to as a fluid transfer line. Preferably, the reactor module is adapted to receive fluid from an external source, which fluid may flow in through the aperture in the side or outer wall of the conduit. By the terms "inner wall, side wall and outer wall of the conduit", we mean sides with respect to the position of the internal cavity, which is formed inside the module. Preferably, the reactor module is adapted to move fluid between the hollow conduit and the internal cavity.

Preferably, the reactor module is adapted to move at least two fluids therein, and preferably between the hollow conduit, and the internal cavity thereof. The two fluids may be dissimilar. Preferably, the reactor module is adapted to move fluid between two adjacent modules, and preferably, between the hollow conduits and/or the internal cavities thereof.

The fluid may be either gaseous or liquid. For example, the fluid may comprise fluid reactants and/or fluid products of the biological or chemical reaction. By the term "fluid reactants", we mean any gaseous, slurry or liquid chemicals or biological media required for the reaction to take place. By the term "fluid products", we mean any gaseous, slurry or liquid chemicals or biological media produced as a result of the reaction. In addition, the fluids may comprise any fluid that may be required to heat the reactants and/or catalyst to optimum reaction temperatures, and thereby function as heat exchanger fluids.

Hence, advantageously and preferably, the conduit is adapted to act as a conduit for the reaction reactants, reaction products, catalysts, and/or heat exchange fluids, and in addition, simultaneously provides structural support for the reactor module. Hence, the hollow conduit provides protection for seals (or sealing joints) on the external surfaces of the reactor module from the extremes of reaction conditions. Accordingly, the tubular conduit allows fluid transfer, heat exchange, and also provides thermal and chemical protection of the seals. This multi-purpose use of the conduit is a substantial improvement over known reactors, and thereby significantly improves the simplicity and compactness of the reactor design.

Preferably, the conduit may form a substantially square-shaped or substantially rectangular-shaped hollow frame, which extends around the internal cavity. In a preferred embodiment, the conduit is substantially rectangular in shape, and comprises two pairs of mutually opposing side walls, wherein the first pair of opposing side walls are substantially longer than the second pair of opposing side walls. For example, the conduit may be about 200mm to 500mm in length, and preferably, about 50mm to 200mm in width. Advantageously, the frame formed by the conduit provides structural support for the reactor module.

The conduit may have a cross-section of any suitable shape. It will be appreciated that the shape will depend on the type and scale of the reaction being carried out in the reactor, as these will at least in part determine the fluid flow through the conduit. For example, the conduit may have a generally circular, square, rectangular, or triangular cross-section. However, it is most preferred that the hollow conduit has a substantially square or rectangular cross-section, which is simple to manufacture and construct. For example, the hollow cross-section of the conduit may be between about $1mm^2$ to $10000mm^2$, suitably, between about $2mm^2$ to $5000mm^2$, preferably, between about $2mm^2$ to $2000mm^2$, and more preferably, between about $10mm^2$ to $1800mm^2$, and even more preferably, between about $50mm^2$ to $500mm^2$.

Preferably, the hollow conduit is substantially tubular and preferably, forms at least a side of the internal cavity. Preferably, the inner and outer walls of the conduit define a space therebetween, in which fluid may be received when the reactor is in use. Preferably, the conduit forms a continuous hollow ring extending around the internal cavity. Hence, the hollow conduit may be defined as an annulus extending around the internal cavity.

Preferably, the hollow conduit comprises at least one aperture extending therethrough, through which fluid may flow either in to, or out of, the hollow conduit.

The conduit may comprise at least one aperture extending through the outer wall (i.e. an end face) thereof, which aperture may communicate with a further fluid conduit. The conduit may comprise at least one aperture extending through a side wall (i.e. a side face) thereof, which may communicate with an adjacent module. The or each aperture may comprise a valve or a manifold to control fluid flow therethrough.

Hence, the or each aperture may be either a fluid inlet or a fluid outlet. When the aperture is a fluid inlet, the aperture may communicate either with an external fluid source (e.g. a heat exchange fuel supply, or a reactant supply), or a fluid conduit extending from another module of the reactor (e.g. circulating combustion fluid).

Preferably, the inner wall of the conduit comprises at least one aperture extending therethrough, through which fluid may flow between the internal cavity and the conduit. Preferably, the inner wall of the hollow conduit comprises at least one aperture at substantially opposite ends thereof. Preferably, in use, fluid may exit the conduit by a first aperture and enter the internal cavity, flow across the internal cavity, and enter the opposite end of the tubular conduit via a second aperture. Preferably, opposite ends of the inner wall of the hollow conduit comprise a plurality of apertures or slots extending therethrough, through which the fluid may flow.

The hollow conduit may comprise at least one wall extending across the inside thereof, which wall is adapted to modulate the flow of fluid through the hollow conduit. The wall may be an impervious block extending completely across the inside of the hollow conduit. Preferably, the at least one wall is adapted to separate at the least two fluids flowing within the hollow conduit. The position of the or each wall is determined by the different fluid flows which are to be kept separate from one another within the hollow conduit. It is preferred that the hollow conduit is substantially rectangular, and therefore has four corners. Therefore, for example, the conduit may comprise a wall positioned at, or at least adjacent, a corner of the hollow conduit. Preferably, a wall is positioned at, or at least adjacent, two, three, or four corners of the conduit.

The hollow conduit may comprise an internal conduit extending internally therealong, and preferably, longitudinally therealong. Hence, it is envisaged that the hollow conduit making up the walls of the reactor module may comprise a thin inner tube extending therethrough. Preferably, fluid may flow along the internal conduit, which fluid may be adapted to cool certain regions of the hollow conduit. For example, cold water may be passed along the internal conduit in order to cool down the inner and, hence, outer walls of a particular area of the hollow conduit. It is preferred that the internal conduit extends along the inside of the hollow conduit of reactor modules that get hot when the reactor is use, for example, a burner module.

Preferably, the at least one reactor module comprises at least one sealing member, which defines a further portion of the internal cavity. Preferably, the at least one sealing member is attached to the hollow conduit, and is adapted to seal and substantially enclose a side of the internal cavity. Preferably, the at least one sealing member comprises a substantially planar plate, which plate may be attached to the hollow conduit by any suitable means so that a seal is formed therebetween. For example, the at least one sealing member may be attached to the conduit by welding. Preferably, the sealing member is attached to an outer portion of the conduit. Accordingly, preferably, the sealing member is welded along its entire peripheral edge to the conduit. The sealing member may be at least partially coated with a material adapted to modify the heat resistance properties thereof, for example, ceramic.

Preferably, the module comprises a first sealing member attached to one side of the conduit, and a second sealing member attached to a second side of the conduit. Preferably, both sealing members are attached to an outer portion of the conduit to substantially enclose and seal the internal cavity. Hence, in a preferred embodiment, the reactor module comprises a sealed box structure comprising a hollow tubular frame (or annular framework), which extends around the internal cavity, which frame has a sealing plate attached to either side of the frame, so that the internal cavity is enclosed, and sealed thereby.

The or each sealing member attached to the conduit may comprise at least one aperture extending therethrough, the position of which preferably corresponds with the position of the aperture in the side wall of the conduit to thereby form a continuous aperture which extends between the side wall of the conduit and the sealing member. Preferably, fluid may exit the conduit of a first module and flow in to a conduit of an adjacent second module via the continuous aperture extending therebetween.

The or each sealing member may comprise at least one aperture, the position of which corresponds to the position of the internal cavity of the module. The at least one aperture may comprise a slot or hole, and preferably a plurality of slots or holes extending through the sealing member. Advantageously, and preferably, the aperture is adapted to allow fluid flow between adjacent modules, and removes the need to transfer fluid flow, which is external to the conduits, between modules by use of pipes or external fluid transfer conduits. Preferably, the at least one aperture will be positioned on the sealing member so as to provide the optimum fluid flow path, in the desired direction, for the process reaction requirements.

The sealing member may enclose an internal cavity containing a catalyst, in which case, the slots or holes have preferably smaller dimensions than those of the catalyst. This prevents loss of the catalyst from the internal cavity through these slots or holes.

Preferably, where heat exchange is required to be optimised between adjacent modules, the sealing member may comprise heat transfer means. The heat transfer means may comprise a metallic protuberance, which may be a fin or rib. Preferably, the heat transfer means comprises at least one flange, which extends away from the sealing member and into the internal cavity of the module. Preferably, the heat transfer means comprises a plurality of flanges. Preferably, the heat transfer means is attached to one or both surfaces of the sealing member, or may extend as at least one continuous flange through the sealing member. The heat transfer means may extend through at least one, and preferably, more than one of adjacent modules. Advantageously, this provides improved strength to the reactor.

The reactor module may comprise at least one valve; at least one flow restrictor; at least one flow diverter; at least one catalyst support or catalyst basket; at least one fluid injector; and/or at least one distributor pipe or thermowell. These units may be associated with the reactor, and preferably, with at least one of the apertures of the or each reactor module.

Advantageously, in use, the constant circulation of fluid through the hollow conduit of the reactor module serves to maintain the temperature of the welded or jointed sections of the sealing member (i.e. the end plates), to their corresponding conduit, below the temperature at which thermal stresses would cause significant expansion, contraction and embrittlement and cause ultimate destruction thereof. Therefore, advantageously, because the seals on the reactor module (i.e. the welded sections) are kept at a sufficiently low temperature, they are prevented from fracturing. Accordingly, leakage of fluid, such as reaction gases and liquids, from the reactor module is prevented. A result of this is that the reactor can be operated for significantly extended periods of time without failure. Furthermore, the transfer of fluids through the hollow conduit ensures that the maximum heat energy is retained within the reactor and not conducted away through external transfer conduits and pipes.

Preferably, the module is adapted to substantially contain or enclose a biological or chemical reaction within the internal cavity. In this case, the internal cavity may be referred to as a reaction chamber, and the module is referred to as a primary reaction module. Hence, a preferred reactor comprises at least one primary reaction module adapted to substantially contain or enclose a biological or chemical reaction within the internal cavity.

The reactor may be adapted to carry out either a catalysed or an uncatalysed reaction. Hence, the reaction chamber may comprise a reaction catalyst, which may accelerate the rate of the reaction, or increase the required reaction product selectivity and/or yield. The reactor module may comprise catalyst removal means. The catalyst removal means may comprise a catalyst conduit extending between the internal cavity and outside of the module. Preferably, the catalyst conduit is adapted to be opened to allow removal of catalyst from the internal cavity of the reactor module. This may be required if the catalyst is poisoned or spent. Furthermore, if required, new catalyst may be inserted in to the internal cavity of the module via the catalyst conduit. Preferably, the dimensions of the catalyst conduit are such that the catalyst is able to pass therethrough. Preferably, the catalyst conduit is adapted to be sealed to prevent loss of catalyst, reactants and products, when the reactor is in use.

Preferably, the reactor is modular, in which the reactor comprises at least one further module in addition to the primary reaction module. The reactor may therefore comprise a plurality of reactor modules as defined in the first aspect of the invention. For example, the reactor may comprise two, three, four, five, six or seven, or more modules. The modules may be physically attached to each other in a sandwich arrangement, preferably, by impervious jointing (for example, by welding), to form a sealed compact unit.

In one embodiment, an additional module of the reactor may be adapted to heat or burn gases in the internal chamber. In this case, the internal cavity may be referred to as a burner, and the module may be referred to as a heater module. Hence, preferably, the reactor comprises at least one heater module adapted to heat or burn gases in the internal chamber. The heater module may be used to transfer heat either directly or indirectly to the reaction chamber. The burner may be powered by combustible fluids, such as liquefied petroleum gas vapour (LPG), and high energy exothermic chemical reactions. The heater module may or may not contain catalyst. However, preferably, the heater module comprises catalyst for catalyst-assisted combustion or reaction, in which case the catalyst is preferably contained in the internal cavity of the heater module. Hence, the heater module may also comprise catalyst removal means. The high temperature products of combustion and or exothermic chemical reaction from the heater module may be used to preheat incoming reactants required for the reaction occurring in the reaction chamber.

Alternatively, the heater module may use electrical resistance heating as a means of heat generation and heat transfer to the reactor module. This form of heating does not produce a hot exhaust fluid and hence the module design will vary from those heat sources producing a hot fluid exhaust stream

Hence, a preferred reactor comprises at least one primary reaction module and at least one heater module. Preferably, the heater module is operatively connected to the primary reaction module. A heater module may be disposed on either side of the primary reaction module. However, it is preferred that the reactor comprises two heater modules, preferably one disposed on either side of the primary reaction module. Accordingly, a preferred reactor comprises three modules attached together, i.e. the primary reaction module and two heater modules in which the primary reaction chamber is preferably in between the two heater modules.

In another embodiment, an additional module of the reactor may be adapted to allow heat exchange to occur therein, and may be referred to as a heat exchanger module. Hence, preferably, the reactor comprises at least one heat exchanger module adapted to allow heat exchange to occur therein between two or more fluids. Hence, a preferred reactor comprises a primary reactor module, and at least one heat exchanger module. An even more preferred reactor comprises a primary reactor module, at least one heat exchanger module, and at least one heater module.

The internal cavity of the heat exchanger module may comprise at least one heat exchange tube extending thereacross. Hence, the module may be adapted to carry a first fluid through the at least one heat exchanger tube, and a second fluid through the internal cavity and/or tubular conduit, such that heat exchange may occur between the first and second fluids. Preferably, the module is adapted to move the first and second fluid flows in substantially opposite directions with respect to each other. Advantageously, this improves the rate of heat exchange between the two fluids.

By way of example, the first fluid may comprise combustion gases at a first temperature, and the second fluid may comprise reactants for the reaction at a second lower temperature. Hence, heat exchange in the module between the two fluids will result in the reactants being heated up. The heat exchanger module may be disposed on either side of the primary reaction module, or if present, on either side of the heater module. Preferably, the reactor comprises at least two, and more preferably, at least three heat exchanger modules. Preferably, the heat exchanger modules are disposed on the side of burner modules, distal from the primary reaction module. Accordingly, a preferred reactor comprises at least one primary reaction module, at least two heater modules, and at least two heat exchanger modules.

In another embodiment, an additional module of the reactor may be adapted to carry out a secondary reaction that is associated with the primary reaction taking place in the primary reaction module. Hence, the additional module may be referred to as a secondary reaction module. Accordingly, the reactor may comprise a secondary reaction module. Examples of secondary reactions include purification of the reaction products, removing toxins or dangerous substances from fluids produced by the reaction, water gas shift reactions, or catalytic oxidation of carbon monoxide, chemical removal of sulphur from product fluids. Therefore, a preferred reactor comprises at least one primary reaction module, and at least one secondary reaction module. A most preferred reactor additionally comprises at least one heater module and/or at least one heat exchanger module in addition to the primary and secondary reaction modules.

Preferably, each module in the reactor is operatively connected to at least one of the other modules in the reactor, such that fluid may flow therebetween. Hence, each module may be operatively connected to an adjacent module and/or a non-adjacent module in the reactor. Preferably, the tubular conduit of a first module is operatively connected to the tubular conduit of a second module, which second module is preferably adjacent the first module. Preferably, the first and second modules are operatively connected to each other by the continuous aperture extending through the side wall and the sealing member of the first module, and through the side wall and sealing member of the second module. Advantageously, fluid may exit the hollow conduit of the first module and flow in to a hollow conduit of the second module via the apertures in their corresponding side walls.

