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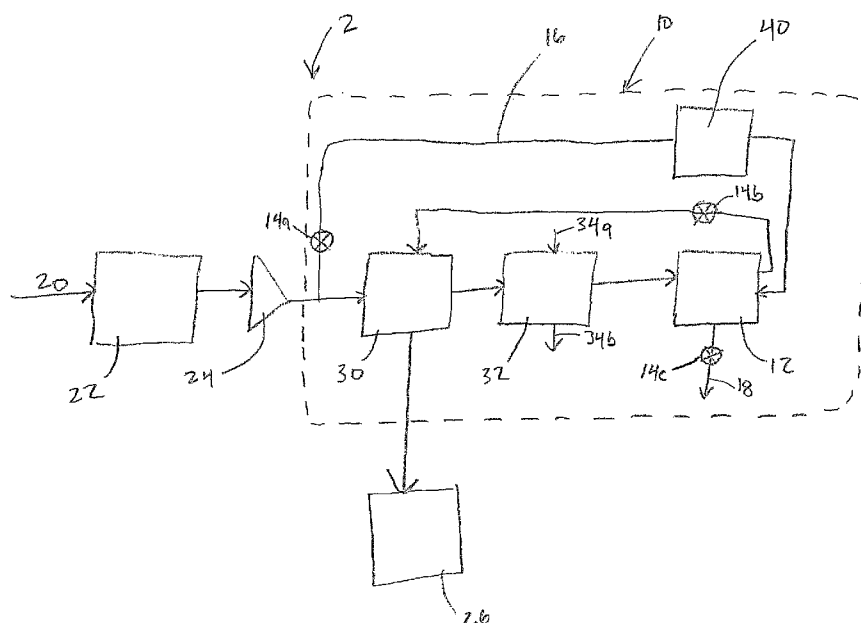
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(54) **Title:** REGENERABLE AIR PURIFICATION SYSTEM



(57) **Abstract:** An air purification system for removing chemical contaminants from an air stream. The air purification system includes an adsorbent filtration material that is regenerable by the application of increased temperature air. In one embodiment, the adsorbent filter is a packed bed that is regenerated by the use of a heater. In another embodiment, the adsorbent filter is a rotating wheel having an adsorption segment where contaminants are removed from an air stream. The wheel also includes a cooling segment and a regeneration segment. Air is passed over the cooling segment to preheat regeneration air and to reduce the temperature of the filter wheel. Regeneration air is further heated by a heater and then passed through the regeneration segment to regenerate the filter.

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REGENERABLE AIR PURIFICATION SYSTEM

Related Applications

This application is being filed as a PCT international application in the name of Donaldson Company, Inc., a U.S. corporation (applicant for all countries except the U.S.), and in the names of Donald H. White et al., on August 8, 2006, designating all countries. This application claims priority to U.S. provisional application 60/706,611, filed August 8, 2005.

Field of the Invention

The invention relates to air purification systems. More particularly, the invention relates to regenerable air purification systems.

Background of the Invention

A flow of high purity air is required in certain settings. High purity air is air that has had contaminants removed, including chemicals such as hydrocarbons, other organic materials, and acidic and basic gases. For example, a large volume of high purity air is required in the operation of fuel cells, with dilution tunnel air systems for emissions testing, and in semiconductor manufacturing. Many other applications also require a large volume of high purity air.

One such application where a large volume of high purity air is required is for use with fuel cells. Fuel cells are electrochemical devices that efficiently convert a fuel's chemical energy directly to electrical energy, which may be used to power electrical devices. For example, fuel cells can be used to power residential or commercial applications, mobile electronics, or vehicles having electrical propulsion systems. As compared with conventional combustion-powered devices, fuel cells are relatively clean and efficient. Fuel cells directly combine a fuel and an oxidant without burning, thereby eliminating certain inefficiencies and sources of pollution.

A fuel cell operates much like a battery. However, unlike a battery, a fuel cell does not run down or require recharging. It will continue to produce energy in the form of electricity and heat as long as fuel is supplied to it. In general, a fuel cell consists of two electrodes (an anode and a cathode) sandwiched around an electrolyte. Hydrogen and oxygen are passed over the anode and cathode electrodes respectively in a manner that generates a voltage between the electrodes, creating electricity and heat, and producing water as the primary by-product.

The hydrogen fuel is supplied to the anode of the fuel cell. Some fuel cells consume hydrogen directly, while others use a fuel reformer to extract the hydrogen from, for example, a hydrocarbon fuel such as natural gas, methanol, ethanol, or gasoline. The fuel cell uses a catalyst to cause the hydrogen atom to split into a proton and an electron, each of which takes a different path to the cathode. The protons pass through the electrolyte. The electrons create a useful electric current that can be used as an energy source, before returning to the anode where they are reunited with the hydrogen protons and the oxygen to form water. The oxygen can be supplied to the cathode in purified form or can come directly from atmospheric air.

However, atmospheric air generally contains contaminants. These contaminants include small particulates suspended in the atmosphere such as dust, pollen, or smoke particulates. Chemical contaminants are also widely present in atmospheric air, whether as a result of man-made pollution or as those which naturally occur. Typical chemical contaminants might include volatile organic compounds such as aromatic hydrocarbons, methane, butane, propane and other hydrocarbons as well as ammonia, oxides of nitrogen, ozone, smog, oxides of sulfur, carbon monoxide, hydrogen sulfide, etc.

It is now generally understood that the air provided to the stack of a fuel cell should be fairly pure to maintain high power conversion rates and to prevent corrosion and premature failure of the fuel cell stack. Accordingly, filters for fuel cells are generally known. See, for example, U.S. Patents 6,780,534; 6,783,881; 6,797,027; and U.S. Published Application 2003/0064271. Such filters may include a particulate filter to remove particles and a chemical filter having an adsorbent to remove chemical contaminants from the inlet air. However, because the chemical contamination level of the inlet air is generally sufficiently high, and the tolerance of the fuel cell to chemical contamination sufficiently low, the chemical filter life may be limited to a short duration. The chemical filter life can be increased by increasing the filter size, and consequently the filter's adsorption capacity, however, this increases the cost of the filter and may not be practical within size constraints. For example, a filter constructed from a size practical for use with a fuel cell powered vehicle may have a filter life of only 600 hours at an average flow operating condition. Such a filter would have to be replaced regularly during the life of the vehicle. To design a filter with a longer life would require that the filter be impractically large to remove all of the insult gases.

Although the power-generating chemical reactions in a fuel cell are silent, the operation

of the air compressor may generate unpleasant noise. Therefore, the filtration system may also desirably be configured to minimize the sound transmission from the air compressor.

However, improved filtration systems for fuel cells are needed. In particular, a filtration system that is capable of functioning for an extended period of time, such as five years, is desired.

Another application that requires a large volume of high purity air is for use with dilution tunnels used in emissions testing, such as emissions testing of vehicle engines. During emissions testing of internal combustion engines, such as automobile engines, a stream of highly clean dilution air is required. A typical emissions testing facility includes an engine for generating exhaust containing emissions, a dilution tunnel, and an emissions sampling apparatus. In the dilution tunnel, the engine exhaust is combined with a quantity of clean air in order to simulate the dilution process that occurs in the atmosphere. Namely, exhaust gas is typically oxygen deficient, the result of the oxygen within the ambient air being consumed in the combustion of fuel within the engine. The exhaust gas from an engine may include certain species that will not oxidize in this oxygen deficient environment, but will oxidize upon introduction to the ambient environment and its relatively greater concentration of oxygen. Therefore, accurate emissions testing often requires a chamber, also called a dilution tunnel, in which a measured quantity of clean air is mixed with the exhaust gases. This clean air is also called dilution air.

However, the purpose of emissions testing is to accurately measure the emissions produced by the engine. Contaminants that exist in the ambient atmosphere could negatively influence the emissions testing results if drawn uncontrolled into the dilution air. These contaminants could be measured by the emissions sampling apparatus and presumed to have been produced by the engine. These contaminants could also chemically combine with the exhaust gas to create new emissions species. In either case, the emissions testing accuracy would be degraded. Moreover, the repeatability of the emissions testing would suffer and the comparability of emissions testing results from one location to another would change as a result of changing ambient concentrations of contaminants. Therefore, it is important that the dilution air be as free from contaminants as possible.

Contaminants of particular concern include acid gases such as sulfur dioxide, hydrogen chloride, hydrogen sulfide, nitric oxides, and carbon dioxide; hydrocarbon vapors; ammonia and amines; volatile organic contaminations; and other contaminant gases.

One known method for cleaning a dilution air supply is to install a nonregenerable sorbent filter. Such a filter typically contains a sorbent that removes harmful contaminants from the dilution air supply. In operation, the sorbent filter tends to lose its effectiveness as the captured mass of contaminants within the filter increases. At some point, after capturing a certain mass of contaminants, this mass being a function of the size of the filter, the filter must be removed and replaced with a new filter in order to ensure suitable contaminant removal effectiveness. The contamination level of the incoming air may be sufficiently high, and the contamination removal effectiveness requirements also sufficiently high, that the filter life is often limited to a short duration. This replacement process can be inconvenient and time-consuming, requires that a supply of replacement filters be maintained, and can be expensive. Alternatively, the sorbent filter could be made larger in order to increase the lifetime of the filter; however, the filter may have to be impractically large to meet the filtration requirements. Therefore, improved air purification systems are needed for use with dilution tunnels. More particularly, air purification systems are needed that are capable of operating for an extended period of time without requiring replacement.

Another application where a large volume of cleaned air is required is in semiconductor manufacturing. The process of manufacturing semiconductors is very sensitive to the presence of gaseous contaminants, such that the presence of even small quantities of contaminants can cause defects in the products. Therefore, semiconductor manufacturing must occur in a clean room where contaminants are tightly controlled. For the same reasons discussed above, improved air purification systems are needed for use with clean rooms, particularly systems that are capable of operating for an extended period of time without requiring replacement.

Summary of the Invention

In one embodiment, the invention relates to an air purification system for use with a fuel cell system. The fuel cell system has an air compressor for generating a flow of inlet air and a fuel cell stack for receiving a flow of inlet air at a fuel cell stack inlet. The filtration system includes a particulate filter located upstream of the fuel cell stack within the inlet air flow and an adsorbent filter located upstream of the fuel cell stack within the inlet air flow, where the adsorbent filter has a media bed of adsorbent filtration material. The adsorbent filter also has an inlet end and an outlet end in fluid communication with the fuel cell stack inlet. The air

purification system also includes a venting passage fluidly connecting the adsorbent filter to the atmosphere and a heater in fluid communication with the adsorbent filter. There are a plurality of valves, and at least one valve is selectively closable to define a first operating mode while the fuel cell is generating power in which inlet air flows through the particulate filter and adsorbent filter and into the fuel cell stack. There is also at least one valve that is selectively closable to define a second operating mode in which air flows through the particulate filter, heater, and the adsorbent filter and out the adsorbent filter atmospheric vent to regenerate the adsorbent filter.

Another embodiment of the invention relates to a method of filtering air for a fuel cell system, where the fuel cell system has an air compressor for generating a flow of inlet air at an air compressor discharge and a fuel cell stack for receiving a flow of inlet air at a fuel cell stack inlet. The method includes the steps of providing a particulate filter within the inlet air flow for removing particulate contamination and providing a chemical filtration system within the inlet air flow for removing chemical contamination. The chemical filtration system includes an adsorbent filter having a media bed of adsorbent filtration material, where the adsorbent filter is characterized by an inlet end fluidly connected through a passage to the air compressor discharge and an outlet end fluidly connected through a passage to the fuel cell stack inlet. The chemical filtration system also has a venting passage fluidly connecting the adsorbent filter to the atmosphere, a regeneration flow passage fluidly connecting the air compressor discharge to the adsorbent filter outlet end, and a plurality of selectively closable valves, where at least one valve is in the regeneration flow passage, one valve is in the passage between the adsorbent filter outlet and the fuel cell stack, and one valve is within the adsorbent filter venting passage. The selectively closable valves are actuated while the fuel cell is generating power to define a first operating mode in which inlet air flows through the particulate filter and adsorbent filter and into the fuel cell stack. The selectively closable valves are actuated while the fuel cell is not generating power to define a second operating mode in which inlet air flows through the particulate filter and the adsorbent filter and out the adsorbent filter atmospheric vent to regenerate the adsorbent filter.

