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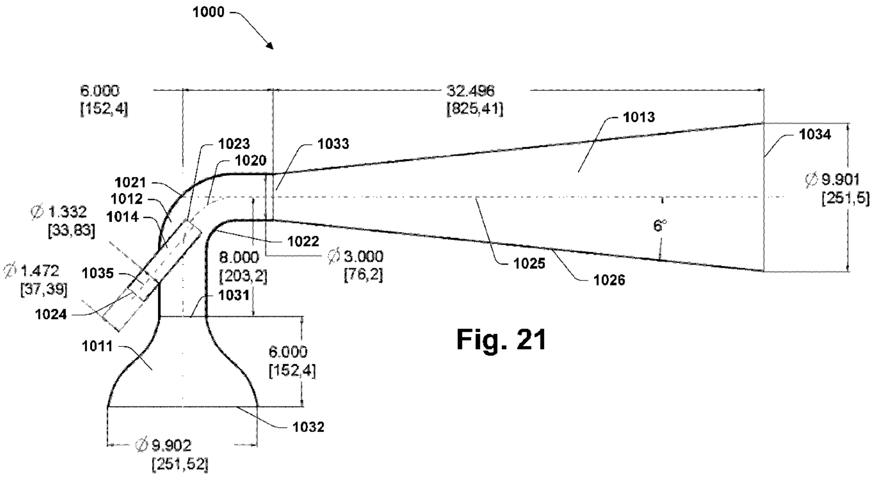

Fig. 21

(57) Abstract: An exhaust aftertreatment system (103) comprises a Venturi (109) positioned downstream from a NOX absorber-catalyst (107) and upstream from an ammonia-SCR reactor (110). The Venturi (109) substantially increases the air-fuel ratio of the exhaust entering the ammonia-SCR reactor (110), which improves the performance of the ammonia-SCR reactor (110) especially during rich conditions that are used to regenerate the NOX absorber-catalyst (107). One aspect of the invention, which is applicable to other exhaust aftertreatment systems, is forming the Venturi (109) in an exhaust pipe bend (201,301,1012). Forming the Venturi (109) in an exhaust pipe bend (201,301,1012) reduces back pressure.

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Exhaust Cooling Module for SCR Catalysts

Priority

[0001] This application claims priority from U.S. Provisional Application No. 61/226880, filed July 20, 2009 and U.S. Application No. 12/762157, filed April 16, 2010.

Field of the Invention

[0002] The present invention relates to vehicle exhaust aftertreatment systems.

Background

[0003] NO_x emissions from diesel engines are an environmental problem. Several countries, including the United States, have long had regulations pending that will limit NO_x emissions from trucks and other diesel-powered vehicles. Manufacturers and researchers have put considerable effort toward meeting those regulations.

[0004] In gasoline powered vehicles that use stoichiometric fuel-air mixtures, three-way catalysts have been shown to control NO_X emissions. In diesel-powered vehicles, which use compression ignition, the exhaust is generally too oxygen-rich for three-way catalysts to be effective.

[0005] Several solutions have been proposed for controlling NO_X emissions from diesel-powered vehicles. One set of approaches focuses on the engine. Techniques such as exhaust gas recirculation and partially homogenizing fuel-air mixtures are helpful, but these techniques alone will not eliminate NO_X emissions. Another set of approaches remove NO_X from the vehicle exhaust. These include the use of lean-burn NO_X catalysts, selective catalytic reduction (SCR) catalysts, and lean NO_X traps (LNTs, also called NOx absorber-catalysts).

[0006] Lean-burn NO_X catalysts promote the reduction of NO_x under oxygen-rich conditions. Reduction of NO_X in an oxidizing atmosphere is difficult. It has proven challenging to find a lean-burn NO_x catalyst that has the required activity, durability, and operating temperature range. A reductant such as diesel fuel must be steadily supplied to the exhaust for lean NO_X reduction, introducing a fuel economy penalty of 3% or more. Currently, peak NO_X conversion efficiencies for lean-burn NO_X catalysts are unacceptably low.

[0007] SCR generally refers to selective catalytic reduction of NO_X by ammonia. The reaction takes place even in an oxidizing environment. The NO_X can be temporarily stored in an absorbent or ammonia can be fed continuously into the exhaust. SCR can achieve high levels of NO_X reduction, but there is a disadvantage in the lack of infrastructure for distributing ammonia or a suitable precursor. Another concern relates to the possible release of ammonia into the environment.

[0008] LNTs are devices that adsorb NO_X under lean conditions and reduce and release the adsorbed NO_X under rich conditions. An LNT generally includes a NO_X adsorbent and a catalyst. The adsorbent is typically an alkali or alkaline earth compound, such as $BaCO_3$ and the catalyst is typically a combination of precious metals including Pt and Rh. In lean exhaust, the catalyst speeds oxidizing reactions that lead to NO_X adsorption. In a reducing environment, the catalyst activates reactions by which hydrocarbon reductants are converted to more active species, the water-gas shift reaction, which produces more active hydrogen from less active CO, and reactions by which adsorbed NO_X is reduced and desorbed. In a typical operating protocol, a reducing environment will be created within the exhaust from time-to-time to regenerate (denitrate) the LNT.