Advantageously, the ability to move fluid flow between modules improves heat exchange between the two fluids therein. For example, in use, a first fluid may comprise a combustion fluid (e.g. a hydrocarbon gas and air), which is fed in to a first heater module where it is combusted and heated up, to thereby produce a heated combustion product fluid. The heated combustion product fluid is then fed in to a first heat exchanger module, preferably into the internal cavity of the heat exchanger module. A fluid comprising reaction reactants may be fed in to the heat exchanger module, preferably into the heat exchanger tubes thereof. Heat exchange may then take place between the 'cool' reactant fluid and the heated heat exchanger fluid, resulting in the reactant fluid being heated up. The heated reactant fluid may be circulated around the same heat exchanger module, fed in to a second heat exchanger module for further heat exchange or fed into the reaction chamber to undergo chemical reaction.

Preferably, the reactor comprises at least one fluid transfer means, which is adapted to transfer fluid to and away from the reactor module. The reactor may comprise at least one fluid transfer means extending through a sealing member. Such a fluid transfer means may comprise at least one opening extending through the sealing member. A manifold and/or a conduit may be attached to the or each opening, and through which fluid may enter or exit the reactor module. The at least one fluid transfer means may operatively connect to two or more modules in the reactor, which may be adjacent or, preferably, spaced apart from each other. The fluid transfer means may comprise a fluid transfer port.

According to a second aspect, there is provided a modular reactor comprising a plurality of reactor modules according to the first aspect.

Preferably, the modular reactor comprises at least one primary reaction module, at least one heater module, and at least one heat exchanger module. Preferably, the at least one heater module is adjacent the primary reaction module. Preferably, the reactor comprises a primary reaction module disposed in between two heater modules. Preferably, the or each heater module has a heat exchanger module attached to a face distal to that of the primary reaction module.

Preferably, the or each heater module is an oxidative combustor. Preferably, exhaust gases produced from the combustor are used for heat exchange with reactants in each module.

It will be appreciated that in order to initiate or start the reactor according to the invention, there is a requirement for means of starting the combustion of burner gas in the at least one heater module of the reactor. The heater module may or may not contain catalyst in its internal cavity. Once the burner gas has been ignited, further fresh burner gas introduced in to the heater module(s) should be self-igniting. Hence, preferably, the reactor comprises an igniter assembly, which is adapted to ignite combustion gas prior to flowing in to the or each heater module. It is preferred that a small flow of incoming combustion gas is heated to a temperature at which the gas self-ignites, preferably, over a catalyst. The hot exhaust gases from the igniter assembly are lead into the main heater module to heat up the oxidation catalyst contained therein up to a point at which fresh gas and air will self ignite. Once the heater module is alight the mini-burner is turned off.

The igniter assembly may be either internal or external of the or each heater module. If the igniter assembly is internal, it is preferably located substantially adjacent the inlet of combustion gas of the or each heater module. If the igniter assembly is external, it is preferably in operable communication with the or each heater module, such that ignited combustion gas is fed from the igniter assembly in to the heater module.

Preferably, the igniter assembly comprises igniting means adapted to ignite combustion gas. The igniting means may comprise means to produce a spark, for example, an electric discharge spark, by a spark plug. However, the igniting means may comprise any electrical heating means, providing sufficient temperatures are reached to ignite of heat the gas. For example, the igniting means may comprise a glow plug, or other suitable sparking means, for example, an electrical hot air blower.

The igniter assembly preferably comprises an inlet for combustion gas, and an outlet for ignited combustion gas. The inlet is preferably connected to a combustion gas supply, which may be a gas cylinder. For external igniter assemblies, the outlet is connected to the gas inlet of the heater module. For internal igniter assemblies, the outlet for ignited gas is disposed adjacent the gas inlet of the heater module.

It will be appreciated that the design of the reactor lends itself for use in carrying out either catalysed or uncatalysed chemical reactions, or biological reactions therein. Hence, the reactor may be a chemical reactor, in which chemical reactions may be carried out. Examples of suitable chemical reactions include steam, carbon dioxide and partial oxidative reformation of hydrocarbons to produce hydrogen and carbon oxides as described in part in Example 2, the production of 3,5 xylenol as described in Example 3, the hydrogenation of unsaturates as described in Example 4 and the desulphurisation of gases by chemical reaction as described in example 5. It will be appreciated that this list of chemical reactions is not exhaustive and is provided merely to illustrate examples of reactions that could be carried out in the reactor of the present invention.

Hence, in a further aspect, there is provided a method of producing hydrogen using steam reformation of hydrocarbons, or a method of producing 3,5-xylenol, or a method of hydrogenating unsaturated compounds, or a method of de-sulphurising gas, the method comprising using the reactor according to the first aspect.

Alternatively, the reactor may be a biological reactor, in which biological reactions may be carried out. For example, the reactor may be adapted to carry out biological fermentations. By the term "fermentation", we mean any process for the production of product (or biomass) by the mass culture of a micro-organism. Examples include the production of ethanol, methanol, organic solvents, and organic acids.

According to a further aspect of the present invention, there is provided a method of carrying out a biological or chemical reaction, the method comprising (i) feeding reactants in to the reactor according to the first or second aspect; (ii) contacting the reactants in the internal cavity of the reactor module; and (iii) removing products of the reaction from the internal cavity of the reaction module.

All of the features described herein (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined with any of the above aspects in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

For a better understanding of the invention, and to show how embodiments of the same may be carried into effect, reference will now be made, by way of example, to the accompanying diagrammatic drawings, in which:-

Figure 1 shows a schematic side view of a first embodiment of a reactor according to the invention;

Figure 2 shows an enlarged cross-sectional perspective view of a typical reactor module according to the invention;

Figure 3 shows an enlarged partially cross-sectional perspective view of a burner module in accordance with the invention;

Figure 4 shows a schematic perspective view of a burner module and heat exchanger module assembly of the reactor shown in Figure 1;

Figure 5 shows an exploded perspective view of the burner and heat exchanger assembly shown in Figure 4;

Figure 6 shows an exploded perspective cross-sectional view of the burner and heat exchanger assembly shown in Figure 4 and 5, showing fluid flows;

Figure 7 shows a schematic cross-sectional view of a primary reaction module in accordance with the invention, showing fluid flows;

Figure 8 shows a schematic cross-sectional view of the heat exchanger module according to the invention, showing fluid flows;

Figure 9 shows a schematic cross-sectional view of the reactor showing internal flow of gas, in which "H" corresponds to heat exchanger, "B" corresponds to Burner, and "RX" corresponds to Reactor or Reaction Chamber. The solid lines indicate fluid flows within external box sections, and dashed lines indicate fluid flows within internal cavities or heat exchanger tubes;

Figure 10 shows a schematic plan view of the reactor shown in Figure 9, in which "H" corresponds to heat exchanger, "B" corresponds to Burner, and "RX" corresponds to Reactor or Reaction Chamber;

Figure 11 shows a schematic cross-sectional view of a second embodiment of the reactor used to carry out steam reforming of hydrocarbons to produce impure hydrogen gas (Reaction 1 described in Example 2);

Figure 12 shows a schematic cross-sectional view of a third embodiment of the reactor used to produce 3,5-xylenol (Reaction 2 described in Example 3); and

Figure 13 shows a schematic cross-sectional view of a fourth embodiment of the reactor used to hydrogenate unsaturated organic and to reduce inorganic ionic compounds (Reaction 3 described in Example 4).

Example 1 - Reactor Design

Referring to Figures 1 to 10, there is shown a reactor 2 in which a variety of biological or chemical reactions may be carried out. Examples 2 to 5 describe four examples of different chemical reactions that could be carried out in the reactor 2, and are explained with reference to Figures 11 to 13, respectively. However, it will be appreciated that the design of the reactor 2 is also well-suited for carrying out biological reactions, such as fermentations.

Referring to Figure 1, the reactor 2 is shown having a base 4 by which it can be supported on a surface. The reactor 2 is modular, being made up of a series of side by side, interconnected reactor modules, or units 6 each having similar shape and dimensions to each other. Each of the modules 6 of the reactor 2 are very similar to each other in terms of size and dimensions. However, some of the modules 6 have different internal structures and functions depending on their specific function, and also their position within the reactor 2. As shown in Figure 1, the reactor 2 is fitted with at least one in-flow tube 38 through which reactants flow in to the reactor 2, and at least one out-flow tube 40 through which products flow out of the reactor 2 when it is in use.

The reactor 2 consists of a number of different reactor module types, for example, a burner module 8, a primary reaction module 9, or a heat exchanger module

10 etc. The reactor 2 shown in Figure 1 consists of a total of six reactor modules 6 positioned side by side, although it will be appreciated that the reactor 2 can include more or less modules 6 depending on the type and scale of the specific chemical or biological reaction which is to be carried out in the reactor 2. For example, the reactor 6 can include one or more primary reaction modules 9, one or more burner modules 8, and one or more heat exchanger modules 10. A number of such modules 6, for example, heat exchangers 10 or burners 8, are attached to each other by welding face to face, i.e. side by side, to form the complete chemical reactor 2. It will be appreciated that it is not essential that all of the modules 6 are physically attached to each other, providing they are in functional communication with each other. Some specific examples of reactor 2 arrangements are provided hereinafter.

Referring to Figure 1, the reactor 2 is shown having an external igniter assembly 110. However, in other embodiments of the reactor 2, the igniter assembly 110 can be internally disposed inside the or each burner module 8. The external igniter assembly 110 shown in Figure 1 has a spark plug 112 with which combustion gases to be bruned in the burners 8 are ignited prior to being fed by conduit 114 into the burner modules 8, as will be described hereinafter.

Referring to Figure 2, there is shown a simplified perspective view of a typical reactor module 6. The reactor module is fabricated from a metallic hollow tubular frame 18, which can be made from heat and corrosion resisting metal, for example, Stainless steels, Inconel alloys, Nickel alloys, Titanium and other similar materials. The tubular frame 18 forms an annulus structure, an inner face of which extends around and thereby defines an internal cavity 42. The specific type of the reactor module 6 determines the function of the internal cavity 42, as will be described hereinafter.

As shown in Figure 2, the hollow tubular frame 18 is rectangular in shape and is about 350mm long, 150mm wide, and 15mm deep. The hollow portion forming the tubular frame 18 is about 140mm^2. These dimensions are suitable for a standard chemical or biological reaction, although the invention is not limited to the specific dimensions of the reactor 2. In addition, even though in the Figures, the tubular frame

18 is shown as having a square cross-section, it will be appreciated that the frame 18 could be any shape in cross-section, for example, circular or triangular etc, providing it is substantially hollow. Although not shown in the Figure, in another embodiment of the reactor 2, the tubular frame 18 may contain a second smaller internal tubular conduit therein. This internal conduit has smaller dimensions to that of the outer frame 18, and is disposed substantially centrally therein, and is arranged to carry fluid therein, for example cooling fluid (water).

Referring to Figure 3, there is shown the construction of a burner module 8. The burner module 8 consists of the hollow frame 18 having an aperture 12a in the outer end wall thereof. The aperture 12a allows fluid to flow in to the frame 18 from outside the frame, for example from an in-flow tube 38 as shown in Figure 1. The hollow frame 18 also has two apertures 12b in the outer side wall thereof. These two apertures 12b allow fluid to flow between adjacent modules 6 of the reactor 2. The internal faces of opposite ends of the hollow frame 18 of the burner module 8 are provided with a series of spaced apart parallel slots 48 through which the fluid flows between the hollow frame 18 and the internal cavity 42. The internal cavity 42 can in some embodiments contain catalyst 120 to promote combustion of combustion gases therein. Inside two of the corners of the hollow frame 18 of the burner module 8, there is provided an impervious block or wall 61, which is provided in order to maintain the separation of dissimilar fluids within the burner module 6, as will be described hereinafter.

Although not shown in Figure 3, the tubular frame 18 of the burner module 8 can in some embodiments contain a smaller internal tubular conduit (not shown) therein. Because the burner modules 8 have a tendency to get very hot when in use, it can in some circumstances be advantageous to have an internal conduit disposed substantially centrally therein, along which cooling fluid may flow, for example, water. Hence, the inner tubular conduit is connected to a cooling fluid supply which deliver the cooling fluid thereto, which then circulates around the burner frame 18, thereby cooling it during use.

Referring to Figure 4, there are shown two modules 6 of the reactor 2 welded together to form a reactor assembly. Only two modules 6 are shown in Figure 3 for simplicity, although it should be appreciated that in practice, normally the reactor 2 is made up of more than two modules 6. The lower reactor module 6 shown in Figure 3 is a hydrocarbon burner module 8, and the upper reactor module 6 shown in Figure 3 is a heat exchanger module 10.

Referring to Figure 5, there is shown an exploded view of the reactor assembly shown in Figure 4 consisting of a heater module 8 and a heat exchanger module 10. A thin metallic face plate 14 is attached to either side of the hollow tubular frame 18 of each reactor module 6 (the burner 8 and the heat exchanger 10) to thereby form a hollow box module 6 having internal cavity 42. Hence, the construction of each hollow box module 6 (of which six are shown in Figure 1, and two are shown in Figures 4 and 5) is such that the hollow tubular frame 18 is encased on both sides by a face plate 14. The face plates 14 are the same length and width of the external rectangular frame 18 (i.e. 350mm by 150mm), and of sufficient thickness and metal composition to provide the mechanical and thermal strength required by each reactor module 6. For examples, the face plate 14 is made of Stainless Steel or Inconel alloy. In addition, face plate 14 may be coated with ceramic, which improves the heat resistance properties of the face plates 14 between adjacent modules 6.

As can be seen in Figure 5, one of the face plates 14 of the burner module 8 is provided with a series of metal fins 92. The fins 92 are provided on the face plate 14 of a burner that is disposed adjacent a primary reaction module 9 of the reactor 2. The fins 92 protrude into the internal cavity 42 of the reaction module 9 and are provided to increase heat transfer from the burner module 8 in to the reaction module 9. The fins 92 conduct heat away from the burner plate 14 into the reactants flowing in the reaction module 9. The fins 92 can be continuous and join several modules 6. This is for both heat transfer therebetween and also for providing additional strength and support for the reactor 2. This is important due to the pressure exerted on the burner module/reaction module face plate 14 at high temperatures. Without the strengthening fins 92, the face plate 14 could bow under pressure into the burner module 8. Hence, if the reactor 2 is operated at high pressures, the fins 92 (or strengthening ribs) need to be present.

The plates 14 are sealed at their edges to the peripheral edges of the hollow frame 18 by welding to form welded sections 50 as shown in Figure 4. This ensures that reactants and/or products of the reaction, such as liquids or gases, cannot escape from the join position between the face plate 14 and the hollow tubular frame 18 of each module 6.