A further embodiment of the invention includes an air purification system for removing chemical contaminants from an air stream. The air purification system includes a rotating wheel adsorbent filter constructed with adsorbent media and positioned within the air stream. The rotating wheel defines an inlet surface and an outlet surface. The system also includes a non-

rotating inlet structure in proximity to the inlet surface of the rotating wheel that is configured to define an adsorption segment, a cooling segment, and a regeneration segment of the rotating wheel and to direct a first portion of the air stream through the adsorption segment and to direct a second portion of the air stream through the cooling segment. A non-rotating outlet structure is provided in proximity to the outlet surface of the rotating wheel and is configured to correspond to the adsorption, cooling, and regeneration segments of the rotating wheel defined by the inlet structure. The outlet structure is also configured to direct the air stream exiting from the cooling segment of the outlet surface of the rotating wheel through a first fluid conduit. A heater is located in fluid communication with the first fluid conduit and in fluid communication with a second fluid conduit. The outlet structure is further configured to direct air received from the second fluid conduit into the regeneration segment of the outlet surface of the rotating wheel and the inlet structure is further configured to direct air exiting from the inlet surface of the regeneration segment of the rotating wheel through a third fluid conduit. There is a blower in fluid communication with the third fluid conduit for drawing regeneration air through the cooling segment, first fluid conduit, heater, second fluid conduit, regeneration segment, and third fluid conduit. An atmospheric vent is provided in fluid communication with the blower for discharging the regeneration air.

Yet another embodiment of the invention relates to a method of purifying air. The method includes the step of providing an adsorbent filter configured as a rotating wheel and partitioning the rotating wheel into a plurality of non-rotating segments, the segments comprising at least an adsorption segment, a cooling segment, and a regeneration segment. A service air stream is passed through the adsorption segment of the adsorbent filter to remove contaminants from the air stream to generate a cleaned air stream, and the cleaned air stream is directed to service an application. A regeneration air stream is passed first through the cooling segment of the adsorbent filter to absorb heat from the rotating wheel and to increase the temperature of the second air stream, then is passed through a heater to further increase the temperature, and then is passed through the regeneration segment of the adsorbent filter to desorb contaminants contained within the regeneration segment of the filter. The regeneration air stream is lastly directed the away from the adsorbent filter.

The invention may be more completely understood by considering the detailed description of various embodiments of the invention that follows in connection with the

accompanying drawings.

Brief Description of the Drawings

Figure 1 is a schematic diagram of a regenerable filter system according to the present disclosure having a packed bed adsorbent filter.

Figure 2 is a schematic diagram of an alternative embodiment of a regenerable filter having a packed bed adsorbent filter.

Figure 3 is a schematic diagram of another alternative embodiment of a regenerable filter having a packed bed adsorbent filter.

Figure 4 is a schematic diagram of an alternative embodiment of the regenerable filter of Figure 3.

Figure 5 is a schematic diagram of an alternative embodiment of the regenerable filter of Figure 4 having multiple filter beds.

Figure 6 is a cross sectional view of an embodiment of a regenerable filter system according to the present disclosure.

Figure 7 is a schematic diagram of a regenerable air purification system that includes a rotating wheel adsorbent filter.

Figure 8 is a perspective view of a rotating wheel adsorbent filter

Figure 9 is a conceptual drawing of the system of Figure 5 indicating locations for pressure losses within the system.

Figure 10 is an illustration of velocity vectors for the air flow through the system of Figure 5 as predicted by computer modeling.

Figure 11 is an illustration of pressure losses for the air flow through the system of Figure 5 as predicted by computer modeling.

Figure 12 is an illustration of acoustic pressures within the system of Figure 5 as predicted by computerized acoustical finite element analysis at 800 Hz.

Figure 13 is a graph showing the sound attenuation by the intake air adsorbent filter of Figure 5 as predicted by computerized acoustical finite element analysis.

While the invention may be modified in many ways, specifics have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the

contrary, the intention is to cover all modifications, equivalents, and alternatives following within the scope and spirit of the invention as defined by the claims.

Detailed Description

The present disclosure relates to a regenerable air purification system. The system includes a regenerable adsorbent filter that is constructed to remove chemical contaminants from an air stream. In use, the adsorbent filter has a maximum capacity of contaminants that it is capable of removing based on its size, composition, and operating conditions. The air purification system is constructed to regenerate the adsorbent filter before its maximum capacity is reached in order to provide long service life and high contaminant removal effectiveness. The adsorbent filter is regenerated by increasing its temperature to free the captured contaminants, where the contaminants can then be entrained within an air flow and exhausted from the filter.

Generally, the present disclosure includes a chemical adsorbent filter that removes chemical contaminants from air. The adsorbent filter functions primarily through physi-sorption, or adsorption through physical forces (as opposed to chemical reactions, and low temperature catalysis). Physi-sorption, however, is a reversible process, so that collected contaminant can be removed, or desorbed, from the filter to regenerate the filter. Generally, it has been found that the adsorbent filter has an equilibrium capacity that determines the filter's contaminant removal capacity. For example, as pressure inside the adsorbent filter is increased or the temperature is decreased or the inlet contamination concentration is increased, the equilibrium capacity of the filter is increased, such that the filter is capable of adsorbing a greater quantity of contaminants. Conversely, if the pressure is decreased or the temperature is increased or the inlet contaminant concentration is decreased, the adsorbent filter equilibrium capacity is decreased. These relationships are shown below:

Temperature ↑, Equilibrium Capacity ↓

Temperature ↓, Equilibrium Capacity ↑

Pressure ↑, Equilibrium Capacity ↑

Pressure ↓, Equilibrium Capacity ↓

Inlet Concentration ↑, Equilibrium Capacity ↑

Inlet Concentration ↓, Equilibrium Capacity ↓

The adsorbent filter can be designed to take advantage of these relationships so as to

increase the amount of contaminants that the filter can remove during normal operation, as well as to selectively reduce the adsorbent capacity of the filter to cause captured contaminants to be desorbed from the filter, thereby allowing the filter to be regenerated for further use before it reaches its capacity. For example, the adsorbent filter can be designed so that under normal operating conditions, when the filter is being used to remove contaminants from an air stream, the pressure can be elevated and/or the temperature can be held to a minimum value in order to increase the equilibrium capacity of the filter. Note that the inlet contaminant concentration is a function of the environmental conditions, which for practical purposes are not changeable. By increasing the equilibrium capacity of the filter, the contaminant removal ability and filter lifetime are both increased. However, the filter can also be operated at standard pressures and/or temperatures if required by the application.

As discussed above, however, the adsorbent filter is only capable of adsorbing so many contaminants before it reaches a point where it will no longer remove contaminants sufficiently. At this point or before, it is desired that the filter be regenerated, or cleaned, to allow further use. Under these conditions, either the pressure of gas supplied to the filter can be reduced to a minimum value or the temperature of the filter can be elevated in order to reduce the equilibrium capacity of the filter, or both the pressure can be reduced and the temperature can be increased. Reducing the equilibrium capacity of the filter causes the captured contaminants to be desorbed from the filter and released into the gas stream within the filter. This gas stream can then be vented to the atmosphere to remove the contaminants from the filter so that it is regenerated for further use.

Adsorbent materials are chosen for use as filter media based on their capacity for capturing detrimental ambient contaminants; the primary contaminants of interest include hydrocarbons, acid gases and other organics. Gases are adsorbed within the adsorbent filter according to their boiling point. Higher boiling point gases such as heavy hydrocarbons are adsorbed preferentially, and will displace other lower boiling point compounds such as light hydrocarbons within the adsorbent bed. Because water vapor is present in ambient air in higher quantities than other contaminants, and has a high heat of adsorption, much of the energy consumed during the regeneration phase is used to desorb water, even though its presence is not generally harmful to the performance of downstream components such as a fuel cell. Furthermore, the high heat of adsorption of water vapor can cause a large temperature rise in the

adsorbent media when water is adsorbed. This temperature rise can cause physical damage to the filter if not controlled. To minimize the penalties associated with collecting water vapor, an adsorbent should be chosen that has the lowest possible capacity for water vapor (preferably less than about 4.5%, or more preferably less than 2%).

The adsorbent filter can be constructed from any of a number of sorbent materials, including silica gel, molecular sieve or activated alumina. Preferably, the sorbent is silicalite or aerogel that is hydrophobic. For acid gas removal, the sorbent can be a carbonate or a hydroxide (sodium hydroxide, calcium hydroxide, lithium hydroxide or potassium hydroxide).

There are many usable embodiments of the adsorbent filter. One usable embodiment comprises a packed bed, while another usable embodiment comprises a plurality of packed beds. In another usable embodiment the adsorbent filter comprises a rotating wheel or drum. These embodiments will be discussed in detail.

Packed Bed Embodiments

In one embodiment, the chemical adsorbent filter consists of a packed bed of adsorbent material, typically in cylindrical form. The packed bed typically comprises a housing containing a granular adsorbent media. Both the inner and outer diameters of the cylinder are lined with a fine wire mesh designed to filter out any mechanically generated particles from adsorbent bed attrition (2-10 μm). In a separate embodiment, the chemical adsorbent filter comprises a plurality of packed beds; however, in this embodiment each bed is constructed according to the same principles of a single bed filter.

The size of the adsorbent filter is based on the required adsorbent capacity and the desired pressure drop. A larger filter will tend to have greater adsorbent capacity and lower pressure drop. However, a filter that is larger than necessary increases costs and increases the space that must be devoted to the filter. It is desirable to size the adsorbent bed as small as possible without excessive pressure drop. Another very important reason for keeping the bed as small as possible is to minimize the energy necessary for desorption of contaminant vapors. This amount of energy is directly related to the mass of adsorbent in the filter, where more adsorbent mass will use a proportionally larger heat input.

Referring now to Figure 1, a regenerable air purification system constructed according to the principles of the present disclosure and having a packed bed adsorbent filter is shown. This system is particularly suited for use with a fuel cell. The application to a fuel cell creates some

additional considerations. For example, where the regenerable air purification system provides air to a fuel cell, it is desired that the air entering the fuel cell be both at relatively high temperature and pressure because this enhances the performance and operation of the fuel cell. Thus, in the fuel cell embodiment, there are two temperatures within the system that must be maintained in order to ensure proper operation. The first temperature is at the inlet of the adsorbent filter, which, as discussed above, is desirably kept low to increase the equilibrium capacity of the filter. As this temperature rises, the capacity of the adsorbent bed will decrease. In fact, if this temperature rises to a sufficient level, it is possible that the adsorbent bed will begin to desorb contaminant, in which case, the air exiting the filter will contain more contaminant than the inlet air. The second temperature to be maintained is the fuel cell stack inlet temperature, which would ideally be maintained at 80°C or higher.

The fuel cell system ordinarily includes an air compressor to increase the pressure and flow rate of the inlet air. When air is compressed adiabatically, however, its temperature increases in a manner that, while desirable for the fuel cell stack inlet, is not desirable for the adsorbent filter if the filter is located downstream of the air compressor. For example, the discharge temperature from the air compressor, elevated from ambient by the heat of compression, is typically about 107°C to 150°C (about 226°F to 300°F).

Figure 1 is a schematic of one embodiment of the invention for use with a fuel cell. A fuel cell 2 includes an inlet gas stream 20, a particulate filter 22, an air compressor 24, a chemical filtration system 10, and a fuel cell stack 26. Chemical filtration system 10 includes an adsorbent filter 12 that removes chemicals from the inlet gas stream 20 and a plurality of valves 14 to control the flow of air during a regeneration mode. System 10 further includes a heat exchanger or plurality of heat exchangers, shown in Figure 1 as first heat exchanger 30 and second heat exchanger 32.