[0009] Regeneration to remove accumulated NOx may be referred to as denitration in order to distinguish desulfation, which is carried out much less frequently. The reducing environment for denitration can be created in several ways. One approach uses the engine to create a rich exhaust-reductant mixture. For example, the engine can inject extra fuel into the exhaust within one or more cylinders prior to expelling the exhaust. A reducing environment can also be created by injecting a reductant into lean exhaust downstream from the engine. In either case, when valves are not used, a portion of the reductant is generally expended to consume excess oxygen in the exhaust. The reducing agent reacts with oxygen and substantially consumes it. The reactions between reductants and oxygen can take place in the LNT, but it is generally preferred for the reactions to occur in a catalyst upstream from the LNT so that the heat of reaction does not cause large temperature increases within the LNT with each regeneration. To lessen the amount of excess oxygen and reduce the amount of reductant expended consuming excess oxygen, the engine may be throttled, although such throttling may have an adverse effect on the performance of some engines.

[0010] WO 2004/090296 describes a diesel automotive exhaust aftertreatment system with a fuel reformer configured within an exhaust line upstream from LNT and SCR catalysts. The reformer has a high thermal mass. The reformer uses Pt and Rh to produce syn gas from diesel fuel at exhaust gas temperatures. For the reformer to be operative at exhaust gas temperatures, a relatively large amount of catalyst must be used to provide enough catalyst activity. The reformer both removes excess oxygen and converts the diesel fuel reductant into more reactive reformate.

[0011] U.S. Pat. Pub. No. 2004/0050037 (hereinafter "the '037 publication") describes a different type of fuel reformer placed in the exhaust line upstream from an LNT. The reformer includes both oxidation and steam reforming catalysts. Pt and/or Pd serves as the oxidation catalyst. Rh serves as the reforming catalyst. The inline reformer of the '037 publication is designed to be rapidly heated and to then catalyze steam reforming. Temperatures from about 500 to about 700°C are said to be required for effective reformate production by this reformer. These temperatures are substantially higher than typical diesel exhaust temperatures. The reformer is heated by injecting fuel at a rate that leaves the exhaust lean, whereby the injected fuel combusts to generate heat. After warm up, the fuel injection rate is increased and or the oxygen flow rate reduced to provide a rich exhaust. U.S. Patent No. 7,213,395 describes an exhaust aftertreatment system comprising a similar reformer-LNT system, but with an SCR reactor configured downstream from the LNT.

[0012] Designing the fuel reformer to heat and operate at least partially through steam reforming reactions as opposed to operating at exhaust stream temperatures reduces the catalyst requirement, increases the reformate yield, and reduces the amount of heat generation. In principal, if reformate production proceeds through partial oxidation reforming as in the reaction:

$$CH_{1.85} + 0.5\,O_2 \rightarrow CO + 0.925\,H_2 \qquad (1)$$

1.925 moles of reformate (moles CO plus moles H_2) could be obtained from each mole of carbon atoms in the fuel. $CH_{1.85}$ is used to represent diesel fuel having a typical carbon to hydrogen ratio. If reformate production proceeds through steam reforming as in the reaction:

$$CH_{1.85} + H_2O \rightarrow CO + 1.925\,H_2 \qquad (2)$$

[0013] 2.925 moles of reformate (moles CO plus moles H_2) could in principle be obtained from each mole of carbon atoms in the fuel. In practice, yields are lower than theoretical amounts due to the limited efficiency of conversion of fuel, the limited selectivity for reforming reactions over complete combustion reactions, the necessity of producing heat to drive steam reforming, and the loss of energy to heating the exhaust. Nevertheless, the benefits are sufficient that a low thermal mass reformer that must be preheated to operate effectively is preferred over a large thermal mass reformer that does not require preheating.

[0014] In spite of advances, there continues to be a long felt need for an affordable and reliable diesel exhaust aftertreatment system that is durable, has a manageable operating cost (including fuel penalty), and reduces NO_X emissions to a satisfactory extent in the sense of meeting U.S. Environmental Protection Agency (EPA) regulations effective in 2010 and other such regulations that will limit NO_x emissions from trucks and other diesel-powered vehicles. Manufacturers and researchers have put considerable effort toward meeting those regulations.

Summary

[0015] The inventors have developed a Venturi for vehicle exhaust systems, an exhaust aftertreatment system comprising the Venturi, and related methods of operation. The preferred embodiment comprises a fuel reformer, a NO_X absorber-catalyst, a diesel particulate filter, and an ammonia-SCR reactor with an exhaust conduit. A Venturi is formed within a bend in an exhaust conduit upstream from the SCR reactor. Preferably this bend is formed between the device immediately upstream from the ammonia-SCR reactor and the ammonia-SCR reactor itself.

[0016] One invention embodied by this system is the placement of a Venturi in an exhaust conduit between an NO_X absorber-catalyst and an ammonia-SCR reactor. The NO_X absorber-catalyst generates ammonia during regeneration. The ammonia is captured and later used by the ammonia-SCR reactor to reduce NO_X. The inventors have demonstrated that the Venturi is functional upstream from the ammonia-SCR reactor and have concluded that the Venturi improves the performance of the ammonia SCR reactor. The ammonia SCR reactor performs better under lean conditions and the Venturi makes the exhaust more lean.

[0017] The Venturi increases the air-fuel ratio of the exhaust from the NO_X absorber-catalyst. Preferably the Venturi adds at least 5% air to the exhaust stream under peak flow conditions. Preferably, the Venturi draws sufficient air to keep the ammonia-SCR reactor under lean conditions throughout the NO_X absorber-catalyst regenerations. The inventors have found that a Venturi placed upstream from the ammonia-SCR reactor can be made effective for drawing air from the ambient surroundings in spite of the back-pressure created by the ammonia-SCR reactor and without itself causing excessive back-pressure.