As can be seen in Figure 5, the internal cavity 42 of the heat exchanger 10 has a series of spaced apart, parallel heat exchanger tubes 20, which extend from one end of the tubular frame 18 to the opposite end. The heat exchanger tubes 20 are sealed into each end of the tubular frame member 18 such that fluid passes freely down the inside of each tube 20 without escaping into the internal cavity 42 of the exchanger 10.

Referring to Figure 6, the heat exchanger module 10 and the burner module 8 are shown in cross-sectional exploded view to illustrate the flow of fluids (either reaction gases or liquids) therethrough, and therebetween. Fluid A (as illustrated by arrow A), may consist of combustion gas, and is shown by the arrows in Figure 6. The hollow tubular frame 18 of the burner module 8 has an aperture 12a extending through an end face thereof. This aperture 12a is attached to an inlet 38, and is provided to allow the cold combustion fluid A to flow in to the hollow frame 18 of the burner module 8. The cold combustion fluid A is prevented from flowing around the tubular frame 18 due to the presence of the two impervious walls 61 provided in the corners of the hollow frame 18 closest to the inlet aperture 12a.

Accordingly, the cold combustion gas A has to flow from the hollow frame 18 and immediately through the apertures 48 provided on the internal face thereof and into, and across the internal cavity 42 of the burner module 8, where combustion takes place. The two face plates 14 either side of the frame 18 contain the combustion and prevent leakage of the combustion gas A. The internal face of the hollow frame 18 at the opposite end of the burner 8 to that of the inlet aperture 12a is also provided with a series of slots 48 through which the now hot combustion gas A flows back in to the frame 18. This end of the hollow frame 18 of the burner module 8 does not have any impervious walls 61. Hence, the combustion gas A is able to flow around the perimeter of the hollow tubular frame 18 and back towards the internal impervious walls 61 at the opposite end of the frame 18 adjacent to where it originally entered. The two impervious walls 61 prevent the returned hot combustion gas A from mixing with cold combustion gas A incoming through the inlet aperture 12a.

The hollow burner frame 18 has two further apertures 12b extending through a side thereof, adjacent the walls 61, and through which the hot combustion gas flows (as illustrated by arrows B), thereby exiting the burner module 8. The face plate 14 welded to the tubular frame 18 of the burner module 8 has two similarly sized apertures 16 extending therethrough, which are located at positions which correspond with the apertures 12b in the side of the hollow frame 18 of the burner module 8. The hot combustion gas B exits the burner module 8 through apertures 12b, and passes through the apertures 16 in the face plate 14, and then in to the tubular frame 18 of the neighbouring module, which in Figure 6 is a heat exchanger module 10.

The heat exchanger module 10 has an impervious wall 61 positioned inside the hollow frame 18 at each corner thereof. Therefore, once the combustion gas B has entered the hollow frame 18 of the heat exchanger module 10, it is able to partially circulate inside one side thereof. The hot combustion gas B then passes in to the internal cavity 42 via apertures 62 in the sides of the frame 18, of the heat exchanger 10. Once within the internal cavity 42 of the heat exchanger module 10, the hot combustion gas B is able to circulate around the heat exchanger tubes 20, allowing heat exchange to take place between the hot combustion gas B in the cavity 42, and fluid D passing through the heat exchanger tubes 20. The combustion gas B exits the heat exchanger 10 through slots 46 present in the face plate 14 at the opposite end of the heat exchanger 10 to entry, as illustrated by arrows C.

As shown in Figure 6, a second fluid (reactant gas or liquid), which may be cold reaction reactants, as illustrated by arrow D, is fed in to the hollow frame 18 of the heat exchanger module 10 via an aperture 12a. The heat exchanger module 10 has an impervious wall 61 positioned inside the hollow frame 18 at each corner thereof, so the cold reactant gas D can only partially circulate in the hollow frame 18. Hence, the cold reactant gas D is forced to flow from the hollow frame 18 of the heat exchanger 10 and through each of the heat exchanger tubes 20, which extend across the internal cavity 42 thereof. As the cold reactant gas D passes through the heat exchanger tubes 20, heat exchange occurs with the hot combustion gas B circulating inside the internal cavity 42 of the heat exchanger 10. This causes the reactant gas D to heat up to reaction temperature.

The hot reactant gas D exits the heat exchanger tubes 20 from the opposite side thereof, and enters the opposite end of the tubular frame 18, again where it partially circulates. Hence, the flow of the reactant gas D is separated from the flow of the combustion gas B by the impervious walls 61 located at each end of the hollow frame 18 containing the transfer apertures 62, thereby isolating the flow of combustion gases B, from the burner module 8, from the reactant fluid D, passing through the heat exchanger module 10.

Referring to Figure 7, there is shown a simplified schematic view of fluid flows (B, D) into and through the heat exchanger module 10. The Figure shows reactant gas D entering the hollow tube 18 via inlet 38. Due to the impervious walls 61 at each corner, the fluid D has to pass along the heat exchanger tubes 20 to the other side of the internal cavity 42, and then leave the heat exchanger module 10, via outlet 40. Hot combustion gases B are fed from a burner module 8 and enters the internal cavity 42 of the heat exchanger module 10 via apertures 62. In another embodiment, hot combustion gas B passes in to the internal cavity 42 through slots 46 extending through one of the face plates 14 of the heat exchange module 10. Heat exchange takes place between the hot gas B in the internal cavity 42, and the cold reactant gas D passing through heat exchanger tubes 20. The hot combustion gas B leaves the heat exchanger either via apertures 62 extending through the opposite end of the hollow tube 18, or via slots 46 present in the opposite plate 14 as shown in Figure 6.

Referring to Figure 8, if the module 6 shown is a primary reaction module 9, in which the chemical or biological reaction takes place. In the embodiment shown, the reactor 2 is used for heterogeneous catalysed reactions, and so the reaction module 9 has a catalyst bed 90. In addition, the hollow frame 18 of the module 9 is equipped with a catalyst filling and unloading tube 70. The catalyst tube 70 is provided so that catalyst 24 can be fed into and out of the catalyst bed 90. This enables the removal of poisoned, spent or otherwise inactive catalyst 24 from the reaction module 9, and the replacement with fresh, active catalyst 24. The catalyst tube 70 is sealed during normal operation of the reactor 2.

Hot reactant gas D, which has been heated up by heat exchange with the hot combustion gases in the heat exchange module 10, are fed in to the primary reaction module 9 via inlet 38. The two impervious walls 61 inside the hollow frame 18 of the module 9 ensure that the hot gas D flows through apertures 48 and into the internal cavity 42 towards the catalyst bed 90, where the reaction takes place producing product gas flow E. The product gas E flows from the catalyst bed 90 and leaves the internal cavity 42 via apertures 48 into the hollow frame 18, in which it can either circulate up to the positions of the walls 61, or exit the reaction module 9 via outflow tube 40. The product gas E is then collected and stored accordingly.

Hence, fluids required for a reaction carried out in the reactor 2 and/or for heating purposes are able to either circulate within or flow through and around the hollow tubular frame 18 in the heat exchangers 10 and the burners 8. The constant flow of fluids through and between the hollow tubular frames 18 of each of the modules 6 in the reactor 2, serve to maintain the temperature of the welded sections 50 of the face plates 14 to their corresponding tubular frame 18 below the temperature at which thermal stresses would cause expansion, contraction and mechanical failure thereof. Therefore, because the welded sections 50 are kept at a sufficiently low temperature, they are prevented from fracturing. Therefore, leakage of fluids, such as reaction gases and liquids, from the reactor 2 is prevented. A result of this is that the reactor 2 can be operated for extended periods of time without failure.

In addition, the reaction or heat exchange (combustion) fluids flow around and through the hollow tubular frames 18 between the modules 6. Hence, the hollow tubular frames 18 of each module 6 act not only as structural supports defining each module, but also as conduits for the reaction fluids. In addition to maintaining the welded seams 50 between the hollow tubes 18 and the corresponding face plates 14 at low temperatures, using the hollow frames 18 as conduits for fluid (gas, slurry or liquid) transfer from one module 6 to another neighbouring section 6, radically simplifies the design of the reactor 2. It allows a compact reactor 2 unit to be produced with a minimum amount of external tubing and process equipment to handle fluid flows as in known reactors. This also advantageously increases the thermal efficiency of the reactor 2 by minimising the heat lost through peripheral conduits.

Referring to Figure 9, there is shown a cross-sectional view of an embodiment of the reactor 2. The reactor 2 consists of a primary reaction module 9 in which a catalysed biological or chemical reaction is carried out. Examples of chemical reactions, which may be carried out in the reaction module 9 are described herein with reference to Figures 11 to 13. The reactor 2 further includes two burners 8, one connected to each side of the reaction module 9. In addition, the reactor 2 further includes a total of three heat exchangers 10 connected to the burners 8. The aforementioned six modules 6 are inter-connected in series by welding to form the compact modular chemical reactor 2 as illustrated in Figure 9.

The reaction module 9 is shown provided with a catalyst 24 in a catalyst bed 90 which catalyses the reaction carried out therein. The catalyst 24 may be in the form of spheres, micro-spheres, powders, tablets, extrudates, a liquid, or an activated catalytic wash coat coated onto a sealing member or onto an insert in the reaction chamber. However, it will be appreciated that the requirement of a catalyst 24 and the nature of the catalyst 24 depends on the specific nature of the chemical reaction being conducted in the reactor 2. The embodiment of the reactor 2 shown in Figure 9 allows the process fluids (gases or liquids) to flow through the hollow box frames 18 of each module 6 (heat exchangers 10, burners 8, and primary reaction module 9) as indicated by the solid lines. In addition, the reactor 2 allows process fluids to flow through the internal cavities 42 of each module 6 as indicated by the dashed lines. The flow of reaction gases to the reaction module 9, heat exchangers 10, and burners 8 are arranged to flow through the hollow frame structures 18, which define the sides of each of the rectangular box modules 6. This allows for both heat exchange across the inner cavity 42 wall, and for the compactness of design of the reactor 2.

As shown in Figure 9, the reactor 2 has in-flow tubes 38 for the inlet of reactants, and also an out-flow tube 40 for the outlet of products. The reactor 2 is also fitted with a number of transfer fluid lines 44 which divert the process fluid flows from one module 6 to a second (or more) non-adjacent module 6. As shown in Figure 5, some of the face plates 14 forming the faces of the rectangular box modules 6 have slots 46 extending therethrough, which allow the flow of gases from one box module 6 to the other opposite side as required by the process gas flows. This fluid transfer method may be used when the fluids need to be passed between two adjacent cavities 42, for example, between two heat exchangers 10, between a burner 8 and a heat exchanger 10, or between the reaction module 9 and a heat exchanger module 10.

In this manner, the flow of fluids is retained within the compact unit and the outer sealed edges of the face plate 14. Hence, use of this transfer method allows the hollow tubular sections 18 to be maintained at temperatures below the operating temperatures of the burners 8 and also the primary reaction module 9. The integrity and strength of the face plate 14 sealing procedure by welding at the welded sections 50 is thereby maintained for substantially long periods of time without leakage.

In the reactor 2 shown in Figure 9, a mixture of liquefied petroleum gas vapour (LPG) and air 28 is fed into the bottom of the two gas burners 8. The LPG/air mixture (Calor gas) 28 flows up through internal cavity 42 of the burners 8 which contain a pre-heated oxidation catalyst 120 at a temperature such that combustion of the gases 28 occurs, and an increased volume of hot exhaust gas 34 is produced. The oxidation catalyst 120 in the burner 8 is pre-heated up to optimum reaction temperature by an external igniter assembly 110 as shown in Figure 1. Pre-heating of the combustion gas, and hence, catalyst 120, is often required before combustion of the gases can take place in the main burner 8. However, in some embodiments of the reactor 2, the burners 8 may not contain catalyst 120. However, preheating of the gases 28 themselves will still be required.

The LPG/air combustion mixture 28 is first fed in to the igniter assembly 110 where it is ignited by a spark plug 112. However, it will be appreciated that the gas mix 28 may be ignited by other means, for example, by any form of electrical heating element, a glow plug or by a hot air blower. The igniter assembly 110 may itself contain a bed of oxygen catalyst (not shown) to facilitate ignition of the combustion gas 28 before it is fed in to the burner module 8.

The ignited gas is fed from the igniter assembly 110 via conduit 114 in to the base of the burner 8 to initiate combustion gas burning in the burner module 8 itself and to preheat the catalyst 120. In some embodiments of the reactor 2, the igniter assembly 110 can be disposed inside the burner 8 (i.e. an internal igniter assembly 110), instead of being disposed outside the burner 8. For example, the igniter assembly 110 can be disposed in the air/LPG inlet conduit 38 inside the burner 8. As with the external igniter assembly 110, a spark plug 112, glow plug or hot air blower is arranged in the internal assembly 110 to ignite the feed LPG/air mixture 28 as it enters the burner module.

While the catalytic combustion of the gas 28 is being initiated by the igniter assembly 110, the burner module 8 is switched off. However, once the catalytic combustion of the burner gases 28 has been successfully initiated in the assembly 110, and the catalyst 120 and gases 28 are up to optimum reaction temperature, the igniter assembly 110 is then switched off, and the burner 8 is switched on. At this point, the burner module 8 is able to function efficiently burning fresh combustion gas feed 28 supplied by inlet 38 on its own without the requirement for further pre-heating, i.e. the gas 28 in the burner 8 is self-igniting. It will be appreciated that the feed of hot gas ignited by the igniter assembly 110 enters the burner modules 8 through the same entry point 38 as the air/LPG gas in normal operation, i.e. when the burner 8 has been started and the igniter assembly 110 has been turned off.

From the top of the two burners 8, the hot exhaust gas 34, then flows (solid line) downwardly through the hollow tubular frame 18 to the bottom of the burners 8. The two feeds of hot burner exhaust 34 from the two burners 8 are then transferred to the inner cavity of the heat exchanger 10 via the transfer apertures (or ports) 62 as shown in Figure 6. The exhaust 34 passed over the outer surfaces of the heat exchanger tubes 20, in order to heat incoming reactants by heat exchange therewith, before exiting the heat exchanger 10, via transfer tubes 38 passing through the hollow tubular section 19, into a transfer line 44 at the opposite end to entry.

From the top of the exchanger module 10, the burner exhaust 34 is fed via the transfer line 44 to the internal cavity 42 of a further heat exchanger 10 on the opposite side of the reactor 2. The burner exhaust 34 flows (dashed line) down through the internal cavity 42 of the heat exchanger 10, to allow heat exchange with further reactants, and then through apertures 46 in to the neighbouring heat exchanger 10, for further heat exchange with reactants. The burner exhaust 34 flows (dashed line) upwardly through the internal cavity 42, and eventually exits the heat exchanger 10 as cooled burner exhaust gas 34.

Accordingly, the LPG/air mixture 28 is burnt in the burners 8 to produce hot burner exhaust gases 34. These hot gases 34 are used to heat incoming reactants due to heat exchange therebetween by passing both feeds through the heat exchangers 10. The hot exhaust gases 34 flow through the internal cavity 42 of a heat exchanger 10 in one direction, and the reactants flow through the internal heat exchanger tubes 20 of the same heat exchanger 10 in a contra-flow system such that cold reactants are heated up. The impervious walls or blocks 61 provided at the corner of the heat exchangers prevent the two fluids from mixing.