Also included is heater 40 within regeneration line 16 between compressor 24 and filter 12. Heater 40 is configured to heat the regeneration air entering filter 12 during regeneration mode to increase the temperature and thereby promote regeneration of the filter. Heater 40 is shown schematically in Figure 1 as being separate from filter 12. However, the actual construction of heater 40 may be located immediately adjacent to, or even within, filter 12. Locating heater 40 as close as possible, or within, filter 12, reduces heat losses between heater 40 and filter 12, and thereby lowers the required energy consumption of heater 40. Heater 40 can be

constructed according to the principles known to those of skill in the art for heating an air stream. For example, heater 40 can be an electrical heater, or heater 40 can be a combustion-powered heater (where the combustion by-products are kept separate from the regeneration air stream), or heater 40 can be a heat exchanger that utilizes a separate source of heat energy to heat the air stream.

In a normal operating mode, valves 14a and 14c are closed, and valve 14b is open. Inlet air 20 flows through particulate filter 22, then to air compressor 24 where its pressure and temperature are increased. The heated, compressed air then flows to first heat exchanger 30 and then second heat exchanger 32, where heat is removed from the inlet air. First heat exchanger 30 is typically a shell and tube type that cools the inlet air by way of cross flow air exiting the filter 12. Second heat exchanger 32 is typically a plate type that uses an inlet stream 34a of water, preferably at about 30°C, to cool the inlet air. The inlet air next enters adsorbent filter 12, where chemical contaminants are removed. Because the air entering adsorbent filter 12 is at relatively high pressure and relatively low temperature, the equilibrium capacity of the filter is relatively high. Cleaned air exits adsorbent filter 12 and travels to first heat exchanger 30, where its temperature is increased, and then enters fuel cell stack 26.

In the regeneration mode, valves 14a and 14c are open and valve 14b is closed. The direction of gas flow through the adsorbent filter 12 is then reversed to clean the filter. Inlet gas flow 20 continues to flow through particulate filter 22 and air compressor 24. However, instead of flowing through heat exchangers 30 and 32 and then to adsorbent filter 12, gas flow 20 is directed through passageway 16 and heater 40 to what is normally the discharge end of adsorbent filter 12. Gas flow 20 passes through adsorbent filter 12 in a reverse direction as compared to normal. Preferably, the reverse gas flow, also called regeneration air, is at elevated temperature with respect to atmospheric air. As the regeneration air flows through the adsorbent filter 12 in a reverse direction, contaminants are desorbed from the adsorbent filter 12 into the regeneration air. The regeneration air then passes out through vent 18 into the atmosphere.

The duration of the regeneration mode depends on various parameters including the size of the adsorbent filter bed and the temperature rise of regeneration air across the heater 40. Preferably, the system is constructed so that the regeneration mode lasts for about 10 minutes so as to minimize the disruption of the operation of the fuel cell. However, the duration could be more or less depending on the system design and operating conditions. The regeneration mode

typically is initiated once every 24 hours, although it could be more or less depending on the system design and operating conditions.

The regeneration mode occurs only if the fuel cell is shut down. In certain applications the fuel cell cannot readily be shut down to allow for regeneration. In these applications, it is desirable to have a plurality of filter beds so that while one filter bed is being regenerated, the other filter bed is available to clean the air provided to the fuel cell stack. An embodiment of such a system is shown in Figure 2. This embodiment is similar to the embodiment of Figure 1, however, filter 12 instead comprises first filter 12a and second filter 12b. The embodiment of Figure 2 further includes additional valves to selectively direct air flow through filters 12a, 12b. Valve 14d₁ selectively controls the inlet flow of air to filter 12a and valve 14d₂ selectively controls the inlet flow of air to filter 12b. Valve 14b₁ controls the flow of air from filter 12a to heat exchanger 30 and valve 14b₂ controls the flow of air from filter 12b to heat exchanger 30. Furthermore, valve 14a₁ controls the flow of air from heater 40 to filter 12a and valve 14a₂ controls the flow of air from heater to filter 12b. Valve 14c₁ controls the flow of air from filter 12a to atmospheric vent 18a and valve 14c₂ controls the flow of air from filter 12b to atmospheric vent 18b.

To utilize filter 12a to supply air to fuel cell stack 16, valve 14d₁ and valve 14b₁ are open, and valves 14a₁ and 14c₁ are closed. Likewise, to utilize filter 12b to supply air to fuel cell stack 16, valve 14d₂ and valve 14b₂ are open, and valves 14a₂ and 14c₂ are closed. To initiate regeneration of filter 12a, valves 14d₁ and 14b₁ are closed and valves 14a₁ and 14c₁ are open. During regeneration, air flows through regeneration line 16 through an orifice 80 which reduces its pressure and flow rate. Regeneration air is then heated in heater 40, and in the case of regeneration of filter 12a, flows through open valve 14a₁, into filter 12a, through open valve 14c₁, and out to atmosphere through vent 18a. To initiate regeneration of filter 12b, valves 14d₂ and 14b₂ are closed and valves 14a₂ and 14c₂ are open and proceeds analogously to the regeneration of filter 12a. Filters 12a and 12b could both be used at the same time to provide clean air to fuel cell stack 26, and filters 12a and 12b could both be regenerated at the same time. However, it is preferable that one of filters 12a, 12b be regenerated while the other filter is used to provide clean air to fuel cell stack 26.

Yet another embodiment is depicted in Figure 3. In this embodiment, compressor 24 is located downstream of filter 12. Air 20 is drawn through particulate filter 22 and adsorbent filter

12; however, because this air is on the suction side of compressor 24 its temperature has not been increased by the heat of compression. Therefore, the temperature of air 20 within filters 22, 12 is near ambient, and no additional heat exchangers are needed to lower the temperature of the air entering adsorbent filter 12. Furthermore, because the outlet of compressor 24 is immediately upstream from fuel cell stack 26, the air 20 entering fuel cell stack 26 will be at an elevated temperature from the heat of compression and no additional heat exchangers are needed to increase the air temperature. However, in some cases it may actually be necessary to install a heat exchanger between compressor 24 and stack 26 to reduce peak temperatures that could damage stack 26. The disadvantage of having the filter 12 upstream of compressor 24 is, however, that the pressure of air 20 within filter 12 is equal to or less than ambient pressure, and this relatively low pressure reduces the equilibrium capacity of the filter. The filter size may need to be increased to account for the lower filter capacity.

The embodiment of Figure 3 also includes a heater 40 and an atmospheric vent 18, as well as valves 82, 84. During normal operation where air is being provided to the fuel cell stack, valve 82 is open and valve 84 is closed, and heater 40 is not energized. During regeneration, valve 82 is closed and valve 84 is open. Compressor 24 is energized during regeneration, but at a reduced power level to provide the relatively small air flow needed for regeneration. Heater 40 is energized during regeneration. Air 20 is drawn through heater 40, where its temperature is increased, then passed through filter 12 where it desorbs and entrains captured contaminants. Air 20 then passes through compressor 24, through open valve 84, and out atmospheric vent 18.

An alternative embodiment of the embodiment depicted in Figure 3 is depicted in Figure 4. This embodiment uses a separate fan 44 to push regeneration air through filter 12 during regeneration. Valves 50, 52, 54, 56 are provided to control the flow of regeneration air. During regeneration, valves 52, 56 are closed and valves 50, 54 are open, and fan 44 and heater 40 are energized. Regeneration air 46 flows through heater 40 where its temperature is increased, through filter 12 where it desorbs and entrains contaminants, and out through atmospheric vent 18.

The embodiment depicted in Figure 3 could also be constructed according to the dual bed principles discussed above. One such dual bed embodiment is shown in Figure 5. First and second filters 12a, 12b are provided to allow continuous operation, so that one filter can be taken off line for regeneration while the other filter is used for gas cleaning. In a first operating mode

both filters 12a, 12b are used for gas cleaning. In the first operating mode, air 20 passes through particulate filter 22. Valves 90, 92 are both open, and valves 14c₁ and 14c₂ are both closed, causing air 20 to flow into both filters 12a, 12b and then into heaters 40a, 40b. In the first operating mode, neither of heaters 40a, 40b is energized. Valves 94 and 96 are both open, and valves 98 and 99 are both closed, causing air to enter compressor 24 and travel into fuel cell stack 26.

A second operating mode exists where one filter is regenerated while the other filter is used for gas cleaning. For the sake of example, assume that filter 12a is to be regenerated. In this case, valve 98 is open, valve 94 is closed, valve 92 is closed, and valve 14c₁ is open; furthermore, valve 90 is open, valve 14c₂ is closed, valve 96 is open, and valve 99 is closed. Air 20 flows through filter 12b and related components in the same way as discussed above in reference to the first operating mode. However, because of the position of the various valves, some air flows through flow regulating device 97, through valve 98, and into heater 40a. Heater 40a is energized and heats the air. Air then flows into filter 12a, through valve 14c₁, and out through atmospheric vent 18a. In this way, filter 12a is regenerated while filter 12b continues to provide filtration. Filter 12b could be regenerated by similar principles. The components in this embodiment are constructed according to the principles associated with the other embodiments discussed herein.

It is worthwhile to note that the discharge of contaminants through vent 18 during regeneration, which would have been harmful to the operation of the fuel cell had they not been captured, is not considered harmful to the atmospheric environment or people nearby since they originally were in the atmosphere and are being returned to the atmosphere in relatively low concentrations.

The components of the fuel cell air filtration system 10 are preferably constructed in a compact, space-efficient orientation. This is particularly true where system 10 is to be installed in a confined environment, such as onboard a fuel cell powered vehicle. A cross sectional view of one embodiment of system 10 is shown in Figure 6. The heat exchangers 30, 32 and the adsorbent filter 12 may be packaged in a cylindrical or otherwise generally circular cross-sectional housing 42. A round housing offers more noise attenuation than a housing consisting of flat walls. This is particularly true with the pulsating flow associated with the use of a positive displacement screw compressor. Housing 42, along with the other components of the system, can

be thermally insulated to reduce heat losses from the shells and thereby reduce the quantity of air required to sustain the regeneration and the heat input required. The thermal insulation can be either thermally insulating material applied to the inside or outside of the filter 12 or housing 42, or can be a second isolation shell around one or more of the components. The space between components or shells can be air filled, or preferably a permanent vacuum can be contained.

Other components may be included within the air filtration system as needed without altering the principles of the invention. For example, certain systems may incorporate a mass air flow sensor or a humidifier. Now various aspects of the individual components will be described in greater detail.

1. Particulate Filter

Particulate filter 22 is preferably a PowerCoreTM particulate filter which includes Ultraweb® nanofiber media. Such a filter is commercially available from Donaldson Company, Inc, Minneapolis, Minnesota. However, other particulate filters may be used.

2. Compressor

Compressor 24 is typically a positive displacement screw compressor. However, other types of compressors may be used. The size of the compressor, as it relates to the flow rate and pressure rise of the compressor, is sized based on the needs of the fuel cell stack or other application and the pressure drop of the inlet air system. The design of a fuel cell stack is beyond the scope of this disclosure. Based on the pressure drop and flow rate requirements, the compressor can be selected or designed according to principles known to those of skill in the art.

3. Heat Exchangers

Heat exchangers 30, 32 are used to reduce the temperature of the air entering the adsorbent filter because the adsorbent filter can capture more contaminants at a lower temperature than at a higher temperature. However, the fuel cell stack operates preferably at a higher temperature, so the heat exchangers are also used to increase the temperature of the air discharged from the adsorbent filter before it enters the fuel cell stack.