[0018] Another invention embodied by the exhaust aftertreatment system is the formation of a Venturi in an exhaust conduit bend. Normally, a Venturi creates a reduced pressure for drawing air by forcing a fluid flow through a necking region. The inventors have noted that reduced pressure regions form within exhaust pipe elbows and conceived utilizing these reduced pressure regions in a Venturi. One refinement of this invention is a Venturi formed by inserting a cold chute (air entry port) into an exhaust pipe elbow.

[0019] A refinement of the invention of forming a Venturi in a pipe bend is forming the Venturi with a cold chute having an outlet offset from the center of the bend toward the inner side of the bend. In a pipe bend, momentum concentrates the exhaust flow onto the outer side of the bend. As a result, exhaust gas velocities are expected to be highest on the outer side of the pipe bend. Pressure is expected to be lowest where velocity is highest. Nevertheless, the inventors have experimentally determined that the Venturi draws best when the cold chute is positioned to admit air primarily to the inner side of the pipe bend.

[0020] Other concepts of the inventors include a pressure actuated check-valve to prevent exhaust from leaking out a Venturi, using ram air to enhance air uptake by a Venturi, providing an exhaust pipe sleeve to capture ram air, a cyclonic air filtration unit for a Venturi air intake, a diffuser manifold for distributing intake air provided by a Venturi evenly through an exhaust flow, a convoluted Venturi neck that improves the distribution of intake air, and a convoluted Venturi neck, with optional heat radiating fins, for cooling exhaust. Each of these concepts can be used together with each of the others, or separately.

[0021] The primary purpose of this summary has been to present inventive concepts in a simplified form to facilitate understanding of the more detailed description that follows. This summary is not a comprehensive description of every one of the inventors' concepts or every combination of the inventors' concepts that can be considered "invention". Other concepts of the inventors will be conveyed to one of ordinary skill in the art by the following detailed description together with the drawings. The specifics disclosed herein may be generalized, narrowed, and combined in various ways with the ultimate statement of what the inventors claim as their invention being reserved for the claims that follow.

Brief Description of the Drawings

[0022] Fig. 1 is a schematic illustration of an exemplary exhaust aftertreatment system.

[0023] Fig. 2 is a cut-away view of one example of a Venturi formed into an exhaust conduit bend.

[0024] Fig. 3 is a cut-away view of another exemplary Venturi formed into an exhaust conduit bend.

[0025] Fig. 4 is a full view of the Venturi of Figure 3.

[0026] Fig. 5 is an illustration of a portion of an exemplary exhaust aftertreatment system having a 90° bend and a Venturi formed into the bend.

[0027] Fig. 6 is a cut-away view of another exemplary Venturi formed into an exhaust conduit bend.

[0028] Fig. 7 is another cut-away view of the Venturi of Figure 6.

[0029] Fig. 8 is an illustration of a portion of an exhaust aftertreatment system showing a Venturi formed into an exhaust pipe elbow.

[0030] Fig. 9 is a sketch of an exemplary Venturi with a hinged opening to prevent backflow.

[0031] Fig. 10 is a cut-away view of an exemplary Venturi with hinged openings to prevent backflow.

[0032] Fig. 11 is a sketch of an exemplary Venturi providing cyclonic filtration of intake air.

[0033] Fig. 12 is a sketch of an exemplary Venturi formed in the entrance cone for an SCR reactor.

[0034] Fig. 13 is an illustration of another exemplary Venturi formed in the entrance cone for an SCR reactor.

[0035] Fig. 14 is a cut-away view of the Venturi of Figure 13.

[0036] Fig. 15 is a sketch of another exemplary Venturi.

[0037] Fig. 16 is a perspective of Figure 15 with a partial cross section taken along line 16-16.

[0038] Fig. 17 is a cross-section of the Venturi of Figure 15 taken along the line 17-17.

[0039] Fig. 18 is a cross-section of the Venturi of Figure 15 taken along the line 18-18.

[0040] Fig. 19 is a plan view of another Venturi formed into an exhaust pipe bend in a system where the exhaust pipe bend and a side-exiting outlet cone of a catalyst together form a 180° turn within an exhaust treatment system.

[0041] Fig. 20 is a plan view of a Venturi formed into one of two exhaust pipe bends forming a 180° turn within an exhaust treatment system.

[0042] Fig. 21 is a cross-sectional drawing of a Venturi formed into a 90° elbow.

[0043] Fig. 22 is a plot of calculation results providing the amount of air dilution provided by the Venturi of Fig. 20.

[0044] Fig. 23 is a plot of calculation results providing the back pressure caused by the Venturi of Fig. 20.

[0045] Fig. 24 is a plot of experimental data showing the relationship between Venturi draw and back pressure for several Venturi with designs corresponding to Figure 20.

[0046] Fig. 25 is a perspective view of an exhaust pipe elbow with a slot cut in the outside to receive and mount a cold chute

[0047] Fig. 26 is a perspective view of the elbow of Figure 25 with the cold chute inserted through the slot.

[0048] Fig. 27 is a sectional view of the elbow of Figure 26.

Detailed Description

[0049] Figure 1 is a schematic illustration of an exemplary power generation system 100. The system 100 is suitable for powering a vehicle, especially a diesel-fueled vehicle such as a medium or heavy duty truck. The system 100 can also be used for stationary power generation.