For steam reforming reactions, water 30 is fed in to one of the heat exchangers 10 and flows (solid line) down the inside of the hollow frame 18 thereof. The water 30 is partially heated up due to heat exchange with the hot exhaust gases 34 flowing through the internal cavity 42 of the heat exchanger 10 and heat transfer from the burner module 8. The water 30 then flows in to the neighbouring heat exchanger 10, and flows (solid line) up through the inside of the hollow frame 18 up to the top portion thereof, again being heated up by heat exchange with the exhaust gases in the heat exchanger 10 internal cavity 42. Again, the walls 61 in the heat exchanger's hollow tube 18 prevents the two fluids from mixing together. At the top of the heat exchanger 10, the water then flows (dashed line) down through heat exchanger tubes 20, where it is heated by the hot burner exhaust gases 34 within the internal cavity 42, and into the hollow frame 18 at the bottom of the heat exchanger 10. The heated water then rises up the heat exchanger tubes 20 to the top of the heat exchanger and exits via transfer tube 44 into the top of the hollow frame 18 of a heat exchanger 10 on the opposite end of the reactor 2.

Simultaneously, additional LPG 26 is fed though an in-flow pipe 38 in to the bottom of the same heat exchanger 10. The LPG 26 flows (solid line) up the inside of the hollow tubular frame 18 to the top of the heat exchanger 10 so that it is partially heated up due to heat exchange with the hot exhaust gas 34 flowing down through the internal cavity 42. The LPG 26 is then mixed with the hot water 30 entering at the top of the heat exchanger 10, and the water/LPG mixture then flows (dashed line) down through the heat exchanger tubes 20 of the heat exchanger 10, where it is further heated up due to heat exchange with the burner exhaust 34 and the water is converted to steam. The steam/LPG mixture is fed from the bottom of the heat exchanger 10 via a transfer line 44 in to the bottom portion of the reaction module 9. The hot steam/LPG mixture then flows (dashed line) over the catalyst 24 in the catalyst bed 90 to allow the reaction to take place. Reaction products (or reformate) 32 exit the reaction module 9 via an out-let flow pipe 40.

Hence, it will be appreciated that the LPG and air burner gas is burnt in the burners 8. Temperatures of between 1000-1200°C may be reached. The hot gas is then fed around through the heat exchanger internal cavities 42 of each exchanger 10 thereby heating up the water and LPG 26 which are fed through the tubular frames 18 and heat exchanger tubes 20 of each heat exchanger 10. Heat exchange changes water into steam and heats up the reactants, steam and LPG, to optimum reaction temperature. The reforming reaction occurs in the reaction module 9 producing reformate 32.

Referring to Figure 10, there is shown a plan view of the reactor 2 illustrated in Figure 9. The Figure shows the up and down flows of the burner exhaust 36, 38; the LPG 40, 42; the water 44, 46; the reformate 48, 50; and the LPG/water mixture 52, 54.

The reactor 2 according to the invention has been designed for a wide range of process reactions. Examples include either biological reactions, such as fermentations, which are normally carried out at temperatures of between 0°C to 40°C, or chemical reactions, which can be operated at temperatures of 50°C, and above. In addition, if necessary, the reactor 2 can be operated at elevated pressures of up to 25 barg dependent on temperatures and up to 850 deg. C dependent on pressures.

The primary reaction module 9 is heated via the gas fired burners 8, which are located either side thereof. The burner exhaust gases 34 are used to heat incoming reactants using the heat exchangers 10. Examples of reactions for which the compact reactor 2 is suitable are described below.

<u>Example 2</u>

<u>Reaction 1 – Steam Reforming of Hydrocarbons</u>

Production of hydrogen via steam reforming is an important industrial process. It involves the reaction of hydrocarbons with steam, or with steam and oxygen, at high temperatures (350°C - 1100°C). The endothermic reaction is carried out over a multi-metal oxide catalyst 24 and produces a mixture of hydrogen, carbon oxides and residual hydrocarbon.

The general steam reforming equation for methane (CH_4) is shown below:-

$$2CH_4 + 3H_2O \rightarrow CO_2 + CO + 7H_2$$

When at optimum conditions of temperature 750 – 850°C and atmospheric pressure, the majority of the hydrocarbon feed (methane) is converted to a reformate gas blend. To maximise the rate of hydrocarbon conversion, high temperatures are employed. Increasing the pressure is one method of increasing the mass conversion but it also reduces the level of hydrogen in the product reformate as a consequence of chemical equilibria.

The purity of the reformate product stream may be further enhanced by removal of the Carbon Monoxide with steam to produce Hydrogen. This step is known as the Water Gas Shift (WGS) reaction and is favoured by low temperatures, 240 – 500°C. The reaction is pressure independent and described by:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The process also increases the overall level of hydrogen production. In order to maximise hydrocarbon conversion and hydrogen production with a minimum CO content, the reactor 2 is operated with a high inlet temperature in the primary reaction module 9. Choice of operating pressure is a compromise between reasonable conversion and an acceptable product gas composition.

Referring to Figure 11, there is shown the chemical reactor 2 used for hydrocarbon steam reforming and the production of hydrogen rich gases. Burner gas and air 58 is introduced in to the two burners 8, and the reactants (water and hydrocarbon source) 60 are introduced into a heat exchanger 10. Heat exchange is illustrated by arrows 56, which occurs between the hot burner/air mix 58 and the reactants 60 in the directions shown. In addition, the strengthening fins 92 protruding from the face plate 14 of the burners 8 in to the reaction module 9 provide additional heat exchange therebetween. This results in the reactants heating up to the required temperature for the reaction to occur in the reaction module 9. Products of the reaction 62 leave the reactor 2 as indicated in the Figure.

The reforming and shift reactions are carried out in two separate reaction modules 9. The initial conversion step is carried out in the primary reaction module 9 disposed between the two burners 8. If the temperature required to achieve the primary step of the reaction is not achieved purely by heat transfer from the burners 8, the temperature inside the reaction module 22 can be increased by injecting additional oxidising fluids therein to carry out a partial oxidation reaction. These fluids may be air, oxygen or hydrogen peroxide, for example, all of which will oxidise hydrocarbons and hydrogen produced by the primary step of the reaction and thus release heat energy. The products 62 of the reaction are then transferred to a lower temperature Water Gas Shift (WGS) catalytic reaction module 52 for the second stage of the reaction. To achieve the temperatures required for high conversion in the primary reaction module 9, the reactants are passed through several heat exchangers 10 as illustrated in the Figure to allow the heat exchange 56 to take place. These heat exchangers 10 use the hot burner exhaust gases 34 and product gas from the water gas shift reaction 52 to preheat the reactants 60 prior to the primary reaction module 9.

Figure 11 illustrates the arrangement of the modules 9 & 52 in a compact chemical reactor 2 being utilised for steam reformation of hydrocarbons. It should be appreciated that the number of heat exchangers 10 can be changed for particular process requirements, as well as the ordering of the different sections in the reactor 2. It will be appreciated that the reactor 2 consists of hollow tubular frames 18 through which the reactants 60 used for this reaction flow.

An alternative embodiment of the reactor 2 used for producing impure hydrogen by reforming an organic feedstock with water or carbon dioxide includes eleven to twenty one individual, face-to-face interlinked box modules 6 having the following functions:-

i) 3 heating sections (burners 8) containing catalyst;
ii) 2 primary reaction modules 9 containing catalyst;
iii) 2 – 6 heat exchanger sections 10;
iv) 1-3 water gas shift reaction reactors 52 containing catalyst;
v) 1-3 sections containing chemicals for the removal of hydrogen sulphide;
vi) 1-3 sections containing catalyst for the catalytic removal of carbon monoxide; and
vii) 1 catalytic combustor.

The two reaction modules 9 are sandwiched between three burners 8 and are fed with a stream of pre-heated steam and organic feedstock. The burners 8 are combustor modules fed with a blend of air and combustible gas. Sections (i) and (ii) are arranged such that they are of the same sizes and are physically joined together as a compact unit with the reaction modules 9 being sandwiched between three burners 8 such that the design is 8/9/8/9/8. Sections (i) to (vi) are physically joined together as a compact unit. However, it will be appreciated that this is not essential for all of the sections.

The flow of gases to the (ii) primary reaction module 9, (iii) heat exchangers 10, (iv) shift reactor 52, and (v) hydrogen sulphide removal (not shown), are arranged to flow through the hollow framework 18, which forms the sides of the rectangular box modules 6, such that there is fluid transfer between modules 6 and heat exchange between the fluids flowing through the hollow structure and the medium on the internal wall side. The reactor 2 is equipped with transfer lines 44, which divert the process flows from one module 6 to a second non-adjacent module 6.

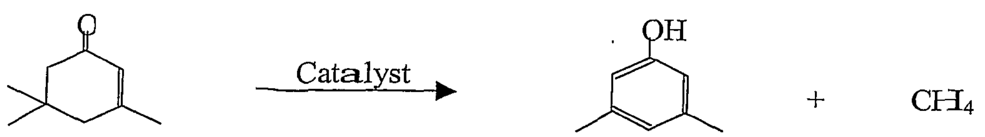
It will be appreciated that all of the modules containing catalyst 24 also include a catalyst removal/insertion tube 70.

Example 3

Reaction 2 – 3,5-Xylenol Production

The reaction to form 3,5-Xylenol from Isophorone occurs in commercial yields between 500-620°C. The product of the reaction is used as a precursor in the production of disinfectants.

Referring to Figure 12, burner gas and air 58 is fed in to the two catalytic burners 8. The reactant 60 isophorone is fed in to the reactor 2 as a liquid at room temperature (boiling point 215°C), and is vaporised in the heat exchangers 10 due to heat exchange as indicated by arrows 56 in the direction shown. The vapourised isophorone 60 is then passed over a multi-metal oxide catalyst 24. The general reaction occurs as shown below :-



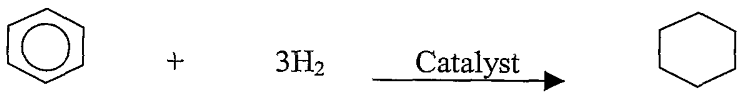
Methane is also produced in the reaction, which involves C-C bond cleavage and aromatisation. Carbon deposits are formed as a by-product of the reaction and are removed by combustion at regular intervals. The product 62 (melting point 64°C) is collected as a solid.

The chemical reactor 2 employs heat exchangers 10 heated by the burner 8 exhaust gasses 34 for the initial vaporisation of the Isophorone. This would then pass into the catalyst 24 filled reaction module 9 housed between the two burner modules 8. The reaction product would be passed through one heat exchanger 10 and then cooled by external means to solidify the product. An arrangement for the reactor 2 used is illustrated in Figure 12.

Example 4

Reaction 3 – Hydrogenation of Unsaturates

The compact reactor 2 assembly can be used for hydrogenation reactions, which are exothermic. A typical example of such a reaction is the hydrogenation of benzene to cyclohexane 62 over a supported, reduced metal, catalyst 24. The reaction occurs as shown below –



Referring to Figure 13, the chemical reactor 2 employs heat exchangers 10 heated and or cooled by the heater 8 and or the hot reaction products 62, to bring the reactants, benzene and hydrogen, to reaction temperature. The reactants then pass into the catalyst 24 filled reaction module 9 housed between the two heaters 8. The reaction product is passed through one heat exchanger 10. Heat exchange occurs as indicated by arrows 56. The reaction module 9 would be run at a lower temperature than as described in Examples 1-3, because of the exothermic nature of the reaction. The heaters 8 may be combustible gas/air or electrically heated. Gas/air passed into the burners 8 is metered to achieve the desired reaction chamber temperature.

In conclusion, advantages of the reactor 2 according to the invention reside in its design. The reactor 2 has a very simple design and is therefore compact. The hollow tubular frame 18 assemblies not only provide structural support for each module 6 making up the reactor 2, but also act as conduits for the process fluids (either gaseous or liquid) required during the reaction. Hence, many of the tubes and transfer lines, which are normally required to carry the reactants to, and the products away from, the reaction module 9, are no longer required. This is a substantial advantage over prior art reactors of conventional design.

Furthermore, because the fluids for reaction and heating/cooling purposes flow through the hollow frames 18, they actively keep the temperature of the welded sections 50 between the frames 18 and corresponding face plates 14 at sufficiently low temperatures such that significant expansion and thermal embrittlement, which would rupture the welds, does not occur. This is achieved due to improved thermal conduction away from the weld sections 50 by the constantly flowing fluids. This ensures that thermal tolerances of the reactor 2 are adhered to, so that the welds 50 do not fracture and leak. Particularly the thermal tolerances in the welded gas/air fired burners. Accordingly, the reactor 2 and burner modules 8 can be operated for longer periods without weld failure compared to conventional non-tubular welded reactors (i.e. prior art reactors).

Example 5

Reaction 4 – Purification of hydrogen

The modular reactor 2 assembly shown in the Figures can also be used for the purification of hydrogen gas containing hydrogen sulphide. A high temperature reaction is carried out between zinc oxide and hydrogen sulphide at 380°C with the following chemical reaction:-.

$$ZnO + H_2S \quad \text{-------} \quad ZnS + H_2O$$

This is a standard reaction used commercially to purify hydrogen by removal of hydrogen sulphide.

CLAIMS

1. A reactor for a biological or chemical reaction, the reactor comprising at least one reactor module comprising an internal cavity, which cavity is at least partly defined by an inner wall of a substantially hollow fluid conduit, which conduit comprises at least one aperture extending through a side wall and/or an outer wall thereof to allow fluid to flow into the conduit, the conduit comprising at least one further aperture extending through the inner wall thereof so that, in use, fluid flows between the hollow conduit and the internal cavity.

2. A reactor according to claim 1, wherein the reactor module is adapted to receive fluid from an external source, which fluid may flow in through the aperture in the side or outer wall of the conduit.

3. A reactor according to either claim 1 or claim 2, wherein the reactor module is adapted to move at least two fluids therein between the hollow conduit, and the internal cavity thereof.

4. A reactor according to any preceding claim, wherein the reactor module is adapted to move fluid between two adjacent modules, between the hollow conduits and/or the internal cavities thereof.

5. A reactor according to any preceding claim, wherein the conduit is adapted to act as a conduit for reaction reactants, reaction products, catalysts, and/or heat exchange fluids, and in addition, simultaneously provides structural support for the reactor module.

6. A reactor according to any preceding claim, wherein the conduit forms a continuous substantially hollow ring extending around the internal cavity.

7. A reactor according to any preceding claim, wherein the conduit comprises at least one aperture extending through the outer wall (i.e. an end face) thereof, which aperture communicates with a further fluid conduit.

8. A reactor according to any preceding claim, wherein the conduit comprises at least one aperture extending through a side wall (i.e. a side face) thereof, which communicates with an adjacent module.

9. A reactor according to either claim 7 or claim 8, wherein the aperture communicates either with an external fluid source (e.g. a heat exchange fuel supply, or a reactant supply), or a fluid conduit extending from another module of the reactor (e.g. circulating combustion fluid).

10. A reactor according to any preceding claim, wherein the inner wall of the hollow conduit comprises at least one aperture at substantially opposite ends thereof.