The first heat exchanger 30 is typically an air-to-air heat exchanger. It is typically constructed in a conventional "shell and tube" configuration," where a series of tubes are sealed inside a shell to separate the two gas streams while providing a relatively large surface area for heat transfer to occur. However, other constructions are usable. This type of heat exchanger is desirable when the two flows (the flow exiting the compressor and the flow exiting the adsorbent

filter) have the same heat capacity because the two flows are exposed to nearly the same surface area.

The second heat exchanger 32 is typically an air-to-water heat exchanger. This heat exchanger is used to reject excess heat from the inlet air to further reduce the adsorbent filter inlet temperatures. It is typically constructed in a plate-type arrangement, however, other constructions are usable. Preferably, the second heat exchanger uses water at about 30°C to reduce the temperature of the inlet air to less than 50°C, preferably 40°C. The magnitude of the water supply flow rate can be controlled by a mechanical thermostat.

The heat exchangers must be sized to properly handle the required cooling loads. Generally, a fuel cell may be operated at a variety of conditions accounting for the desired power output. For example, a fuel cell powered car would be required to adapt to continuously changing loads based on terrain, traffic, driving style, etc. Thus, for design purposes there is both an average operating condition and a maximum operating condition that must be considered. For the purpose of sizing the heat exchangers, it is generally advantageous to use the maximum operating conditions so that the heat exchangers will be sized sufficiently for all operating conditions. If the sizing were based on the average operating condition, the heat exchangers would likely be undersized at the maximum operating condition.

In some instances, it is possible that the heat exchangers may reduce the temperature of the inlet air sufficiently to cause liquid water to condense. If this occurs, the addition of a demister and drain would be desired. Condensation may actually be beneficial because the presence of liquid water in contact with the inlet air would tend to absorb contaminant (particularly acid gases such as SO₂), and thereby help unburden the adsorbent filter.

4. Fuel Cell Stack

The fuel cell stack should be constructed according to the principles understood by those of skill in the art. The specifics of the design of the fuel cell stack are beyond the scope of this disclosure.

5. Valves

Valves are used to control the regeneration process. Valves may be constructed according to principles understood by those of skill in the art. For example, valves can be electrically or pneumatically actuated valves are used for the control of air flow. Valves may also be check valves, such as check ball valves or flap valves. These valves should be a low

pressure drop design that do not leak when subjected to the working pressure ranges. These valves should also be compact and require little activation energy. Valve controls may be electronic, pneumatic, or otherwise constructed according to knowledge available to those of skill in the art. Valves may also include a controller for controlling the opening and closing actuation of the valves.

Rotating Wheel Embodiments

As discussed above, in one embodiment the adsorbent filter comprises a rotating wheel. A schematic view of an embodiment of the regenerative air purification system including a rotating wheel is shown in Figure 7. Regenerative air purification system 120 comprises a plurality of filter segments 122, 124, and 126, where each of filter segments 122, 124, 126 are segments of a regenerative filter wheel 128. Filter segment 122 is an adsorption segment, filter segment 124 is a cooling segment, and filter segment 126 is a regeneration segment.

In operation, inlet air stream 130 is drawn into system 120 by way of a blower or fan 132 typically located downstream from system 120. A first portion 130a of inlet air stream 130 passes through adsorption segment 122 where contaminants are removed from the air stream by the filter media. A second portion 130b of inlet air stream 130 passes through cooling segment 124, which is at an elevated temperature. Air stream portion 130b absorbs heat from cooling segment 124, causing the temperature of air stream portion 130b to be increased and causing the temperature of cooling segment 124 to decrease. After passing through cooling segment 124, air stream portion 130b enters heater 134 where its temperature is further increased. Air stream portion 130b then passes through regeneration segment 126, generally in a direction opposite to the direction of flow through segments 122 and 124. A blower 136 is provided downstream of segment 126 to draw air stream portion 130b through segment 124, heater 134, and segment 126.

Because air stream portion 130b is at an elevated temperature as it passes through regeneration segment 126, air stream portion 130b heats segment 126, causing the equilibrium capacity of the filter media within segment 126 to be decreased and resulting in at least some of the contaminants captured within the filter media of segment 126 to be desorbed into air stream portion 130b. Air stream portion 130b containing desorbed contaminants is discharged to the atmosphere at discharge 138, effectively removing the captured contaminants from filter segment 126.

As stated above, segments 122, 124, and 126 are segments of a single wheel or drum and

are not separate components. Figure 8 shows an end view of rotating wheel 128. As shown in Figure 8, wheel 128 rotates clockwise; however, segments 122, 124, and 126 remain stationary. Wheel 128 rotates relatively slowly. For example, in one embodiment, wheel 128 rotates at the rate of approximately 1 revolution per hour. Each of segments 122, 124, and 126 are defined by stationary structures in proximity to, and preferably in contact with, rotating wheel 128.

Therefore, as wheel 128 rotates, a fixed point on wheel 128 will rotate through segment 122, then through segment 126, and then through segment 124 before again entering segment 122.

The rotation of wheel 128 causes effective heat transfer from one segment into another. For example, the high heat present in regeneration segment 126 is transferred to cooling segment 124 by way of effective heat transfer 40. This heat transfer 40 does not necessarily occur by conduction, convection, etc., but rather by the fact that the wheel is rotating, which causes a portion of the wheel that is in one segment to be moved into an adjacent segment. In this way, the high temperature present in regeneration segment 126 is transferred into cooling segment 124. Cooling segment 124 is advantageously utilized to recover some of the energy present in the regeneration segment 126 by transferring it to air 130b, helping to minimize the required energy consumption of heater 134 by preheating air 130b. Moreover, the cooling of the wheel within cooling segment 124 increases the equilibrium capacity of the wheel 128, allowing the wheel to adsorb a greater amount of contaminants in the adsorption segment 122.

Referring again to Figure 8, wheel 128 is contained within a housing 142 and has an inlet surface 144. Ductwork or other air handling components (not shown) attach to housing 142 and direct air toward inlet surface 144. Inlet surface 144 is divided into plurality of sectors 122, 124, 126 by way of structures 146, where structures 146 generally include a plurality of seals or wipers 148 that contacts inlet surface 144. Seals 148 prevent bypassing of the gas streams and separate the stationary partitions and the rotating wheel. A seal 150 is also present between the circumference of rotating wheel 128 and the housing 142. Seals 148, 150 are constructed from a sealant material that is heat resistant, smooth, has a low coefficient of resistance, and is non-abrading. For example, the seal material may be graphite or carbon, Teflon, or a polymer impregnated with Teflon such as Delron.

Wheel 128 further comprises an outlet surface 152, located on the opposite surface of wheel 128 from inlet surface 144. Outlet surface 152 is similar to inlet surface 144 and is also divided into plurality of sectors 122, 124, 126 by way of structures 154, where structures 154

generally include a plurality of seals or wipers 154 that contact outlet surface 152.

Ductwork or other gas conducting conduit is provided to connect wheel sectors 124, 126 to heater 134 and blower 136. Specifically, ductwork or other conduit is configured to attach to structures 154 to be in fluid communication with sector 124 on outlet surface 152. This ductwork is in fluid communication with heater 134. Additional ductwork or other conduit is configured to attach to an outlet of heater 134 and to structures 154 so as to be in fluid communication with sector 126 on outlet surface 152. Furthermore, ductwork is configured to attach to structures 146 so as to be in fluid communication with sector 126 on inlet surface 144. This ductwork is in fluid communication with blower 136.

In one embodiment, adsorption segment 122 comprises approximately 75 percent of the surface of inlet surface 144, regenerative segment 126 comprises approximately 12.5 percent of the wheel surface flow area, and cooling segment 124 comprises approximately 12.5 percent of the wheel surface flow area. In another embodiment, adsorption segment 122 comprises approximately 50 percent of the surface of inlet surface 144, regenerative segment 126 comprises approximately 25 percent of the surface of inlet surface 144, and cooling segment 124 comprises approximately 25 percent of the surface of inlet surface 144. In another embodiment, adsorption segment 122 comprises no less than 50 percent of the surface of inlet surface 144, regenerative segment 126 comprises no less than 25 percent of the surface of inlet surface 144, and cooling segment 124 comprises no less than 25 percent of the surface of inlet surface 144.

Wheel 122 can be constructed from a porous or honeycomb media. A honeycomb can be a corrugated substrate medium on which the sorbent is applied to form a low-pressure loss sorbent surface. The substrate can be a high temperature resistant material such as fiberglass, ceramic, Kynar, Nomox, Teflon, or a metal foil such as aluminum. Preferably, the substrate is constructed from aramid fiber, also known by the trade name Kevlar.

The heater 134 can be an electric immersion heater, a steam heater, or other heating source known in the art.

In one embodiment, a chemisorbent media filter is installed downstream of wheel 128. The chemisorbent media filter can contain hydroxides or polymeric amines for removing trace amounts of acid gases that are not removed in wheel 128. Separate media containing an acid impregnate such as citric acid is preferable for removing trace amounts of base contaminants such as ammonia. The chemisorbent provides low concentration level removal of contaminate

gases. The chemisorbent media can be provided inside a stationary filter housing downstream of the rotating wheel 128.

In another embodiment, a particulate filter is installed downstream of wheel 128 to prevent dirt intrusion into the testing apparatus. Most preferably, a high efficiency particulate air (HEPA) filter is provided in a frame assembly to remove aerosol contamination downstream of wheel 128.

System Design Considerations

Each component in the fuel cell filtration system must be designed to operate properly within the filtration system. One important consideration is the pressure drop through the system during operation. It is desired that the air flow pressure drop through the system be minimized. Larger pressure drops cause energy losses, reduced flow rates, and reduced performance compared to smaller pressure drops. Larger pressure drops also require a larger compressor or blower to deliver the same volume of air to the application, such as a fuel cell stack or dilution tunnel.

The sources of pressure loss within the system include valve losses, turning losses, expansion losses, contraction losses, and the flow resistance of the chemical filter. The pressure loss in a rotating wheel embodiment is primarily caused by the flow resistance of the wheel 128, which is a function of the porosity or channel size of the media and the surface area of primary flow sector 122. Generally, the pressure loss associated with a rotating wheel embodiment is very low if the wheel surface area is sufficient. The pressure loss associated with the packed bed embodiments will now be considered. Figure 9 illustrates the relevant sources of pressure loss within the embodiment of Figure 6.

The rated power or maximum flow condition is preferably used to calculate the pressure drop of the filter, as designing the system pressure drop around the average flow condition could result in very large pressure drops at maximum flow. The assumed conditions are given in Table 1 below for the sake of discussion.

Table 1. Assumed operating conditions

	Flow Condition	
	Time Weighted Average	Maximum Flow
Temperature (°C)	52	115
Pressure (kPa)	132	270
Inlet Flow (lpm)	820	3800
Mass Flow (kg/s)	0.016	0.075

The turning, expansion, contraction, and valve pressure losses are typically defined by a loss coefficient K_L . This is a unit-less number used to calculate the pressure loss based on the fluid density and velocity.

$$\Delta p = K_L \frac{1}{2} \rho V^2$$

where,

Δp = pressure drop (Pa)

ρ = fluid density (kg/m³)

K_L = Loss coefficient

V = Velocity (m/s)

The value of K_L for turning losses is based on the ratio of the tube diameter to the bend radius, along with the surface finish of the inside of the tube. For expansion and contraction losses, K_L is based on the area ratio before and after the expansion or contraction. The K_L values for expansions, contractions, and bends are typically less than one. For valves the K_L value can be looked up in a fluid mechanics text. For the sake of discussion, a valve coefficient of $K_L = 0.05$ is assumed.

The pressure drop of the chemical filter is a combination of the pressure drop of the adsorbent bed and the wire mesh. The adsorbent bed pressure drop is determined by the Sabri Ergun equation.

This results in the equation below:

$$\Delta p = L (E_1 \mu v_s + E_2 \rho v_s^2)$$

where,

L = bed length (m)

μ = Fluid viscosity (Pa-s)

E_1 = Ergun Constant ($1/m^2$)

E_2 = Ergun Constant ($1/m$)

v_s = superficial bed velocity (m/s)

In the first term, the pressure drop is proportional to the velocity, as in linear flow. In the second term, the pressure drop is proportional to the velocity squared, as in turbulent flow.