[0050] The power generation system 100 includes a compression ignition diesel internal combustion engine 101 connected by an exhaust manifold 102 to an exhaust aftertreatment system 103. The exhaust aftertreatment system 103 comprises an exhaust line fuel injector 116, an in-line fuel reformer 105, a monolith-structure thermal mass 106, a lean NOx trap (LNT) 107, a diesel particulate filter (DPF) 108, a Venturi 109, an ammonia-SCR reactor 110, and a controller 115. In this example, the controller 115 is also a control unit for the engine 101, but separate units can be used for these purposes. Temperature sensors 117-119, pressure sensor 120, and NO_X sensor 121 all provide information to the controller 115.

[0051] The Venturi 109 is formed in the exhaust conduit 104 that contains the foregoing exhaust aftertreatment devices. The Venturi 109 comprises a constriction zone 111 through which the cross-sectional area available for exhaust flow becomes reduced, a neck zone 112 with an air intake 114, and an expansion zone 113 through which the cross-sectional area available for exhaust flow expands. The constriction zone 111 and the expansion zone 113 can be replaced with abrupt transitions, but this is not recommended.

[0052] Preferably the exhaust aftertreatment system 103 provides a static flow path for the exhaust from the internal combustion engine 101. A static flow path is one that remains fixed while the power generation system 100 is operating. The aftertreatment system 103 preferably lacks exhaust line valves or dampers for dynamically controlling the path or volumetric flow distribution of the exhaust passing through the system 103. The term dynamic control is used to distinguish parts that are designed to move during operation of the exhaust aftertreatment system 103 from parts that may be adjusted by a factory or at a maintenance interval. Dynamically moving exhaust line dampers and especially valves are preferably avoided because such devices are susceptible to failure and would decrease the system 103's durability and reliability

[0053] Preferably, the entire exhaust flow from the engine 101 passes through the fuel reformer 105 and the Venturi 109. Passing the entire exhaust flow through the fuel reformer 105 allows the fuel reformer 105 to eliminate all the excess oxygen from the exhaust when a sufficient amount of reductant is made available. Passing the entire exhaust flow through the Venturi 109 provides the highest degree of air dilution for a given amount of back-pressure.

[0054] The exhaust line fuel injector 116 is functional to selectively inject fuel into the exhaust conduit 104 under the direction of the controller 115. Exhaust line fuel injection can be used to heat and regenerate the LNT 107 and the DPF 108. A preferred fuel injector comprises an atomizing spray nozzle having a check valve. The spray is preferably vaporized by the injection process. If the spray does not entirely vaporize, the spray is preferably oriented to impinge on a downstream catalyst as opposed to exhaust pipe walls. To prevent clogging of the valve, it is preferred that the nozzle be cooled. Clogging can also be prevented by clearing the nozzle with pulses of air between periods of fuel injection.

[0055] A preferred method of cooling the nozzle uses an excess fuel flow. An excess fuel flow is a flow of fuel to the nozzle that is returned to a fuel reservoir rather than injected. The excess fuel carries heat away from the nozzle. One way of providing an excess fuel flow is to provide a return flow path that allows fuel to exit the nozzle after having passed through most of the same channels used for fuel injection into the exhaust conduit 104. The return flow path is open at least between periods of injection. A check valve can be used to prevent fuel flow from the nozzle to the exhaust conduit 104 between injections. By providing fuel to the nozzle at a pressure below the pressure that would open that check valve, a continuous flow through the nozzle can be maintained between injections without leaking fuel.

[0056] The exhaust line fuel injector 116 preferably controls the flow of fuel from a pressurized fuel source to the exhaust line 104 using a pulse width modulated solenoid valve.

[0057] The fuel reformer 105 processes the fuel-injected exhaust. The exhaust from the engine 101 is normally lean. Typically, the engine 101 is a compression ignition diesel engine producing an exhaust having an oxygen concentration that varies between 4 and 15%. The fuel reformer 105 comprises an oxidation catalyst. The oxidation catalyst typically comprises one or more precious metals such as platinum and palladium dispersed on the high surface area metal oxide, alumina doped with lanthanum for example, although any suitable oxidation catalyst can be used. The oxidation catalyst typically has a minimum operating temperature in the range from 200 to 300°C, typically about 250°C. When the fuel reformer 105 is above this minimum operating temperature and the fuel injector 116 is providing the exhaust with fuel, the oxidation catalyst will oxidize at least a part of the fuel. Oxidation of injected fuel generates heat.

[0058] Preferably the fuel reformer 105 includes a steam reforming catalyst as well as an oxidation catalyst. A steam reforming catalyst is one that catalyzes reforming reactions between water and hydrocarbons. The exhaust from the engine 101 typically includes steam, which is one of the principle products of hydrocarbon fuel combustion. A reforming catalyst typically comprises at least one precious metal such as rhodium dispersed on the high surface area metal oxide, zirconium doped with lanthanum for example, although any suitable reforming catalyst can be used. The reforming catalyst typically has a minimum operating temperature in the range from 450 to 550°C, typically about 500°C. When the fuel reformer 105 is above this minimum operating temperature and the fuel injector 116 is making the exhaust rich by providing the exhaust with fuel at a rate in excess of stoichiometric with respect to the exhaust oxygen flow rate, the fuel reformer 105 will catalyze reactions that consume the bulk of the oxygen in the exhaust and reform a portion of the injected fuel to produce reformate, especially hydrogen and carbon monoxide. Steam reforming is endothermic. The inclusion of the steam reforming catalyst is preferred because it enhances the efficiency with which reformate is formed in comparison with only partial oxidation reforming. In addition, endothermic steam reforming reactions help stabilize the temperature of the fuel reformer 105 during fuel reforming operation.