11. A reactor according to any preceding claim, wherein the hollow conduit comprises at least one wall extending across the inside thereof, which wall is adapted to modulate the flow of fluid through the hollow conduit.

12. A reactor according to claim 11, wherein the wall is an impervious block extending completely across the inside of the hollow conduit.

13. A reactor according to either claim 11 or claim 12, wherein the at least one wall is adapted to separate at the least two fluids flowing within the hollow conduit.

14. A reactor according to any one of claims 11 to 13, wherein the conduit comprises a wall positioned at, or at least adjacent, a corner of the hollow conduit.

15. A reactor according to any preceding claim, wherein the conduit comprises an internal conduit extending internally therealong.

16. A reactor according to claim 15, wherein fluid may flow along the internal conduit, which fluid may be adapted to cool certain regions of the hollow conduit.

17. A reactor according to any preceding claim, wherein the at least one reactor module comprises at least one sealing member, which defines a further portion of the internal cavity.

18. A reactor according to claim 17, wherein the at least one sealing member comprises a substantially planar plate, which plate is attached to the hollow conduit by any suitable means so that a seal is formed therebetween.

19. A reactor according to either claims 17 or claim 18, wherein the module comprises a first sealing member attached to one side of the conduit, and a second sealing member attached to a second side of the conduit.

20. A reactor according to any preceding claim, wherein the reactor module comprises a sealed box structure comprising a hollow tubular frame, which extends around the internal cavity, which frame has a sealing plate attached to either side of the frame, so that the internal cavity is enclosed, and sealed thereby.

21. A reactor according to any one of claims 17 to 20, wherein the or each sealing member attached to the conduit comprises at least one aperture extending therethrough, the position of which preferably corresponds with the position of the aperture in the side wall of the conduit to thereby form a continuous aperture which extends between the side wall of the conduit and the sealing member.

22. A reactor according to claim 21, wherein fluid may exit the conduit of a first module and flow in to a conduit of an adjacent second module via the continuous aperture extending therebetween.

23. A reactor according to one of claims 17 to 22, wherein the or each sealing member comprises at least one further aperture, the position of which corresponds to the position of the internal cavity of the module.

24. A reactor according to any preceding claim, wherein the internal cavity contains a catalyst.

25. A reactor according to any one of claims 17 to 24, wherein the sealing member comprises heat transfer means.

26. A reactor according to claim 25, wherein the heat transfer means comprises at least one flange, which extends away from the sealing member and into the internal cavity of the module.

27. A reactor according to either claim 25 or claim 26, wherein the heat transfer means extends through at least one of adjacent modules.

28. A reactor according to any preceding claim, wherein the reactor comprises at least one primary reaction module adapted to substantially contain or enclose a biological or chemical reaction within the internal cavity or reaction chamber.

29. A reactor according to any preceding claim, wherein the reactor is adapted to carry out either a catalysed or an uncatalysed reaction.

30. A reactor according to claim 29, wherein the reaction chamber comprises a reaction catalyst, which may accelerate the rate of the reaction, or increase the required reaction product selectivity and/or yield.

31. A reactor according to any preceding claim, wherein the reactor module may comprise catalyst removal means.

32. A reactor according to claim 31, wherein the catalyst removal means comprises a catalyst conduit extending between the internal cavity and outside of the module.

33. A reactor according to one of claims 28 to 32, wherein the reactor comprises at least one further module in addition to the primary reaction module.

34. A reactor according to any preceding claim, wherein the reactor comprises a plurality of reactor modules according to any preceding claim.

35. A reactor according to any preceding claim, wherein the reactor comprises at least one heater module adapted to heat or burn gases in the internal chamber.

36. A reactor according to claim 35, wherein the heater module is adapted to transfer heat either directly or indirectly to the reaction chamber.

37. A reactor according to either claim 35 or claim 36, wherein the heater module comprises catalyst for catalyst-assisted combustion or reaction, in which case the catalyst is contained in the internal cavity of the heater module.

38. A reactor according to any one of claims 35 to 37, wherein the heater module comprises catalyst removal means.

39. A reactor according to any preceding claim, wherein the reactor comprises at least one heat exchanger module adapted to allow heat exchange to occur therein between two or more fluids.

40. A reactor according to claim 39, wherein the internal cavity of the heat exchanger module comprises at least one heat exchange tube extending thereacross.

41. A reactor according to claim 40, wherein the module is adapted to carry a first fluid through the at least one heat exchanger tube, and a second fluid through the internal cavity and/or tubular conduit, such that heat exchange may occur between the first and second fluids.

42. A reactor according to any preceding claim, wherein the reactor comprises a secondary reaction module adapted to carry out a further reaction.

43. A reactor according to any preceding claim, wherein each module in the reactor is operatively connected to at least one of the other modules in the reactor, such that fluid may flow therebetween.

44. A reactor according to any preceding claim, wherein the tubular conduit of a first module is operatively connected to the tubular conduit of a second module, which second module is adjacent the first module.

45. A reactor according to claim 44, wherein the first and second modules are operatively connected to each other by the continuous aperture extending through the side wall and the sealing member of the first module, and through the side wall and sealing member of the second module.

46. A reactor according to any preceding claim, wherein the reactor comprises at least one fluid transfer means, which is adapted to transfer fluid to and away from the reactor module.

47. A reactor according to claim 46, wherein the at least one fluid transfer means extends through a sealing member.

48. A modular reactor comprising a plurality of reactor modules according to any preceding claim.

49. A reactor according to claim 48, wherein the modular reactor comprises at least one primary reaction module, at least one heater module, and at least one heat exchanger module.

50. A reactor according to claim 49, wherein the reactor comprises an igniter assembly, which is adapted to ignite combustion gas prior to flowing in to the or each heater module.

51. A reactor according to claim 50, wherein the igniter assembly is either internal or external of the or each heater module, and is located substantially adjacent the inlet of combustion gas of the or each heater module.

52. A reactor according to either claim 49 or claim 50, wherein the igniter assembly comprises igniting means adapted to ignite combustion gas.

53. A method of producing hydrogen using steam reformation of hydrocarbons, or a method of producing 3,5-xylenol, or a method of hydrogenating unsaturated compounds, or a method of de-sulphurising gas, the method comprising using the reactor according to any preceding claim.

54. A method of carrying out a biological or chemical reaction, the method comprising (i) feeding reactants in to the reactor according to any one of claims 1 to 52; (ii) contacting the reactants in the internal cavity of the reactor module; and (iii) removing products of the reaction from the internal cavity of the reaction module.