Table 2 shows all of the pressure drops in the hypothetical system based on the above considerations, and the total expected pressure drop at maximum flow (3800 L/min, 270 kPa, and 115°C).

Table 2. Pressure loss contributions

Loss Location	Loss Description	KL	Δp (kPa)
Inlet Perforated Tube	Bending Loss	1.00	0.13
	Expansion Loss	0.70	0.16
Heat Exchanger A	Heat Exchanger	-	0.20
Heat Exchanger B	Heat Exchanger	-	0.60
Chemical Filter	Bending Loss	1.00	0.25
	Chemical Filter	-	1.75
Transfer Tube Begin Perforation	Bending Loss	1.00	0.12
	Contraction Loss	0.50	0.10
Transfer Tube Bend	Bending Loss	0.75	0.09
Valve	Valve Loss	0.05	0.01
Transfer Tube End Perforation	Bending Loss	1.00	0.12
	Expansion Loss	0.80	0.16
Heat Exchanger A	Heat Exchanger	-	0.50
Outlet Transition	Contraction Loss	0.20	0.03
Total			4.20

The system pressure losses can also be modeled using Computational Fluid Dynamics (CFD). A CFD model can account for the specific geometries of the components and can pinpoint the pressure drops at each point in the system. The results of an example CFD analysis are presented in Figures 10 and 11. This analysis was performed both to confirm the pressure drop calculations shown in Table 2 and to illustrate the any problems with flow distribution that were not accounted for with hand calculations. Note that the secondary flow through first heat exchanger 30 was modeled as a separate heat exchanger. This made the CFD model simpler, as it was not necessary to model each surface within the heat exchanger 30. This was done to decrease the analysis time without jeopardizing the quality of the analysis.

Figure 10 shows the velocity vectors within the system, which illustrate the relative flow velocities through the system, and show the flow distribution through the filter. Note that the flow through the chemical filter element 12 is the lowest velocity in the system. This low velocity minimizes the pressure drop, and allows the formation of a developed mass transfer front that aids in chemical filtration.

Figure 11 shows the pressures within the filter system. As predicted in Table 2, the single largest contributor to the overall pressure drop is the chemical filter. The total pressure drop calculated by the CFD analysis is about 4.6 kPa rather than 4.2 kPa as estimated in Table 2. It is possible that this discrepancy in the pressure drop can be explained by some of the velocity vectors shown in Figure 10, which shows a (presumably) annular recirculation zone just after second heat exchanger 32. This transition zone between heat exchanger 32 and the annulus prior to the chemical filter is difficult to portray with hand calculations. Furthermore, it appears that the air is forced to take a sharp turn after exiting the chemical filter to pass by the perforated tube. This turning could be eliminated by changing the flow pattern from outside-in to inside-out. However, this flow configuration would lead to increased heat losses during regeneration due to the heated air passing by the outer wall of the assembly. Using the outside-in flow configuration shown in Figure 10, there is little chance for heat loss provided the heating element is located within the chemical filter as shown in Figure 6.

Another relevant consideration is the acoustical performance of the air purification system, particularly where the air purification system is used with a fuel cell. Although the power-generating chemical reactions in a fuel cell are silent, the operation of the air compressor

may generate unpleasant noise. Therefore, the filtration system may also desirably be configured to minimize the sound transmission from the air compressor. The volumes and interconnecting passages of each of the system's components are responsible for this reactive silencing. The acoustical performance can be modeled with an acoustical finite element analysis (FEA) program. A preliminary acoustic analysis can be performed using a model made up of only the volumes associated with the system in order to estimate the desired volumes of each component. It should be noted that a transmission loss analysis such as this will not necessarily give any indication as to the reduction in shell noise, or body-borne noise. To estimate the shell noise, a coupled analysis must be performed between the acoustical and structural finite element analysis programs.

Figure 12 shows the configuration of the regenerable air purification system used for an example acoustical finite element analysis. This particular output is for 800 Hz applied on the left hand side of the figure. The color contours indicate internal sound pressure levels, where red is the highest, and blue is the lowest. Each of the volumes within the system shown in Figure 6 was calculated, including the total areas and lengths of the passageways through the heat exchangers.

At frequencies lower than about 800 Hz, the bulk of the attenuation will come from reactive silencing, which relies on the interactions between the volumes within a system. Above 800 Hz, absorptive silencing by medias becomes more prevalent, but is not accounted for by the finite element analysis program. Figure 13 shows the total attenuation expected by the finite element analysis with respect to frequency up to 800 Hz.

The design of housing 42 must consider both the pressure-induced stresses and the desire for sound attenuation. In any case, the housing walls should be no thinner than is needed to contain the pressure within the system. Thicker walls provide improved sound attenuation. However, thicker walls may increase costs and weight undesirably.

The present invention should not be considered limited to the particular examples described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed upon review of the present specification. The claims are intended to cover such modifications and devices.

The above specification provides a complete description of the structure and use of the invention. Since many of the embodiments of the invention can be made without parting from the spirit and scope of the invention, the invention resides in the claims.

What is claimed is:

1. An air purification system for use with a fuel cell system, the fuel cell system having an air compressor for generating a flow of inlet air and a fuel cell stack for receiving a flow of inlet air at a fuel cell stack inlet, the filtration system comprising:
 - (i) a particulate filter located upstream of the fuel cell stack within the inlet air flow;
 - (ii) an adsorbent filter located upstream of the fuel cell stack within the inlet air flow, the adsorbent filter having a media bed of adsorbent filtration material, the adsorbent filter being characterized by an inlet end and an outlet end in fluid communication with the fuel cell stack inlet;
 - (iv) a venting passage fluidly connecting the adsorbent filter to the atmosphere;
 - (vi) a heater in fluid communication with the adsorbent filter; and
 - (vii) a plurality of valves, wherein at least one valve is selectively closable to define a first operating mode while the fuel cell is generating power in which inlet air flows through the particulate filter and adsorbent filter and into the fuel cell stack, and at least one valve is selectively closable to define a second operating mode in which air flows through the particulate filter, heater, and the adsorbent filter and out the adsorbent filter atmospheric vent to regenerate the adsorbent filter.
2. The air purification system according to claim 1, further comprising a heat exchanger located between the air compressor and the adsorbent filter within the inlet air flow.
3. The air purification system according to claim 1, wherein the air compressor is characterized by an air compressor inlet and an air compressor discharge, and further comprising a regeneration flow passage fluidly connecting the air compressor discharge to the adsorbent filter outlet end.
4. The air purification system according to claim 2, wherein the adsorbent filter is located downstream from the air compressor discharge.
5. The air purification system according to claim 1, wherein the plurality of valves where at

least one valve is in the regeneration flow passage, one valve is in the passage between the adsorbent filter outlet and the fuel cell stack, and one valve is within the adsorbent filter venting passage;

6. The air purification system according to claim 2, wherein the heat exchanger comprises two separate components, a first heat exchanger and a second heat exchanger.
7. The air purification system according to claim 6, wherein the first heat exchanger comprises an air-to-air heat exchanger and the second heat exchanger comprises a water-to-air heat exchanger.
8. The air purification system according to claim 7, wherein the first heat exchanger defines a first fluid flow path and a second fluid flow path, where the first fluid flow path is in fluid communication with the air compressor discharge and the second heat exchanger, and where the second fluid flow path is in fluid communication with the adsorbent filter outlet and the fuel cell stack inlet.
9. The air purification system according to claim 1, wherein the adsorbent filtration material comprises activated carbon.
10. The air purification system according to claim 2 further comprising a shell, where the shell encapsulates at least the adsorbent filter and heat exchanger.
11. The air purification system according to claim 1, wherein the adsorbent filter comprises a first adsorbent filter, and further comprising a second adsorbent filter, where the first and second adsorbent filters are located in parallel fluid communication with each other.
12. The air purification system according to claim 1, wherein the adsorbent filter comprises a plurality of media beds.
13. An air purification system for removing chemical contaminants from an air stream, the

air purification system comprising:

- (i) a rotating wheel adsorbent filter constructed with adsorbent media, the rotating wheel adsorbent filter positioned within the air stream and defining an inlet surface and an outlet surface;
- (ii) a non-rotating inlet structure in proximity to the inlet surface of the rotating wheel configured to define an adsorption segment, a cooling segment, and a regeneration segment of the rotating wheel and to direct a first portion of the air stream through the adsorption segment and to direct a second portion of the air stream through the cooling segment;
- (iii) a non-rotating outlet structure in proximity to the outlet surface of the rotating wheel configured to correspond to the adsorption, cooling, and regeneration segments of the rotating wheel defined by the inlet structure, the outlet structure configured to direct the air stream exiting from the cooling segment of the outlet surface of the rotating wheel through a first fluid conduit;
- (iv) a heater located in fluid communication with the first fluid conduit and in fluid communication with a second fluid conduit;
- (v) the outlet structure further configured to direct air received from the second fluid conduit into the regeneration segment of the outlet surface of the rotating wheel;
- (vi) the inlet structure further configured to direct air exiting from the inlet surface of the regeneration segment of the rotating wheel through a third fluid conduit;
- (vii) a blower in fluid communication with the third fluid conduit for drawing regeneration air through the cooling segment, first fluid conduit, heater, second fluid conduit, regeneration segment, and third fluid conduit; and
- (viii) an atmospheric vent in fluid communication with the blower for discharging the regeneration air.

14. The air purification system of claim 13, wherein the rotating wheel adsorbent filter comprises a aramid fiber substrate with a molecular sieve coating.

15. The air purification system of claim 13, wherein the adsorption segment comprises approximately 50 to 75 percent of the rotating wheel adsorbent filter.

16. The air purification system of claim 15 wherein the cooling segment comprises approximately 12.5 to 25 percent and the regeneration segment comprises approximately 12.5 to 25 percent of the rotating wheel adsorbent filter inlet surface area.
17. The air purification system of claim 13, wherein the heater is an electrical heater.
18. A method of filtering air for a fuel cell system, the fuel cell system having an air compressor for generating a flow of inlet air at an air compressor discharge and a fuel cell stack for receiving a flow of inlet air at a fuel cell stack inlet, the method comprising:
- (i) providing a particulate filter within the inlet air flow for removing particulate contamination;
 - (ii) providing a chemical filtration system within the inlet air flow for removing chemical contamination, the chemical filtration system comprising
 - (a) an adsorbent filter having a media bed of adsorbent filtration material, the adsorbent filter being characterized by an inlet end configured to receive the inlet air flow and an outlet end fluidly connected to the fuel cell stack inlet;
 - (b) a venting passage fluidly connecting the adsorbent filter to the atmosphere;
 - (c) a regeneration flow passage fluidly connecting the air compressor discharge to the adsorbent filter outlet end; and
 - (d) a plurality of selectively closable valves, where at least one valve is in the regeneration flow passage, one valve is in the passage between the adsorbent filter outlet and the fuel cell stack, and one valve is within the adsorbent filter venting passage;
 - (iii) actuating the selectively closable valves while the fuel cell is generating power to define a first operating mode in which inlet air flows through the particulate filter and adsorbent filter and into the fuel cell stack; and
 - (iv) actuating the selectively closable valves while the fuel cell is not generating power to define a second operating mode in which inlet air flows through the particulate filter and the adsorbent filter and out the adsorbent filter atmospheric

vent to regenerate the adsorbent filter.

19. The method of claim 18, wherein the step of providing a chemical filtration system further comprises providing a heater within the regeneration flow passage or the adsorbent filter, and the step of actuating the selectively closable valves to define a second operating mode further comprises actuating the heater.