[0059] A stoichiometric amount of hydrocarbon fuel is the amount that would consume all of the available oxygen in the exhaust while being entirely converted to complete combustion products, which are H_2O and CO_2. A stoichiometric amount corresponds to fuel-air equivalence ratio of 1.0. Doubling the fuel amount would give an equivalence ratio of 2.0. A fuel-exhaust mixture having an equivalence ratio less than one is a lean mixture. A fuel-exhaust mixture having an equivalence ratio greater than one is a rich mixture.

[0060] Diesel exhaust temperatures typically range from about 110 to about 550 °C. The higher temperatures typically occur during only a small portion of the engines 101's operating time. Accordingly, it is usually necessary to heat the fuel reformer 105 above the exhaust stream temperature to steam reforming temperatures before operating the fuel reformer 105 to produce reformate.

[0061] The thermal mass 106 is an inert structure providing a heat sink. The thermal mass 106 helps protect downstream devices from the high temperatures at which the fuel reformer 105 operates, particularly when those temperatures are sustained only briefly. Preferably, the heat capacity of the thermal mass 106 is substantially greater than that of the fuel reformer 105. While any suitable structure can be used, a preferred structure for the thermal mass 106 is that of a monolith. Monoliths have high heat transfer coefficients in comparison to other structures for given space and back pressure limitations. While the thermal mass 106 can comprise any suitable material, a preferred material is metal. The high thermal conductivity of metal facilitates rapid dispersal of heat throughout the monolith structure.

[0062] The LNT 107 is a device that absorbs NO_X under lean conditions and reduces NO_X releasing the reduction products (N_2 and NH_3) under rich conditions. Some alternate terms for a lean NO_X trap (LNT) are NO_X absorber-catalyst and NO_X trap-catalyst. An LNT generally comprises a NO_X adsorbent and a precious metal catalyst in intimate contact on an inert support. Examples of NO_X adsorbent materials include certain oxides, carbonates, and hydroxides of alkaline earth metals such as Mg, Ca, Sr, and Ba or alkali metals such as K or Cs. The precious metal typically comprises one or more of Pt, Pd, and Rh. The support is typically a monolith, although other support structures can be used. The monolith support is typically ceramic, although other materials such as metal and SiC are also suitable for LNT supports. The LNT 107 may be provided as two or more separate bricks.

[0063] Normally, the exhaust from the engine 101 is lean and the LNT 107 is accumulating NO_X. From time-to-time, the LNT 107 must be regenerated to remove the accumulated NO_X (denitrated) in a rich phase. Denitration generally involves heating the reformer 105 to an operational temperature and then using the reformer 105 to produce reformate. The reformate fuels the reactions by which NO_X adsorbed in the LNT 107 is reduced and then released.

[0064] Denitration requires only a few seconds. The thermal mass 106 prevents parts of the LNT 107 from being heated to the temperatures at which the fuel reformer 106 operates with each denitration. By reducing the frequency with which the LNT 107 is heated substantially and by increasing the uniformity with which the LNT 107 is heated, the thermal mass 106 extends the lifetime and reliability of the LNT 107.

[0065] The controller 115 schedules denitration of the LNT 107 based on criteria relating to the state and or performance of the exhaust aftertreatment system 103 or a portion thereof comprising the LNT 107. Criteria for scheduling LNT denitration may be based on LNT loading. LNT loading can be characterized in terms of amount of NO_X accumulated, remaining NO_X storage capacity, percent saturation, or another parameter of that type. Numerous methods for estimating NO_X loading and/or remaining NO_X storage capacity are available. These methods generally involve integrating an estimate of the NO_X storage rate and comparing the result to an estimated NO_X storage capacity.

[0066] In addition to storing NO_X, the LNT 107 absorbs and stores SO_X. From time to time, the LNT 107 must also be regenerated to remove accumulated sulfur compounds (desulfated). This process is required much less frequently than denitration, but takes considerably longer. Because the LNT 107 absorbs sulfur more strongly than NO_X, desulfation generally requires heating the LNT 107 in addition to providing a rich environment.

[0067] Desulfation generally involves heating the reformer 105 to an operational temperature, heating the LNT 107 to a desulfating temperature, and then using the reformer 105 to produce reformate. Reformate fuels the reactions by which SO_X absorbed in the LNT 107 is released. Desulfating temperatures vary, but are typically in the range from about 500 to about 800 °C, with optimal temperatures typically in the range of about 650 to about 750 °C. If the temperature is too low, desulfation is very slow. If the temperature is too high, the LNT 107 may be damaged.

[0068] The controller 115 initiates and controls the denitration and desulfation processes, including the heating steps, primarily by operating the fuel injector 116. Optionally, the controller 115 may also be configured to alter the engine exhaust composition and or flow rate to facilitate regeneration. The controller 115 could be configured to actuate a throttle on the air intake for the engine 101. While throttling reduces the fuel required for regenerations and makes temperature control easier in the aftertreatment system 103, the alternative of configuring the exhaust aftertreatment system 103 to operate without affecting operation of the engine 101 also has advantages.