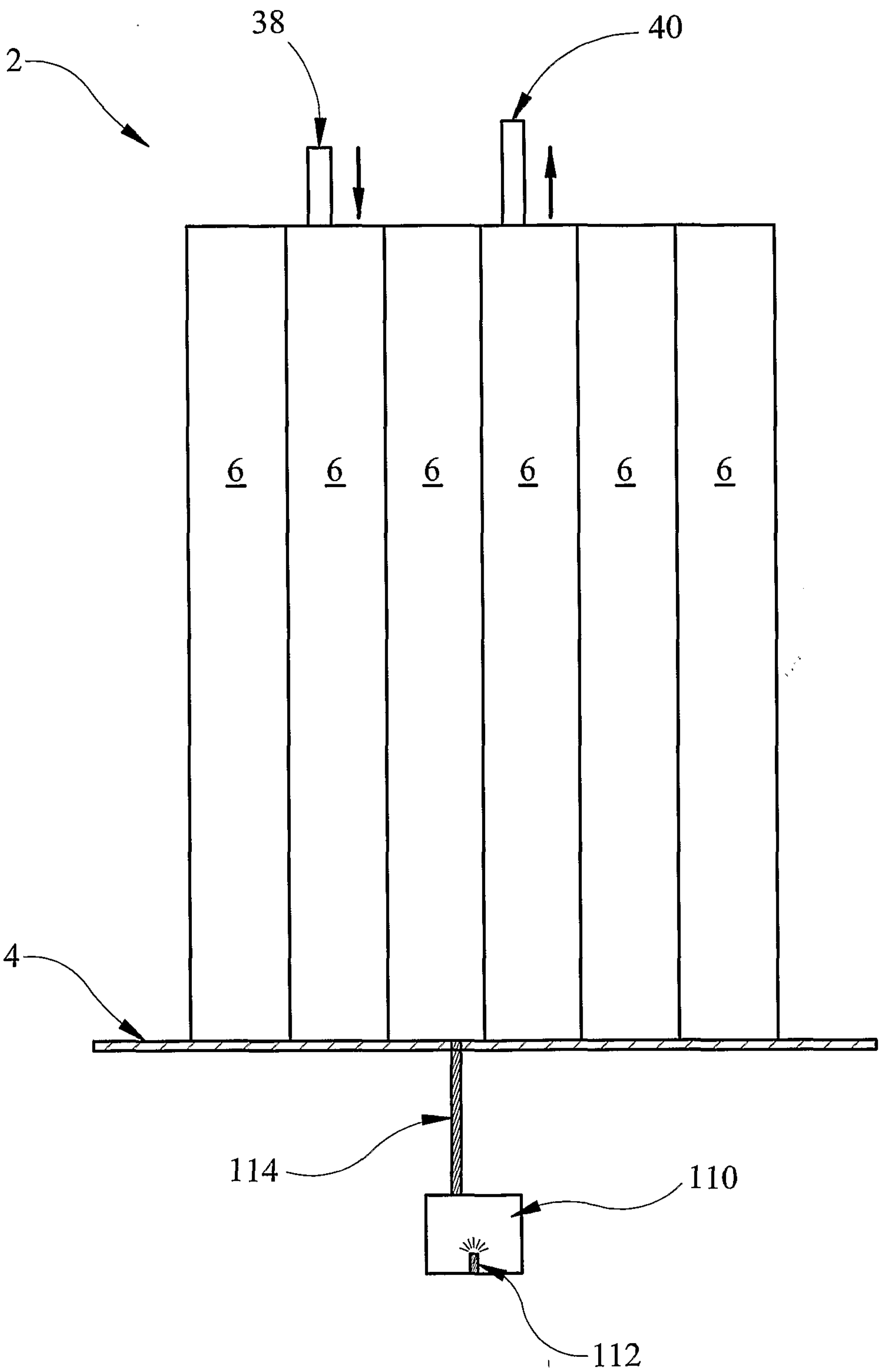


FIG 1

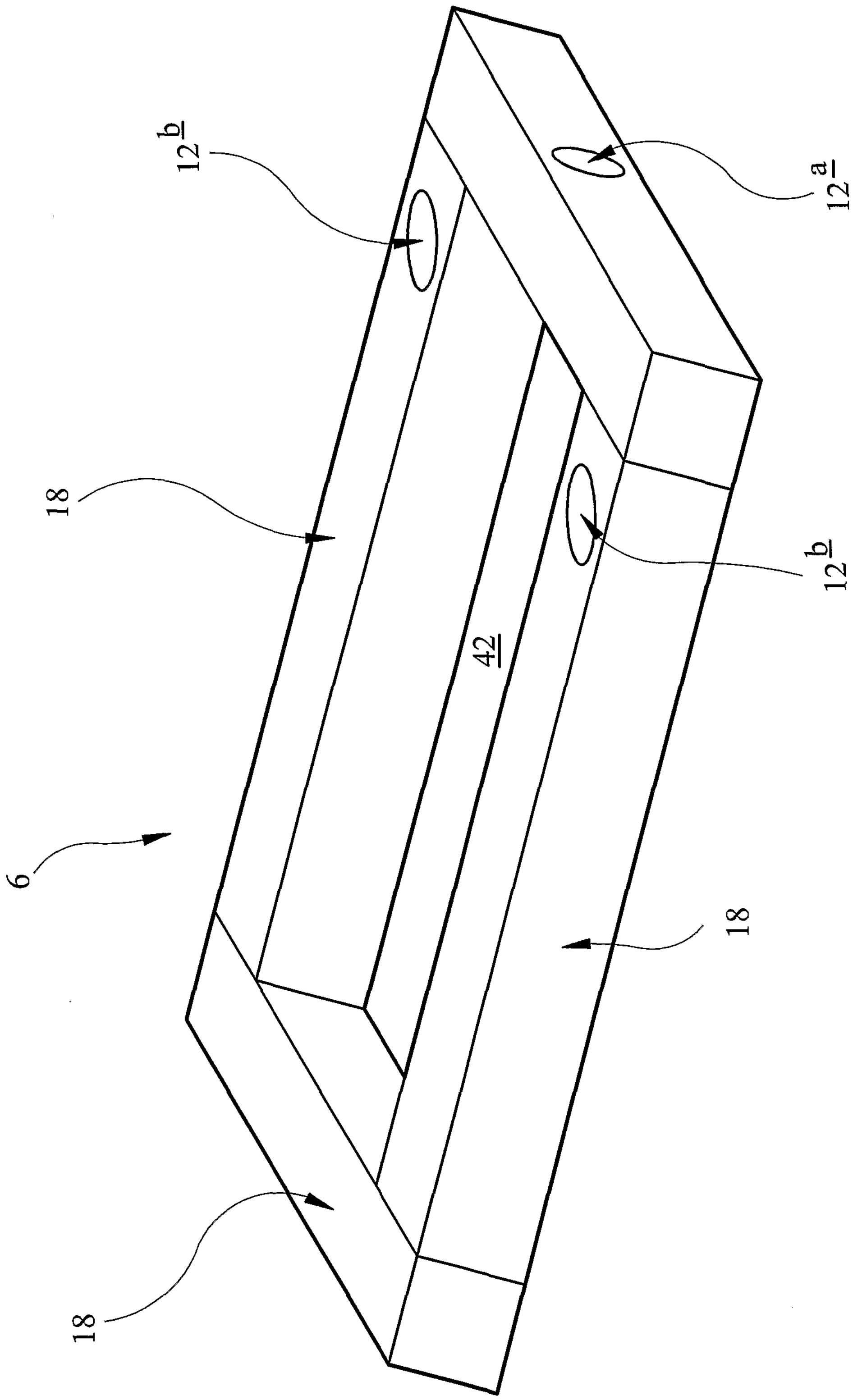


FIG 2

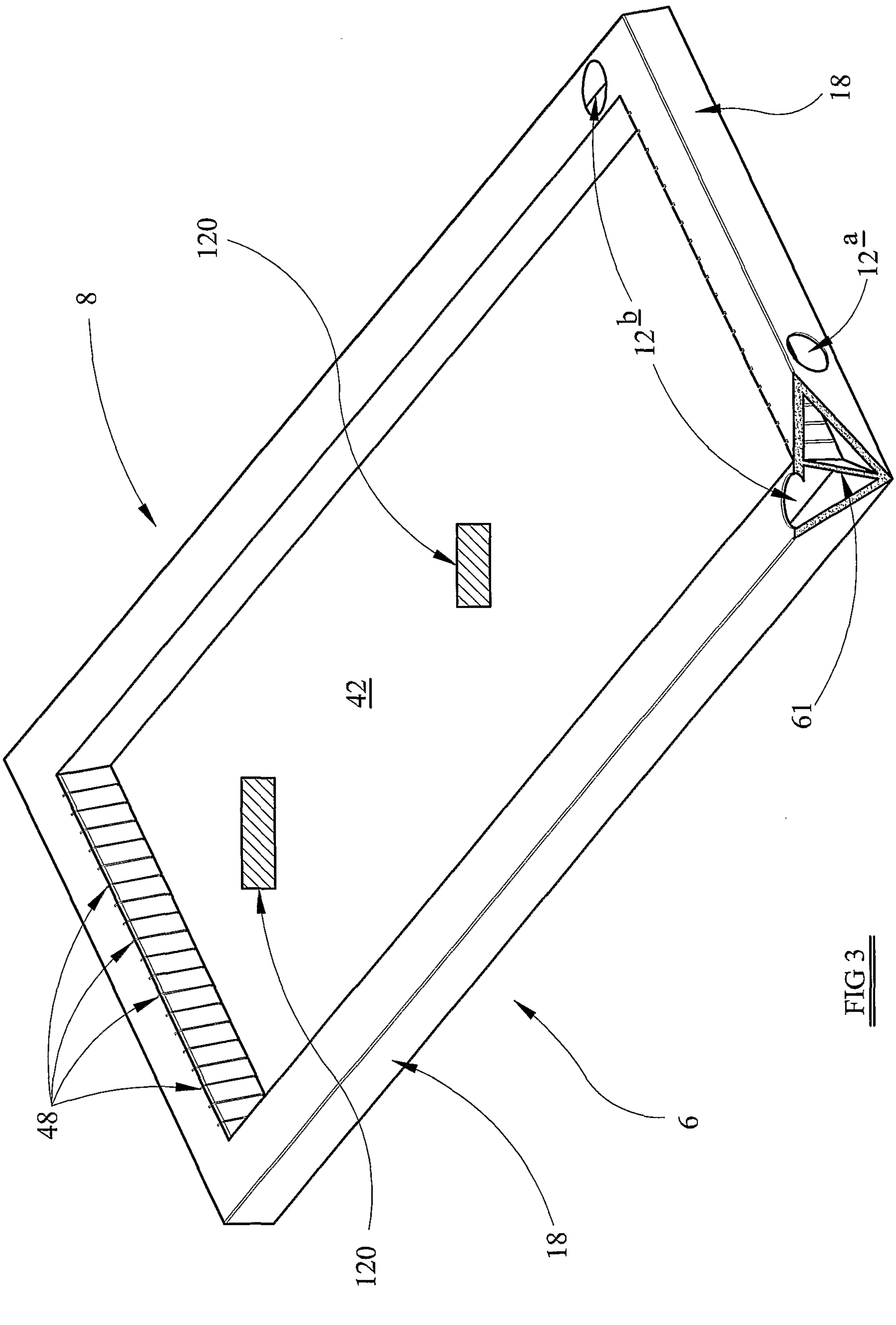


FIG 3

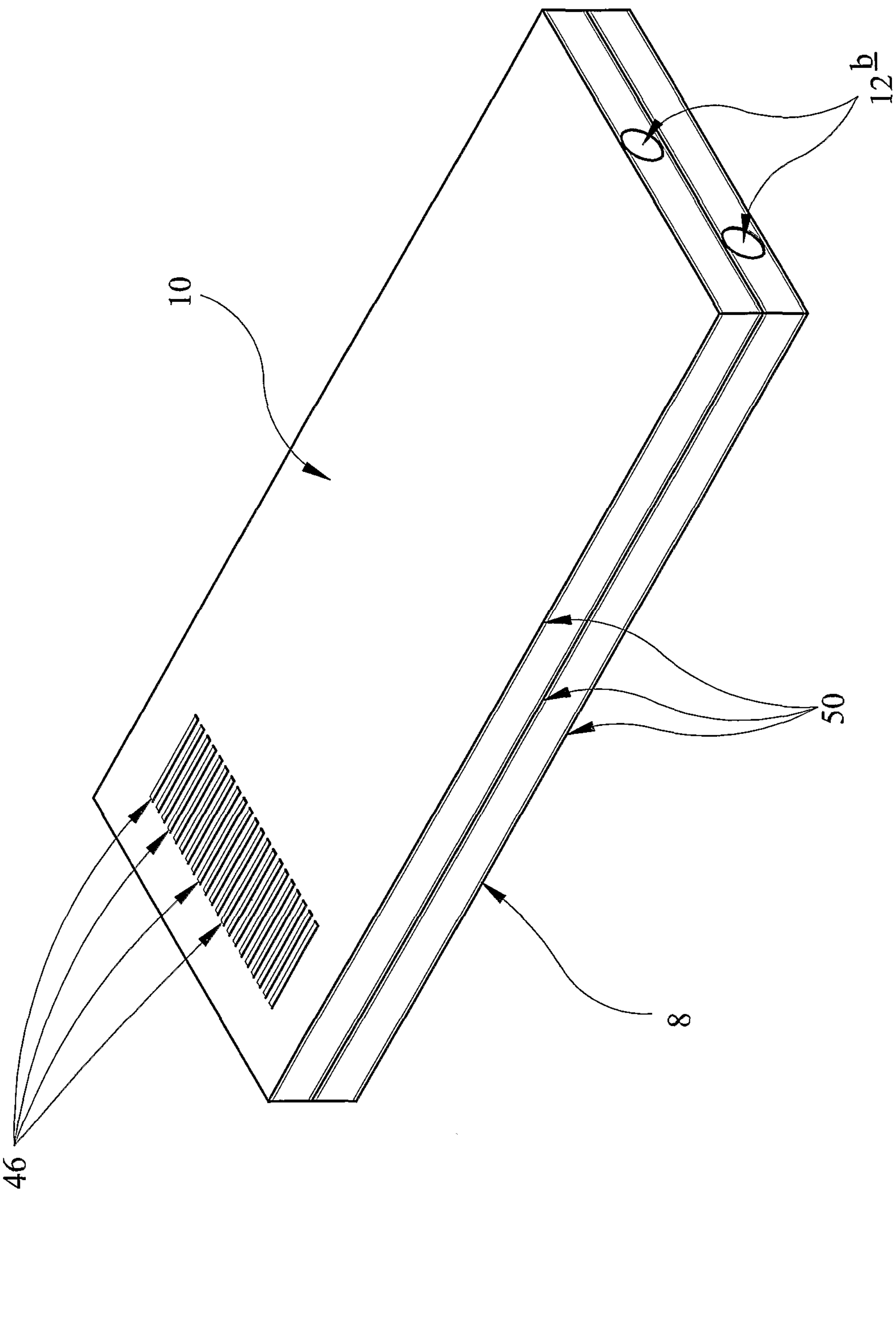


FIG 4

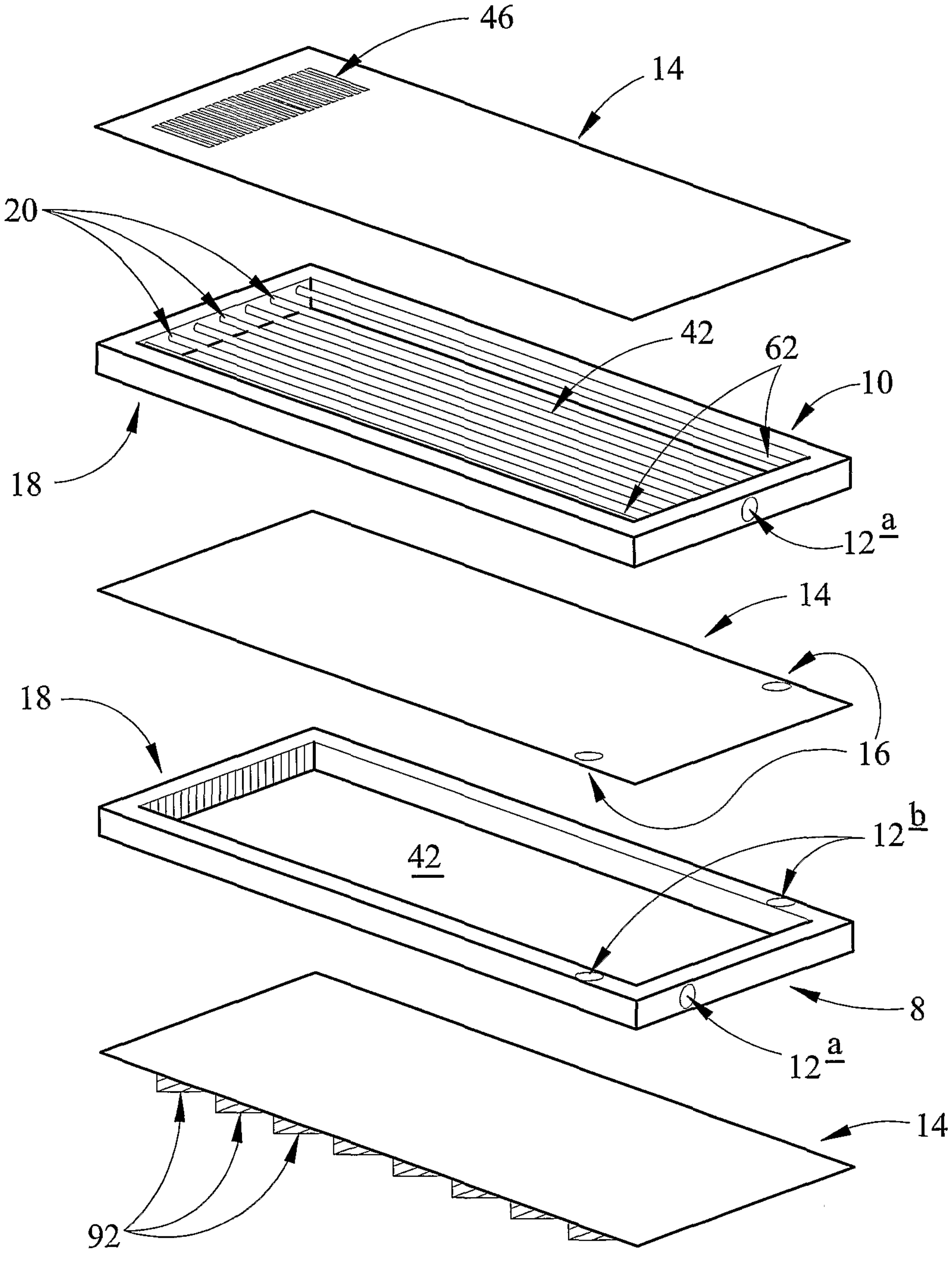


FIG 5

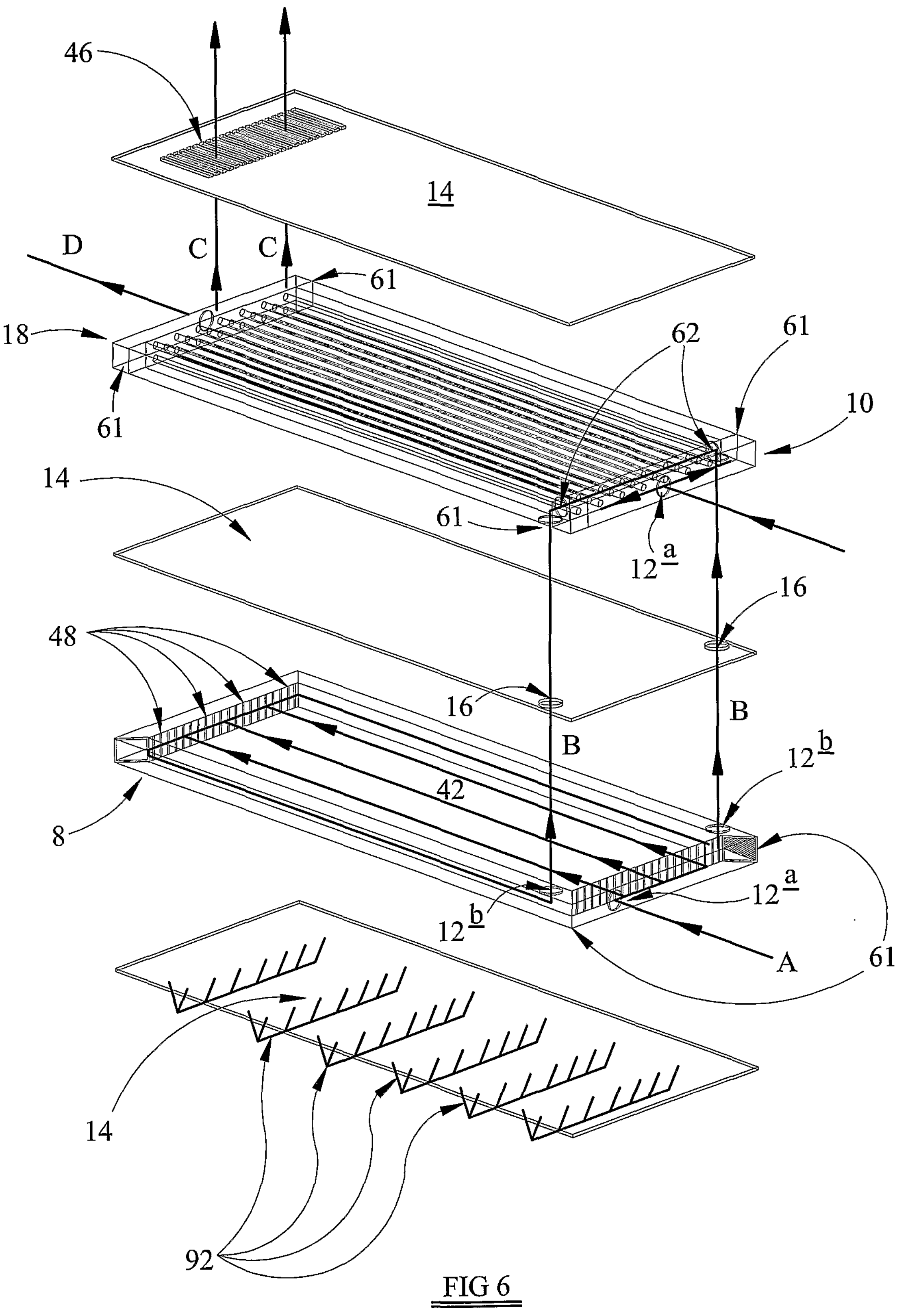

46
14
D
C
C
61
18
61
62
61
10
14
61
12a
16
48
16
B
B
12b
42
8
12a
12b
A
61
14
92

FIG 6

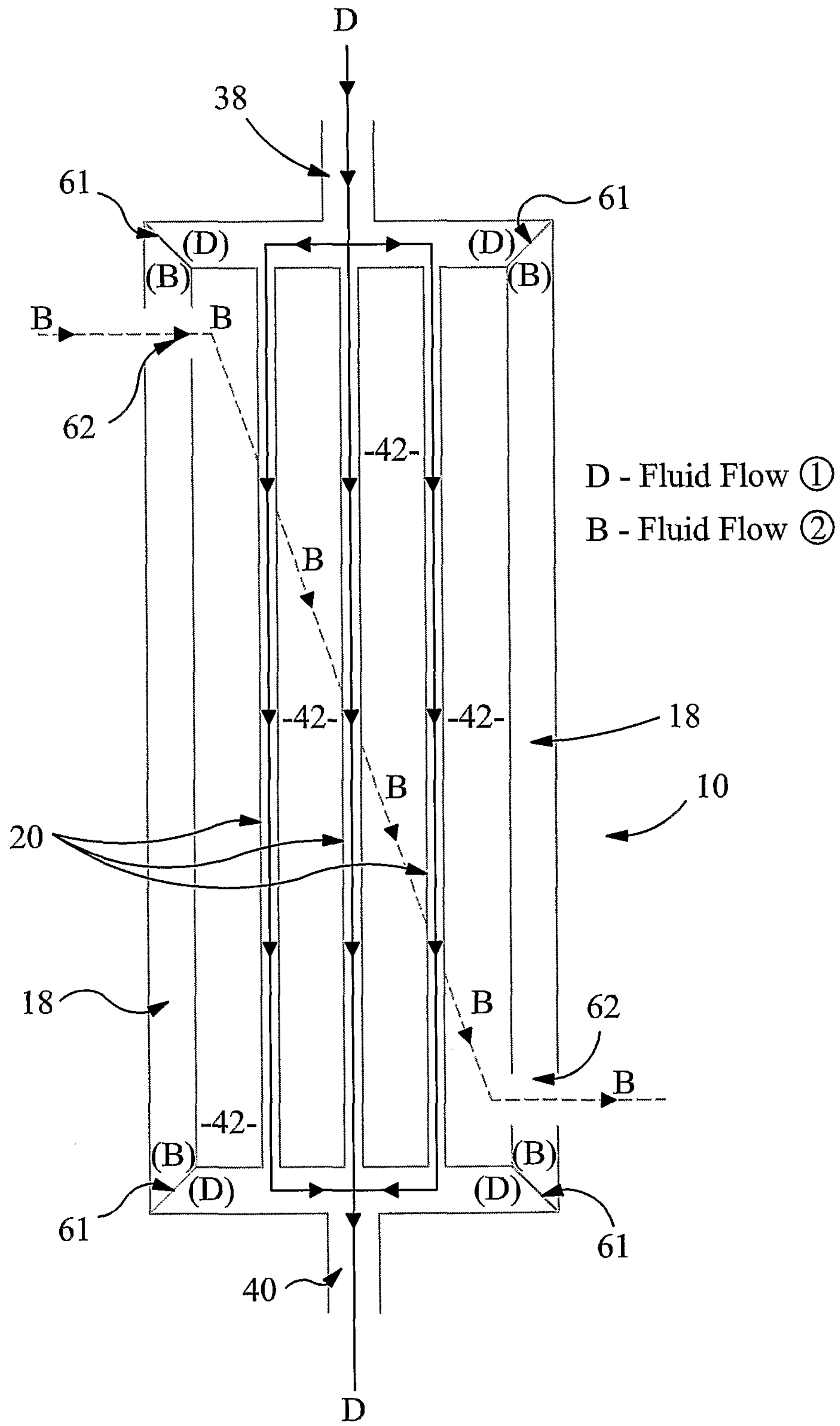

D
38
61
61
(D)
(D)
(B)
(B)
B
B
62
-42-
D - Fluid Flow ①
B - Fluid Flow ②
B
-42-
-42-
18
B
10
20
18
B
62
B
-42-
(B)
(B)
(D)
(D)
61
61
40
D

FIG 7

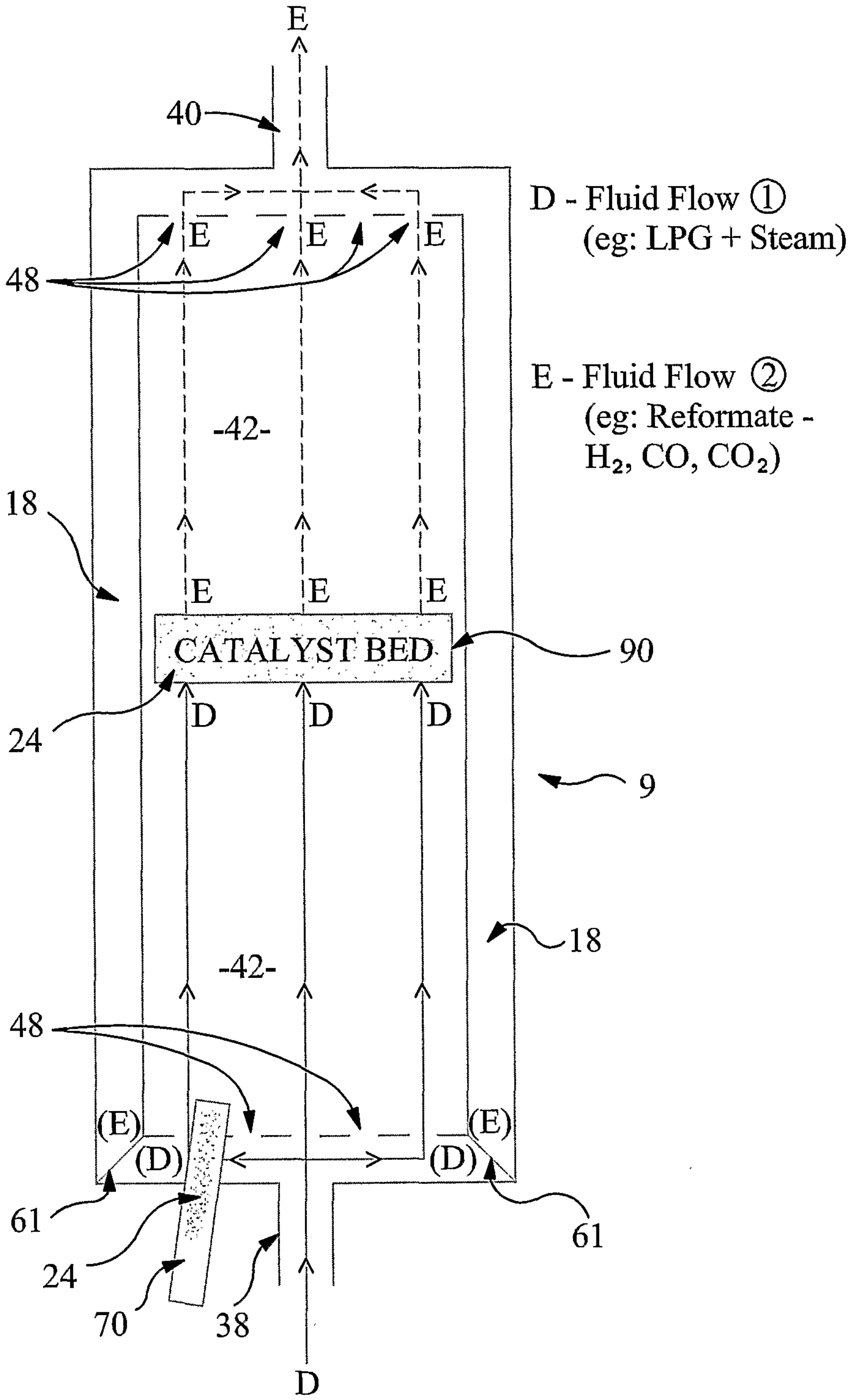

E
40
D - Fluid Flow ①
(eg: LPG + Steam)
E - Fluid Flow ②
(eg: Reformate -