20. A method of purifying air, the method comprising:

- (i) providing an adsorbent filter configured as a rotating wheel;
- (ii) partitioning the rotating wheel into a plurality of non-rotating segments, the segments comprising at least an adsorption segment, a cooling segment, and a regeneration segment;
- (iii) passing a service air stream through the adsorption segment of the adsorbent filter to remove contaminants from the air stream to generate a cleaned air stream, the cleaned air stream being directed to service an application; and
- (iv) passing a regeneration air stream first through the cooling segment of the adsorbent filter to absorb heat from the rotating wheel and to increase the temperature of the second air stream, then passing the regeneration air stream through a heater to further increase the temperature; then passing the regeneration air stream through the regeneration segment of the adsorbent filter to desorb contaminants contained within the regeneration segment of the filter, and then directing the regeneration air stream away from the adsorbent filter.

FIG. 1

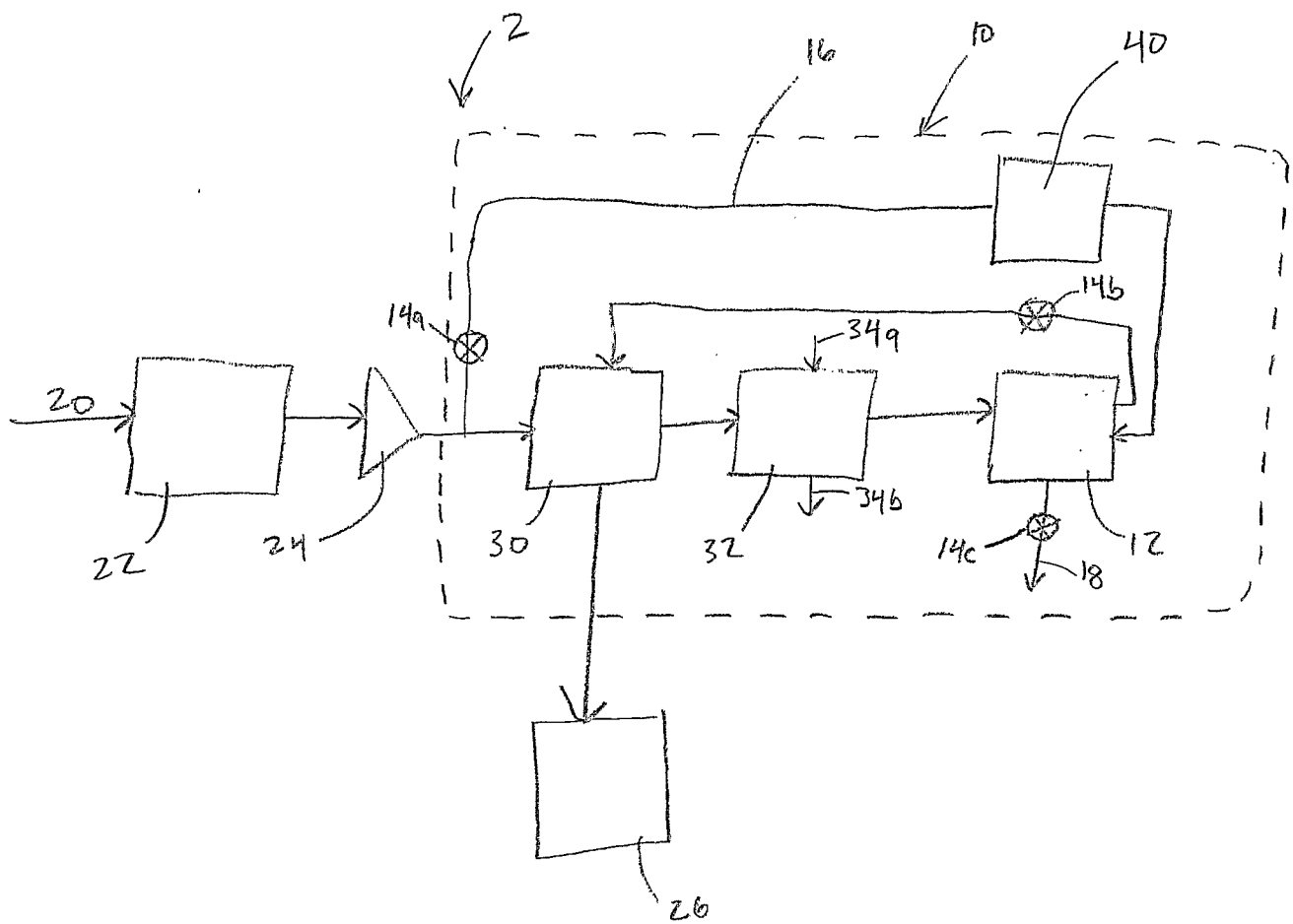


FIG. 2

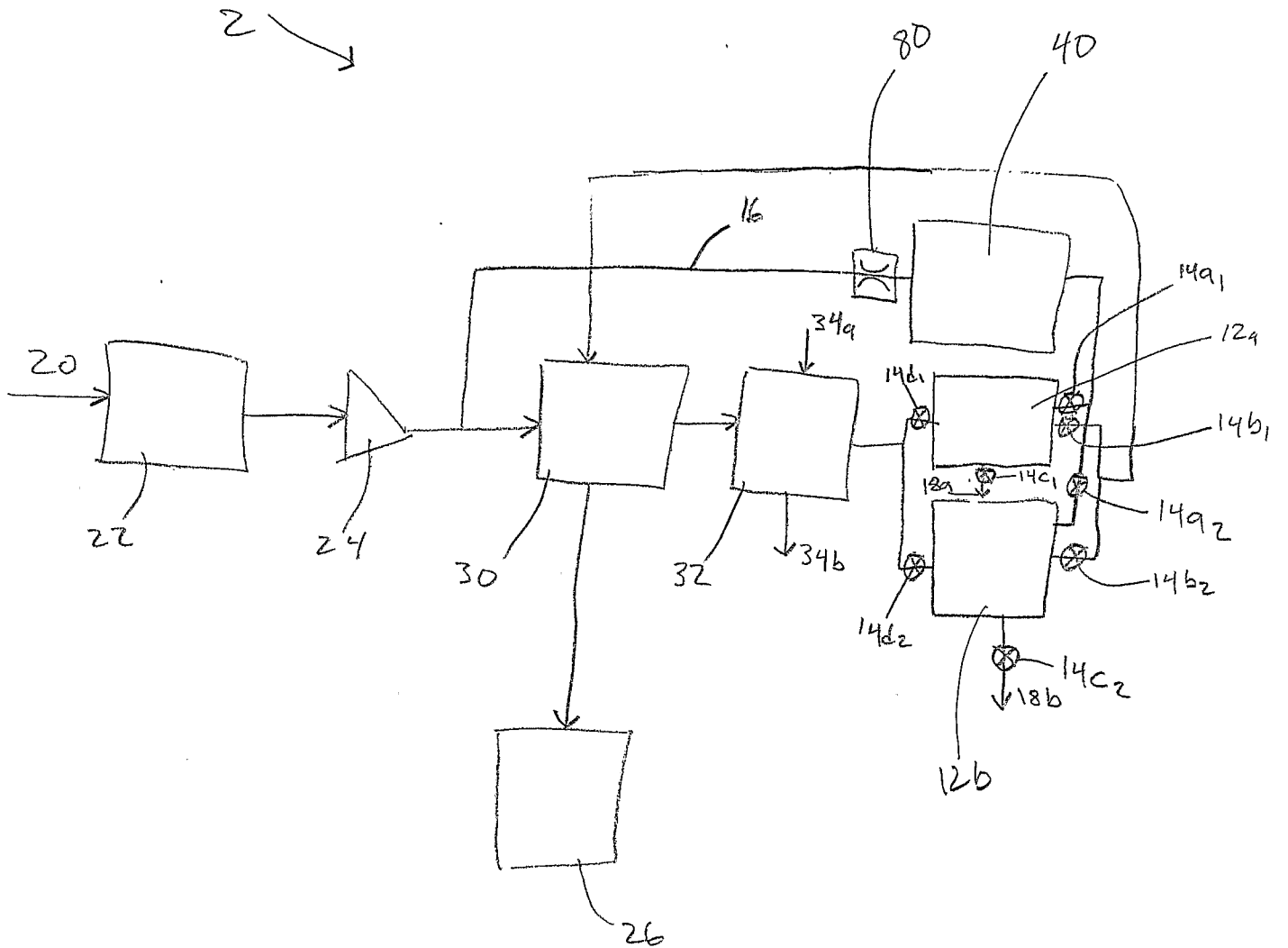
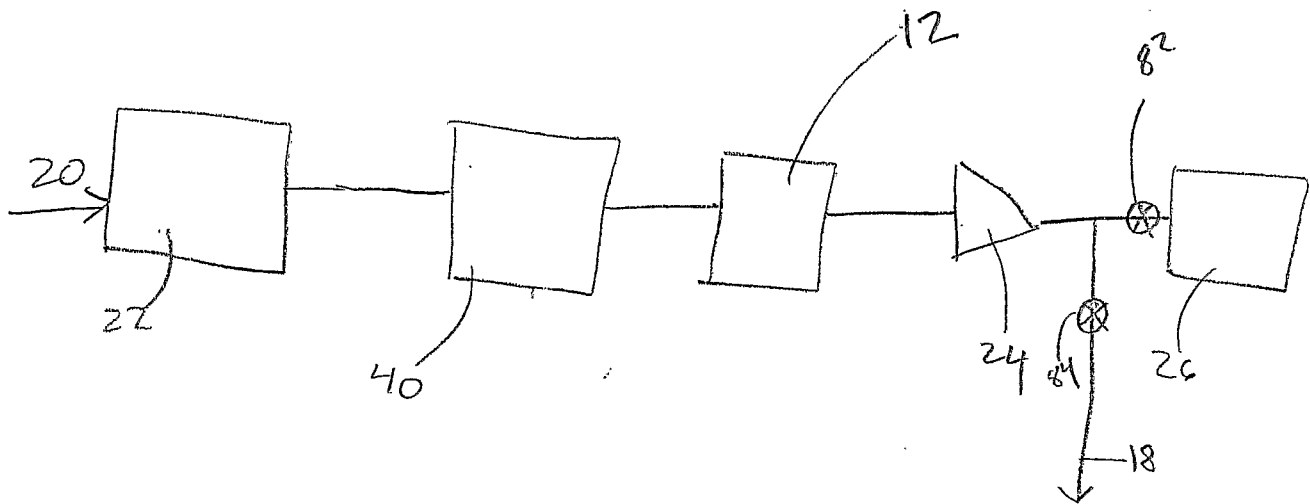