[0069] Generally, the controller 115 heats the fuel reformer 105 by injecting fuel into the exhaust at a rate that leaves the exhaust lean. If the fuel reformer 105 is at an operative temperature for oxidation, at least a portion of the injected fuel will combust in the fuel reformer 105, heating the fuel reformer 105. The exhaust is also heated and if the lean phase is prolonged the hot exhaust will heat downstream devices such as the DPF 108. The controller 115 generally produces rich conditions by increasing the fuel injection rate, although measures that reduce the exhaust oxygen flow rate (by reducing the exhaust oxygen concentration and or the exhaust flow rate) can be used instead of or in addition to increasing the fuel injection rate.

[0070] A pre-combustor can extend the operating temperature range for the fuel reformer 105. A pre-combustor is an optional catalytic device that can be configured upstream from the fuel reformer 105. A pre-combustor catalyzes combustion at temperatures below the light off temperature for the fuel reformer 105. Preferably, a pre-combustor comprises an oxidation catalyst and is designed to combust only a fraction of the injected fuel. Preferably, a pre-combustor vaporizes the portion of the fuel that it does not combust. Fuel vaporization contributes to the mixing of fuel with exhaust. Such mixing enhances the operation of the fuel reformer 105. A preferred pre-combustor design is a monolith having relatively large diameter passages and only a fraction of the passages coated with catalyst.

[0071] The DPF 108 is also an optional component, but one that is commonly included with the exhaust aftertreatment system 103. NO_X and particulate matter are the principal pollutants of diesel engine exhaust. A diesel exhaust aftertreatment system generally requires a DPF to control particulate matter emissions in addition to some means for controlling NO_X emissions.

[0072] A diesel particulate filter is a device that traps particulates, removing them from the exhaust flow. The DPF 108 can be a wall flow filter, which uses primarily cake filtration, or a pass through filter, which uses primarily depth filtration. Wall flow filters are more common. In a wall flow filter, the soot-containing exhaust is forced to pass through a porous medium. Typical pore diameters are from about 0.1 to about 1.0 μm. Soot particles are most commonly from about 10 to about 50 nm in diameter. In a fresh wall flow filter, the initial removal is by depth filtration, with soot becoming trapped within the porous structure. Quickly, however, the soot forms a continuous layer that becomes the primary means of filtration.

[0073] The DPF 108 can have any suitable structure. Examples of suitable structures include monolithic wall flow filters, which are typically made from ceramics, especially cordierite or SiC, blocks of ceramic foams, monolith-like structures of porous sintered metals or metal-foams, and wound, knit, or braided structures of temperature resistant fibers, such as ceramic or metallic fibers.

[0074] The position of the DPF 108 within the exhaust system 103 is optional. Between the fuel reformer 105 and the LNT 107, the DPF 108 can operate as the thermal mass 106. Placing the DPF 108 between the fuel reformer 105 and the ammonia-SCR reactor 110 helps protect the SCR catalyst 110 from high temperature conditions generated to desulfate the LNT 107. Preferably, the DPF 108 is upstream from the Venturi 109. Preferably, the ammonia SCR reactor 110 is the only exhaust treatment catalyst downstream from the Venturi 109. Exhaust treatment catalysts generate back pressure, which can interfere with the performance of a Venturi.

[0075] Trapped soot can be removed from the DPF 108 continuously by catalyzing reactions between soot and NO_X, but to avoid excessive accumulation of soot and excessive back pressure on the exhaust flow the DPF 108 must typically be heated from time-to-time to a temperature at which the DPF 108 regenerates by combustion of trapped soot under lean exhaust conditions. The temperature required for soot combustion can be reduced by a catalyst. Suitable catalysts include precious metals and oxides of Ce, Zr, La, Y, and Nd. Soot combustion is exothermic and is generally self-sustaining once ignited.

[0076] The Venturi 109 is formed in the exhaust conduit 104. The exhaust conduit 104 comprises conduits for the exhaust, typically including exhaust pipes. Exhaust pipes have standard sizes for medium and heavy duty vehicles that form the principle application for the present invention. A recommended size range and minimum size is generally specified by the engine manufacturer. A typical minimum exhaust pipe size is 5.0 inch (12.7 cm) diameter.

[0077] Optionally, the Venturi 109 is formed into an exit cone or other exit region of the DPF 108 or an entrance cone or other entrance region of the ammonia-SCR reactor 110. While the examples provide alternatives, the Venturi 109 is typically designed to constrict an exhaust flow received from either a standard exhaust pipe or from the outlet area of an exhaust treatment catalyst and to expand the diluted flow into another pipe of standard size or into the frontal area of another exhaust treatment catalyst.

[0078] A Venturi is a device that reduces the pressure of a flowing gas by forcing the flow through a constriction. Within the constriction, the neck region 112 of the Venturi 109, the reduced pressure draws air from the surroundings into the exhaust line 104 through an air intake 114. The air mixes with the exhaust increasing the exhaust oxygen content and reducing the exhaust temperature. The Venturi 109 is generic and can have any suitable structure, including a structure corresponding to any one of the exemplary Venturi described herein.

[0079] The ammonia-SCR reactor 110 is a catalyst effective to catalyze reactions between NO_X and NH_3 to reduce NO_X to N_2 in lean exhaust. Examples of SCR catalysts include oxides of metals such as Cu, Zn, V, Cr, Al, Ti, Mn, Co, Fe, Ni, Rd, Mo, W, and Ce and zeolites, such as ZSM-5 or ZSM-11. Preferred SCR catalysts include, without limitation, iron-exchanged zeolites, copper-exchanged zeolites, and vanadium oxide. The ammonia-SCR reactor 110 adsorbs and stores ammonia generated by the LNT 107 during denitration. The ammonia-SCR reactor 110 uses the stored ammonia to reduce NO_X that slips from the LNT 107. This improves the NO_X mitigation performance of the exhaust aftertreatment system 103 in comparison to one having only the LNT 107 for NO_X mitigation.