H2, CO, CO2)
48
E
E
E
-42-
18
E
E
E
CATALYST BED
90
24
D
D
D
9
18
-42-
48
(E)
(E)
(D)
(D)
61
61
24
70
38
D

FIG 8

A: Process Fluid Flow
(With All Internal Flows)

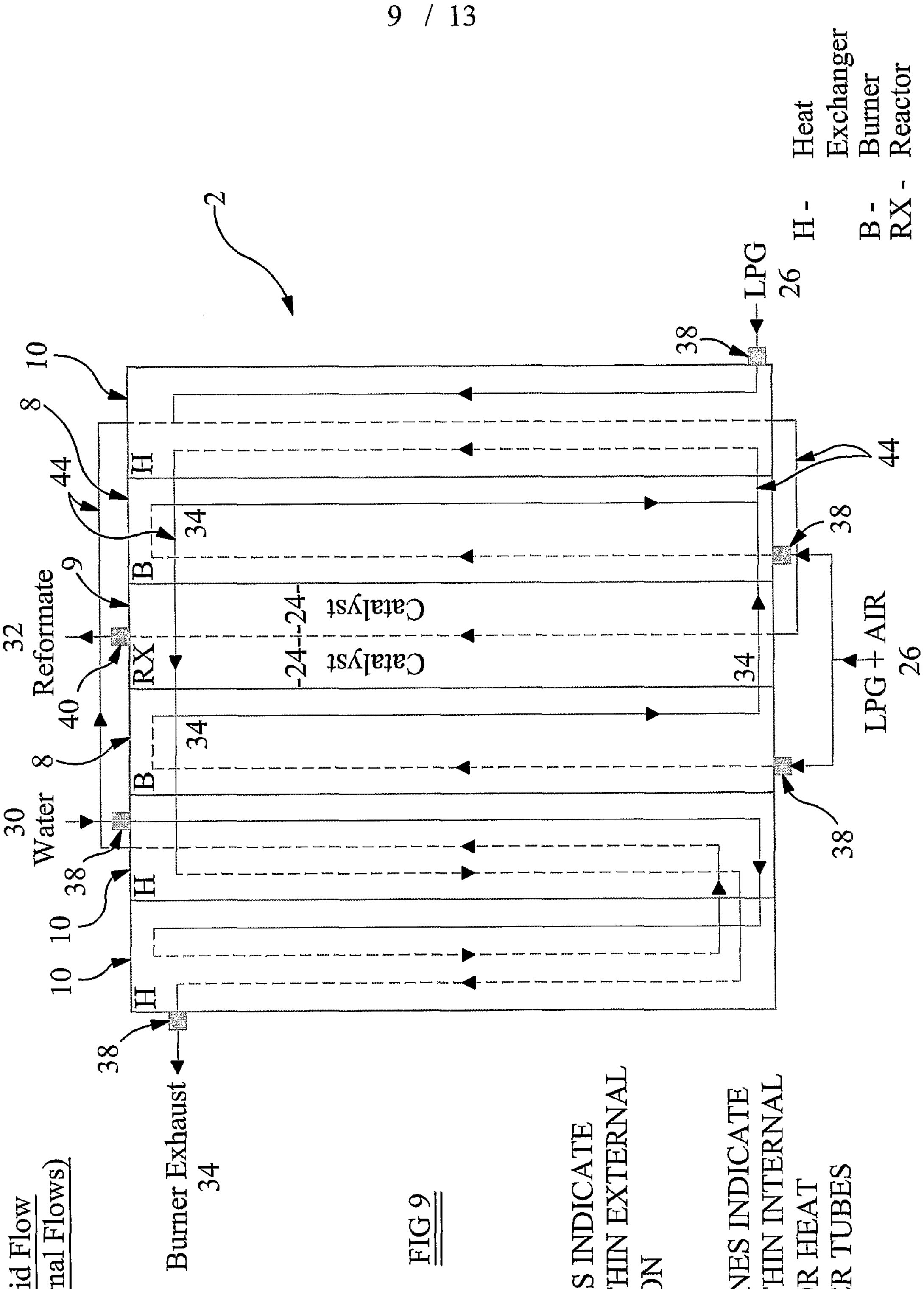


FIG 9

SOLID LINES INDICATE FLOWS WITHIN EXTERNAL BOX SECTION

DASHED LINES INDICATE FLOWS WITHIN INTERNAL CAVITIES OR HEAT EXCHANGER TUBES

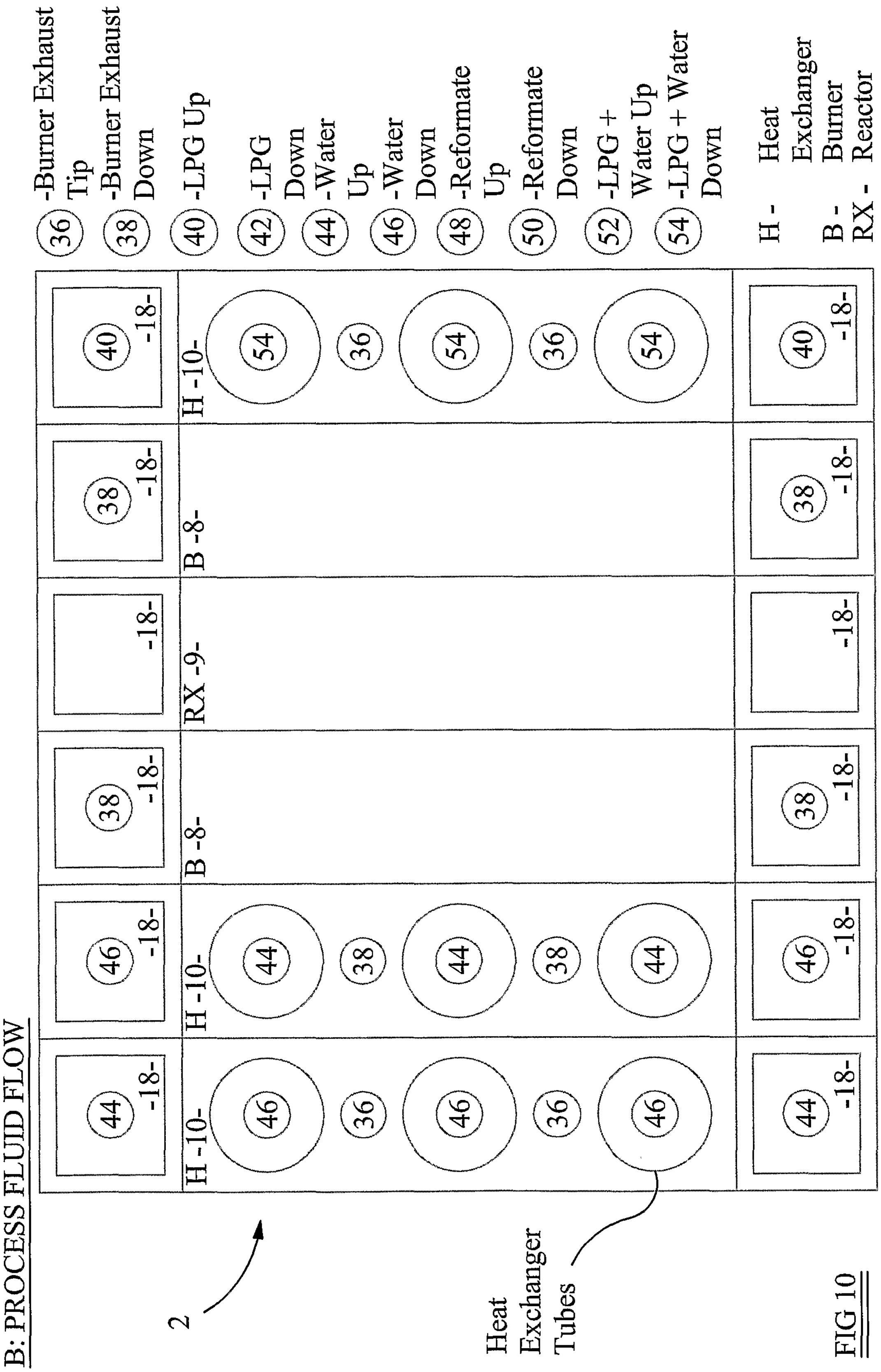

B: PROCESS FLUID FLOW
36 -Burner Exhaust Tip
38 -Burner Exhaust Down
40 -LPG Up
42 -LPG Down
44 -Water Up
46 -Water Down
48 -Reformate Up
50 -Reformate Down
52 -LPG + Water Up
54 -LPG + Water Down
H - Heat Exchanger
B - Burner
RX - Reactor
H -10-
B -8-
RX -9-
-18-
Heat Exchanger Tubes
2