FIG. 3



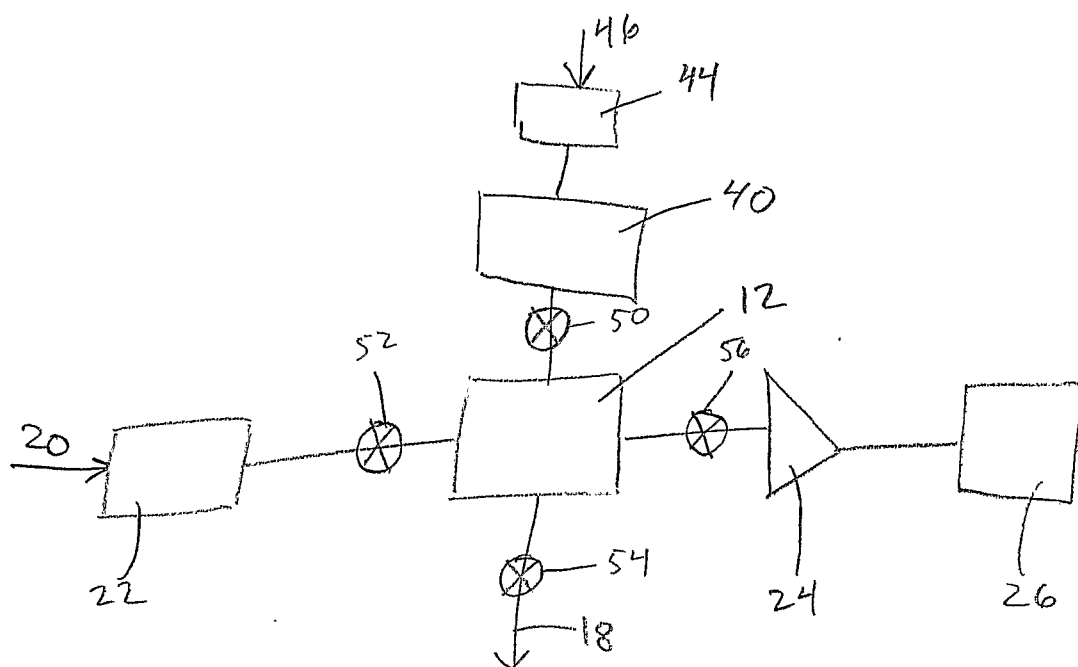
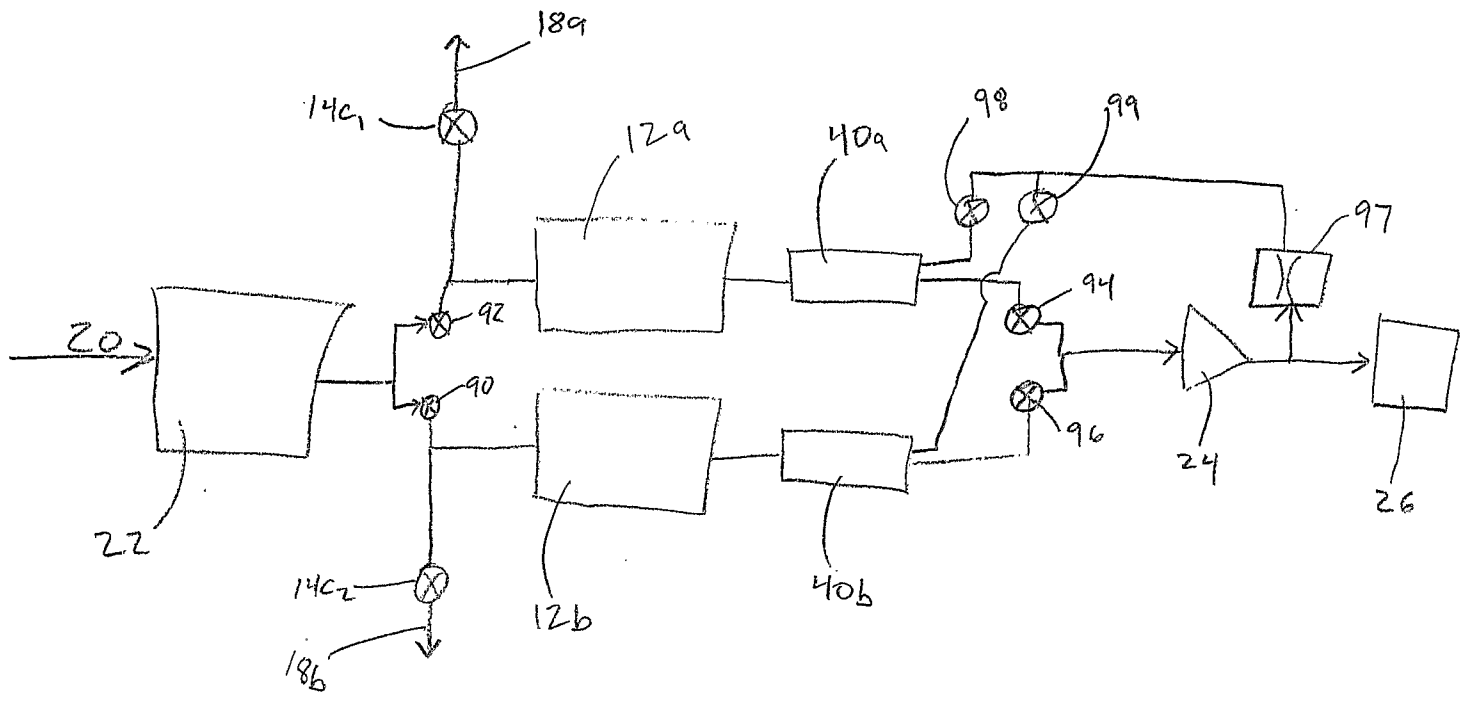


FIG. 5

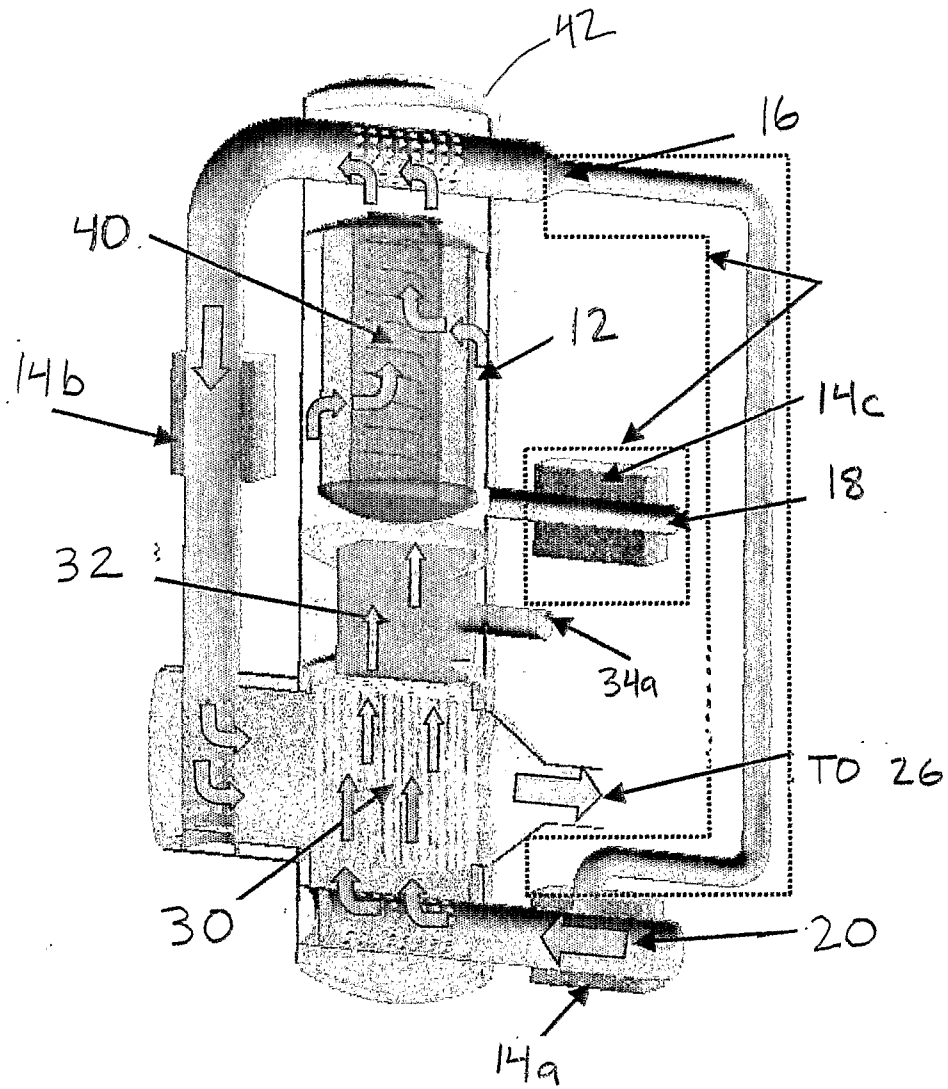


FIG. 6

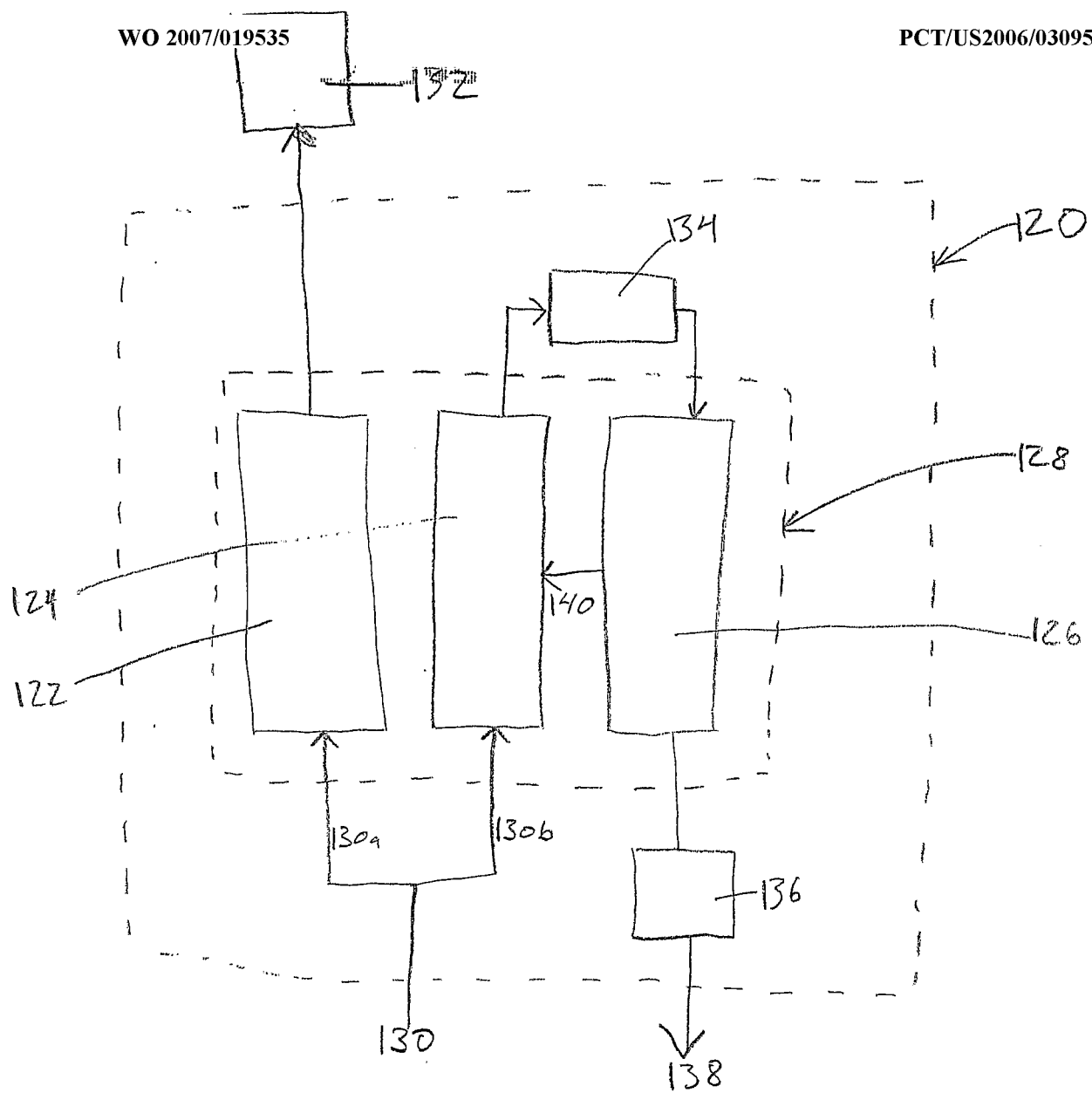
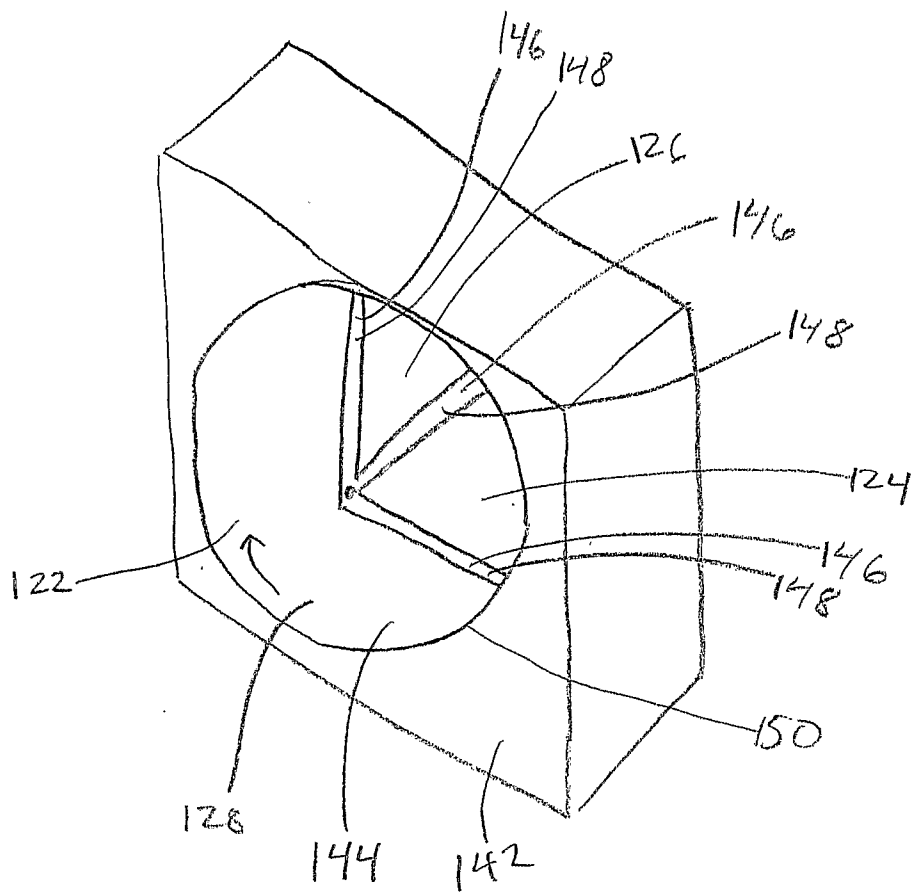