[0080] The ammonia-SCR reactor 110 allows the time between denitrations and the time between desulfations of the LNT 107 to be extended. Denitration of the LNT 107 may be delayed until the stored ammonia has been substantially consumed. Desulfation of the LNT 107 may be postponed until the combined performance of the LNT 107 and the SCR catalyst 110 has become inadequate.

[0081] The inventors have noted that the effectiveness of the ammonia-SCR reactor 110 is diminished during and after regeneration of the LNT 107, even when regeneration has replenished the reactor's ammonia supply. The effectiveness of the ammonia-SCR reactor 110 is diminished due to low air-fuel ratio and/or increased temperature.

[0082] The Venturi 109 is generally functional to improve the performance of the ammonia-SCR reactor 110 by drawing cool air into the exhaust. The effect may be due in part to reduced hydrocarbon adsorption and storage when exhaust conditions are made more lean. The catalytic reduction of NO_X by NH_3 in the ammonia-SCR reactor 110 proceeds at a higher rate when the exhaust is made more lean. Preferably, the Venturi 109 is functional to maintain lean conditions for the ammonia-SCR reactor 110 even as the LNT 107 is being regenerated under rich conditions.

[0083] Drawing air into the exhaust upstream of the ammonia-SCR reactor 110 can potentially heat the ammonia-SCR reactor 110 by fueling hydrocarbon combustion. Hydrocarbon combustion should not be allowed to heat the ammonia-SCR reactor 110 to an excessive temperature. For a typical SCR catalyst 625°C could be excessive while 550°C is not. If the temperature of the ammonia-SCR reactor 110 is allowed to reach an excessive level, the catalyst undergoes irreversible deactivation.

[0084] Heat generated by combustion is offset by the cooling effect of drawing air into the exhaust. By drawing sufficient air into the exhaust and optionally also regulating the hydrocarbon content of the exhaust during regeneration, the net effect can be made one of little or no heating and even one of cooling. A cooling effect is particularly advantageous during desulfation of the LNT 107 and high temperature regeneration of the DPF 108. The amount of hydrocarbon in the exhaust is preferably kept low to minimize the amount of excess air required, but there are practical limits on the extent to which the hydrocarbon content of the exhaust can be reduced.

[0085] For desulfation, the controller 115 preferably operates the fuel injector 116 such that the fuel reformer 105 consumes excess oxygen within the exhaust and provides the exhaust with a hydrocarbon and reformate content between 1% and 6%, typically 2%-4%. Numbers are time averaged for the ubiquitous pulsations in internal combustion engine exhaust flow. About half the total hydrocarbon and reformate is consumed by the LNT 107 and the remaining half reaches the ammonia-SCR reactor 110. The preferred fuel injection rate provides an acceptable rate of desulfation while keeping the rate of hydrocarbon slip from the LNT 107 to the ammonia-SCR reactor 110 within acceptable limits. Excess hydrocarbon may be combusted within the ammonia-SCR reactor 110 using oxygen drawn by the Venturi 109.

[0086] The amount of air drawn by the Venturi 109 depends on the exhaust flow rate. The air draw increases with exhaust flow rate. Through much of the normal operating range of the system 100, the increase is more than proportional to the increase in exhaust flow rate. The back pressure caused by the Venturi 109 also increases with exhaust flow rate.

[0087] In general, design changes that increase the draw of the Venturi 109 also increase the back pressure it causes. The Venturi 109 is preferably designed to draw as much air as possible subject to a limit on the amount of back pressure that can be tolerated by the engine 101 after taking into account other sources of back pressure. The back pressure limit is reached when the engine 101 is at a peak flow condition, which occurs when the engine 101 is operating at its maximum rated power. The back pressure caused by the Venturi 109 include friction loses in the constriction zone 111, the neck zone 112, the expansion zone 113, and the pressure required to draw cold air through the air intake 114.

[0088] For effective mitigation of hydrocarbon poisoning in the ammonia-SCR reactor 110, the Venturi 109 is preferably designed to draw enough air to dilute the exhaust by at least 5% when the engine 101 is running at its maximum rated power. More preferably the Venturi 109 draws at least 10% air at this condition and still more preferably at least 20% air.

[0089] The Venturi 109 must reduce the exhaust pressure sufficiently to draw the desired amount of air. A pressure reduction of 1-4 kPa is generally required just to overcome the back press of the ammonia SCR reactor 109. The pressure must be further reduced to overcome the back pressure created by the Venturi 109 itself from the air entry point onward. Typically, the Venturi 109 will be sized to provide a pressure reduction of at least 5 kPa, more typically from 10 to 30 kPa. An exemplary design target is a 20 kPa reduction.

[0090] The cross-sectional area of the neck 112 that will achieve the target pressure reduction can be estimated based on the volumetric flow rate of the exhaust. The peak flow rate of the exhaust is generally suitable to use for design purposes. For medium duty power generation system the peak flow rate, which occurs when the engine 101 is operating at its maximum rated power, is from about 150 to about 900 kg/hr, typically from about 300 to 600 kg/hr. Heavy duty systems have higher flow rate ranges.