FIG 10

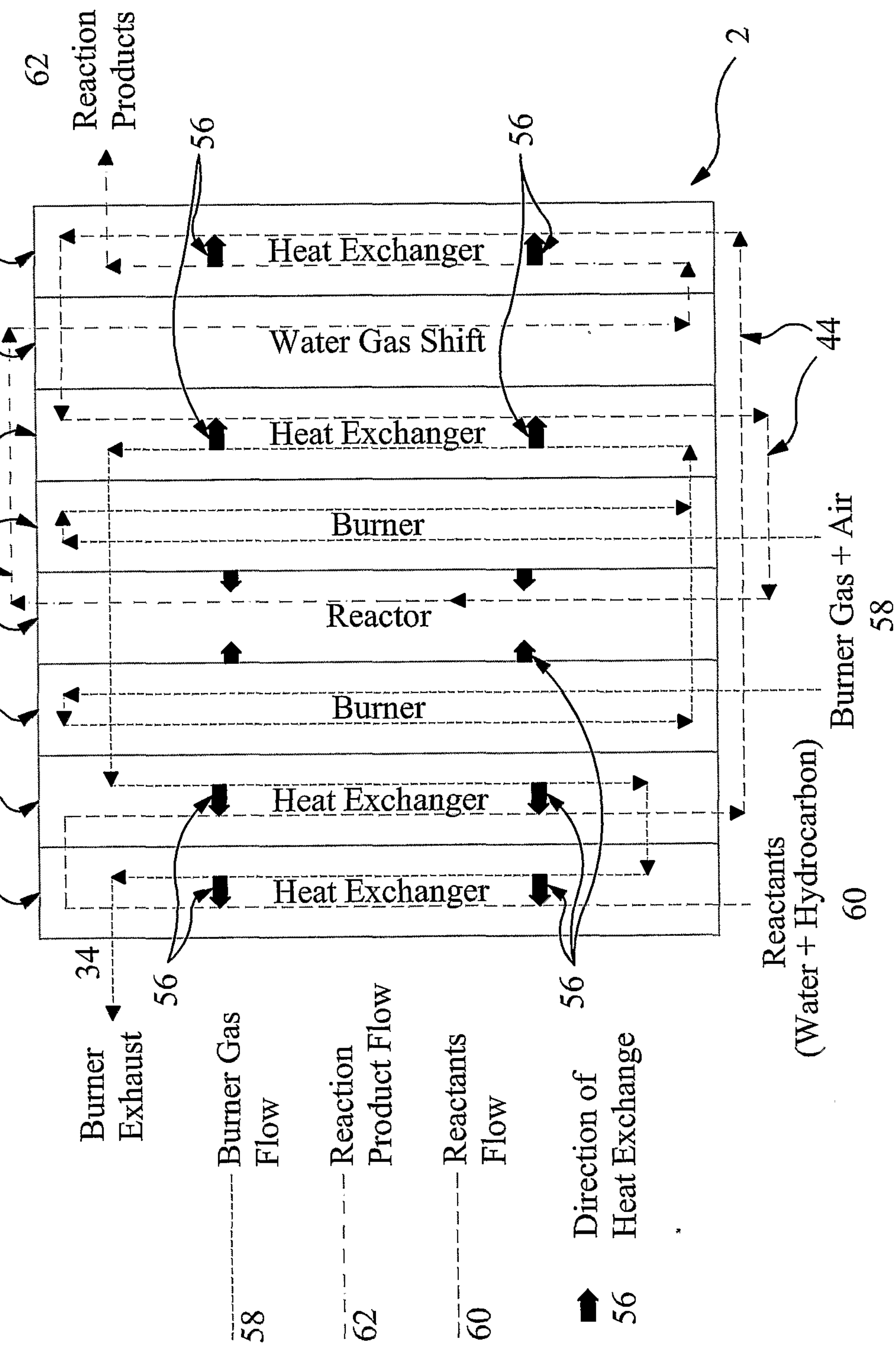
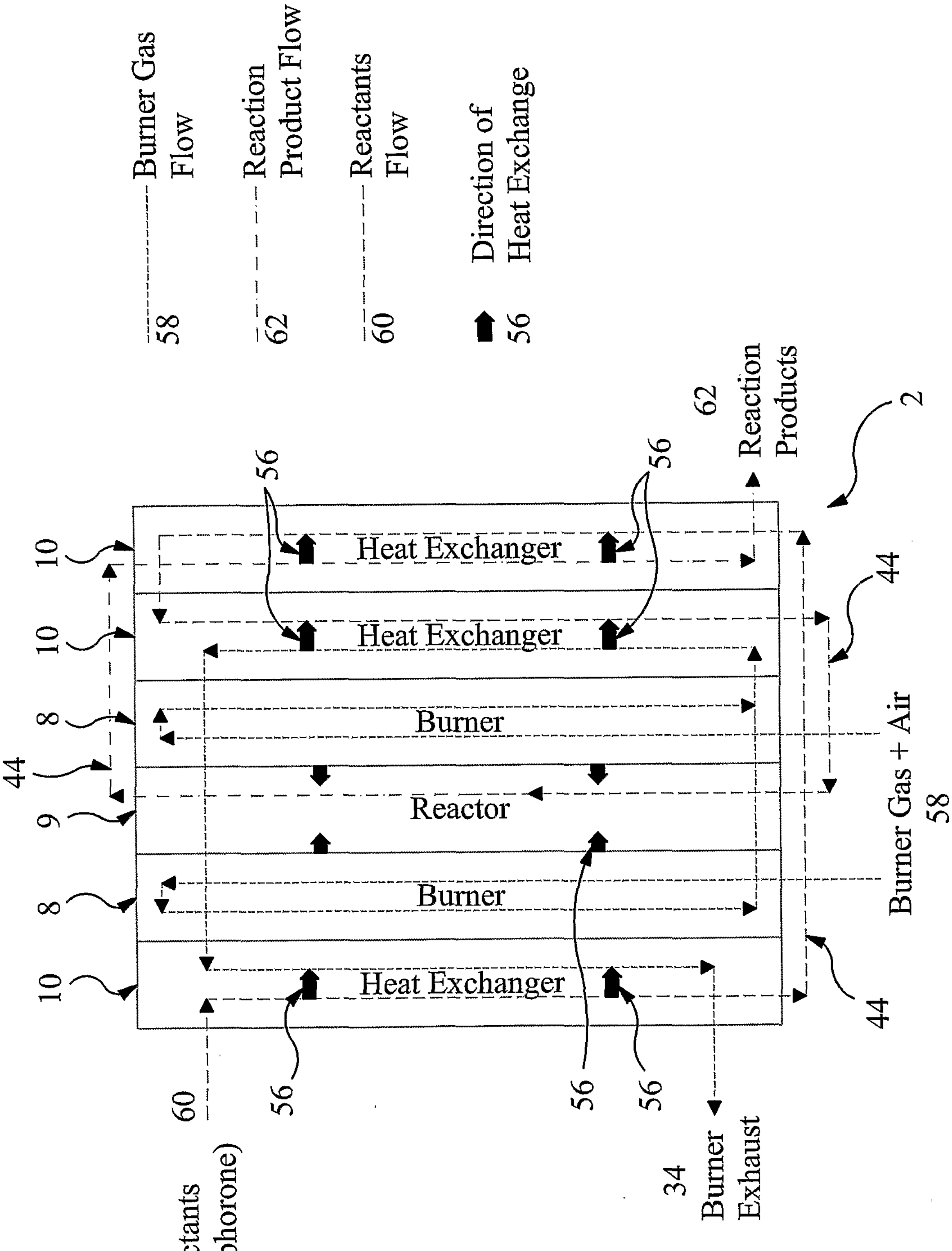

Heat Exchanger
Water Gas Shift
Heat Exchanger
Burner
Reactor
Burner
Heat Exchanger
Heat Exchanger
62
Reaction Products
2
56
56
10
52
10
8
44
9
8
10
10
44
Burner Gas + Air
58
Reactants
(Water + Hydrocarbon)
60
34
56
56
Burner Exhaust
Burner Gas Flow
Reaction Product Flow
Reactants Flow
Direction of Heat Exchange
58
62
60
56

FIG 11



58 Burner Gas Flow
62 Reaction Product Flow
60 Reactants Flow
56 Direction of Heat Exchange
Heat Exchanger
Heat Exchanger
Burner
Reactor
Burner
Heat Exchanger
10
10
8
44
9
8
10
56
56
56
56
56
62 Reaction Products
2
44
Burner Gas + Air
58
44
60
Reactants (Isophorone)
34 Burner Exhaust

FIG 12

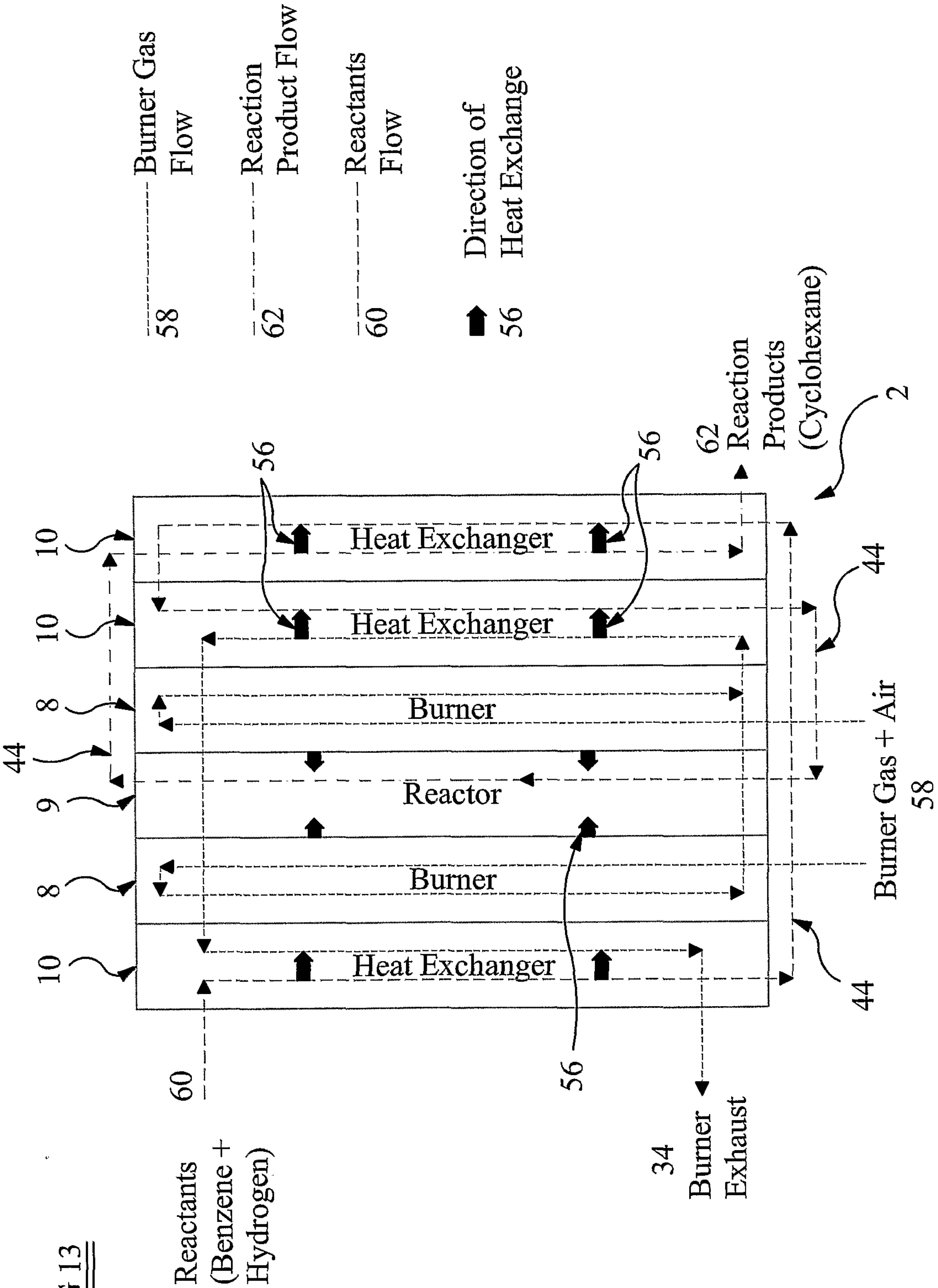

58 Burner Gas Flow
62 Reaction Product Flow
60 Reactants Flow
56 Direction of Heat Exchange
Heat Exchanger
Heat Exchanger
Burner
Reactor
Burner
Heat Exchanger
10
10
8
44
9
8
10
56
56
56
62 Reaction Products (Cyclohexane)
2
44
Burner Gas + Air
58
44
60
Reactants (Benzene + Hydrogen)
34 Burner Exhaust

FIG 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2006/000584

A. CLASSIFICATION OF SUBJECT MATTER
INV. B01J19/24 B01J8/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/002832 A1 (MARX RYAN E ET AL) 6 January 2005 (2005-01-06) paragraphs [0009], [0023], [0024]; figures 1,2	1,2, 4-10,43, 48,54
X	WO 01/36088 A (BASF CORPORATION; BARKEL, BARRY, M; HINZ, WERNER) 25 May 2001 (2001-05-25) page 3, line 35 - page 5, line 26; figures 1A,1B,6,7	1,2, 4-10,15, 43,48
X	US 5 829 517 A (SCHMID ET AL) 3 November 1998 (1998-11-03) column 4, lines 21-60; figures 1,7,8 column 5, lines 7-12 column 6, lines 50-55	1-5,24, 29,48

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 April 2006	08/05/2006

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Veronesi, S

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2006/000584

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2001/045061 A1 (EDLUND DAVID J ET AL) 29 November 2001 (2001-11-29) paragraphs [0047], [0048]; figures 7,8	1,2,4,5, 7

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No
PCT/GB2006/000584

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 2005002832	A1	06-01-2005	EP	1644110 A1	12-04-2006
			US	2004265188 A1	30-12-2004
			WO	2005005036 A1	20-01-2005
WO 0136088	A	25-05-2001	AU	6279700 A	30-05-2001
US 5829517	A	03-11-1998	DE	19617396 A1	06-11-1997
			EP	0805328 A2	05-11-1997
US 2001045061	A1	29-11-2001	AU	4558001 A	24-09-2001
			EP	1265697 A2	18-12-2002
			JP	2003527279 T	16-09-2003
			WO	0168514 A2	20-09-2001