FIG. 7



	Loss Description
1	Valve Loss
2	Turning Loss
3	Expansion Loss
4	Contraction Loss
5	Chemical Filter

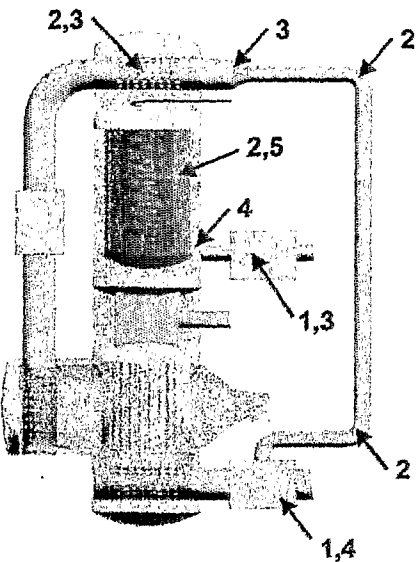
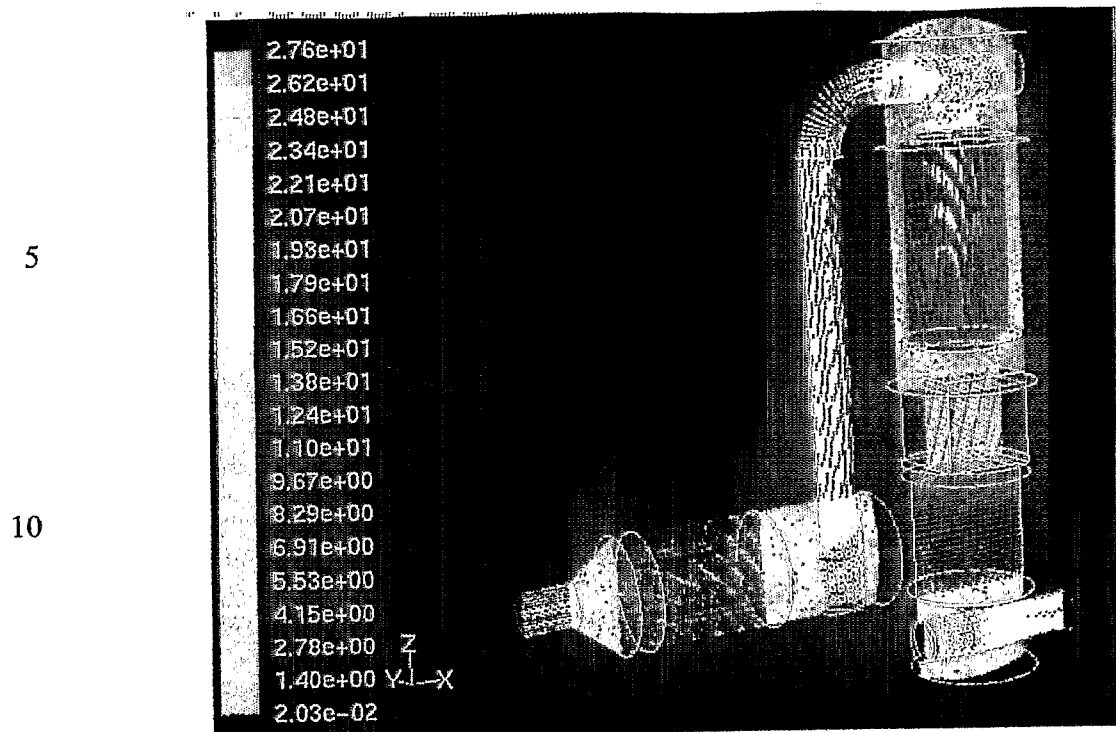


FIG. 9



15

FIG. 10

5

10

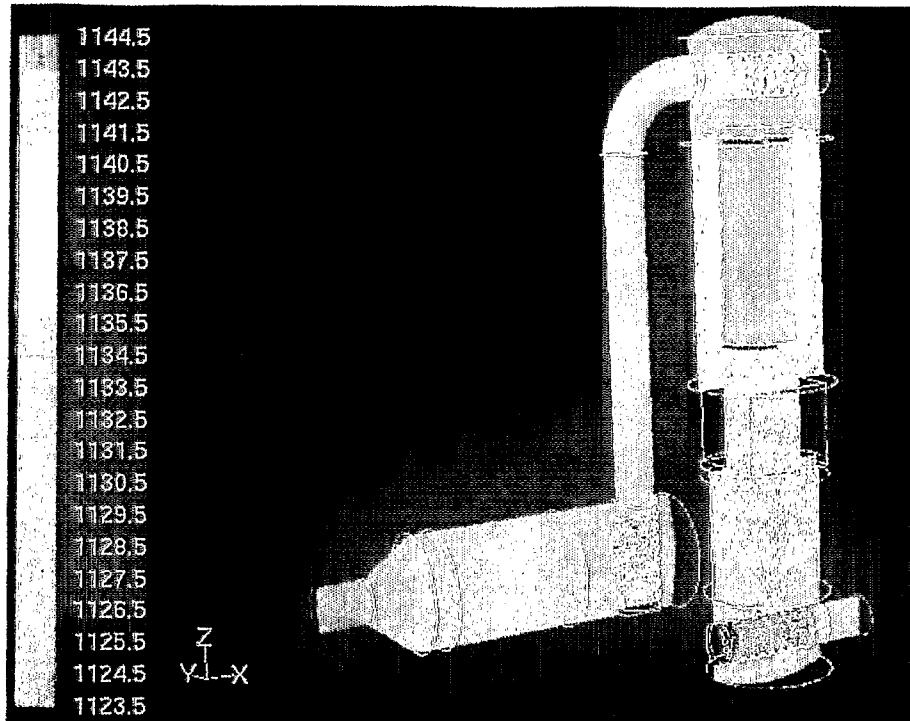


FIG. 11

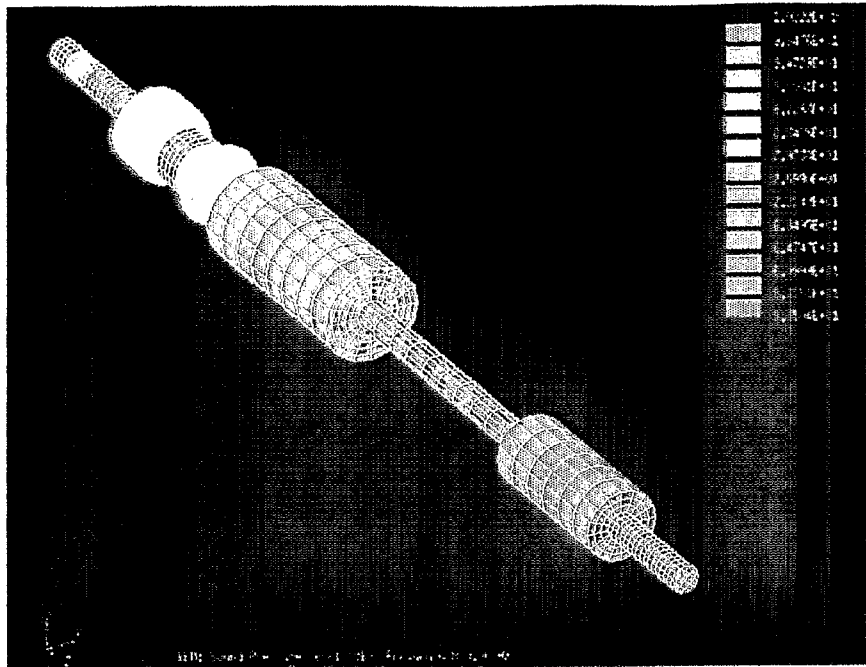


FIG. 12

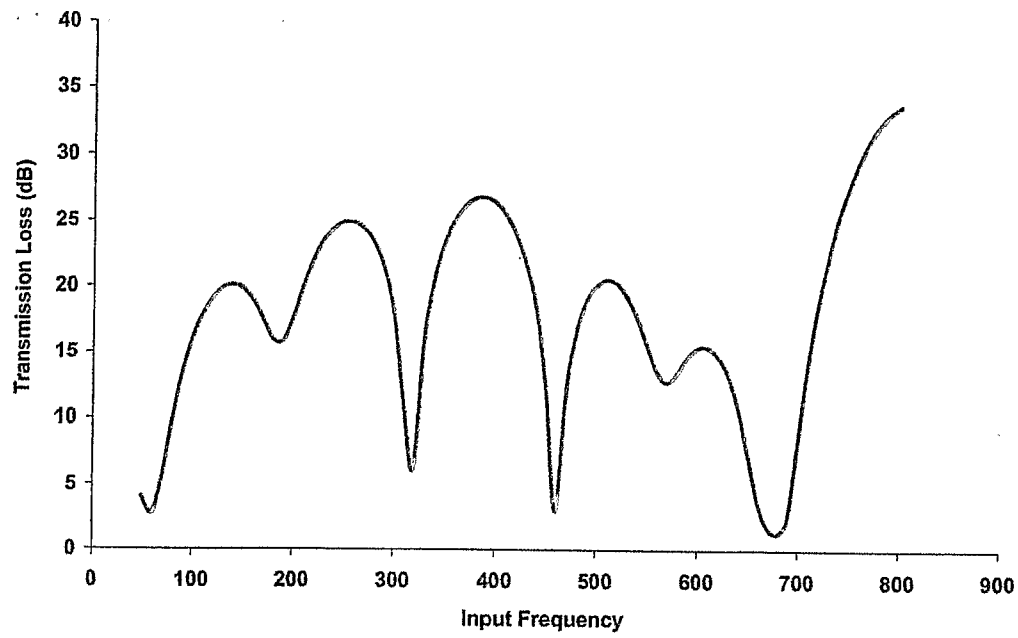


FIG. 13.