[0091] The pressure reduction of the Venturi 109 can be estimated from Bernoulli's principle. Bernoulli's principle states the pressure of a flow will decrease in relation to the flow speed. The decrease is roughly proportional to the density of the fluid multiplied by the flow speed squared. More exact formula are readily available as are tables and tools for computing the desired cross-sectional area for the neck based on the target pressure reduction. Tables and formula typically give the cross-sectional area of the neck that gives a target pressure reduction as a ratio with the cross-sectional area at which the Mach number is one.

[0092] The Mach number is the ratio between the flow speed and the speed of sound under the prevailing conditions. For a typical exhaust composition at 300 ºC, the speed of sound is approximately 480 m/s. The speed of sound varies approximately as the square root of absolute temperature.

[0093] The neck 112 typically raises the Mach number to at least 0.2, commonly at least 0.3, and even 0.5. These are much higher Mach numbers than are typical for exhaust system Venturi that do not need to overcome the back pressure created by a device such as the ammonia-SCR reactor 110. For typical operating conditions and designs, the ammonia-SCR reactor 110 causes backpressure in the 1 to 4 kPa range. The draw pressure provided by the Venturi 109 must be greater than this back pressure, e.g., 5 kPa or more to assure the Venturi 109 is able to draw.

[0094] For a pressure reduction of 20 kPa the area of the neck must be approximately twice the area at which the Mach number would be one (providing mach 0.5). For a 300 kg/hr flow rate at 300 ºC, which is typical for a 5" diameter exhaust pipe, the neck area that achieves mach 0.5 is approximately 0.0012 m^2 (roughly corresponding to a 1.5" pipe diameter). The neck can be made narrower if the resulting back pressure is not excessive, but in no case should the neck be made so narrow as to raise the Mach number to 1.0 or greater. For typical medium and heavy duty diesel truck applications, the requirements make the preferred neck area in the range from about 0.0005 m^2 to .0025 m^2. The neck area is preferably sized to provide a mass flux rate in the range from 50 to 200 kg/m^2s when the engine 101 is in a peak flow condition.

[0095] To limit the back pressure caused by the Venturi 109, and limit the pressure reduction required of the

Venturi 109, the Venturi 109 is preferably designed to minimize friction losses. Sudden contractions and expansion can cause large friction losses in exhaust flows. These losses can be greatly reduced by making the increases and decreases in flow area gradual. For example, limiting the taper within the expansion zone of a duct (exhaust pipe) to an angle less than about 8° avoids boundary layer separation and greatly reduces irreversible head losses due to flow through the expansion zone. Where a very gradual taper is not practical, guide vanes can be used to reduce friction loses.

[0096] Friction losses caused by pipe bends, sudden expansions, and sudden contractions, can all be reduced using guide vanes, typically by 50% or more. Space is often at a premium within exhaust aftertreatment systems and the advantages of compact designs weigh against the advantages of gradual taper. Where momentum drives the flow toward concentrating in one part of a duct, guide vanes can be used to more uniformly distribute the flow. The advantages of guide vanes must be balanced against the friction loses they cause. Also, the addition of guide vanes increases complexity and cost. The examples that follow do not illustrate guide vanes, but can be modified to include guide vanes with the shape number and location being best determined using a combination of intuition, flow simulation, and experimentation.

Venturi integrated with a pipe bend

[0097] A concept disclosed herein is a Venturi 109 in which the constriction zone 111, the neck zone 112, and/or the air inlet 114 are integrated into a bend of an exhaust pipe or similar flow-turning exhaust conduit. This concept is applicable to any internal combustion engine exhaust system in which a Venturi is desired. For example, a Venturi may be desired to cool the exhaust. Forming the Venturi according to this concept reduces the back pressure required by the Venturi.

[0098] Exhaust flows are turbulent. Within exhaust pipe bends, the momentum of the gases concentrates the flow on the outer portion of the bend. As the flow concentrates, it must accelerate. By Bernoulli's principle, the pressure along the outer portion of the bend will be reduced as it accelerates along flow streamlines. Bernoulli's principle does not explain the entire pressure distribution across the bend: pressures near the inner side of the bend are also reduced. By arranging a cold air inlet to admit ambient air into one or more low pressure regions within a conduit bend, a Venturi can be created within the bend with or without narrowing the flow passage. By forming a Venturi in a conduit bend, the back pressure required by a Venturi is partially subsumed within the back pressure required to change the direction of the exhaust flow, reducing the total back pressure as compared to providing the conduit bend and the Venturi separately.

[0099] Forming a Venturi in a conduit bend is particularly suited for internal combustion engine exhaust systems where both Venturi and exhaust pipe elbows are desirable. Internal combustion engines are sensitive to back pressure. Venturi create back pressure. Exhaust pipe elbows also create back pressure, but are nevertheless used in many internal combustion engine exhaust systems, especially vehicle-mounted systems, to accommodate packaging limitations. Such limitations may relate to available space, required location, manufacturing cost, or ease of installation. Packaging considerations often motivate the placement of a bend between the DPF 108 and the ammonia-SCR reactor 110, making a Venturi formed in a pipe bend particularly well suited for this system. Figure 5 provides an example of this type of packaging with a 90° bend, and Figures 19 and 20 provide examples of 180° bends.

[0100] A bend is a portion of a conduit over which the direction of the channeled flow, averaged through complete cross-sections of the flow, changes. A typical bend is a 90° bend, but a Venturi can be constructed in a greater or lesser bend. While there is no precise minimum, it is expected that suitable bends will provide a turn of at least 45 degrees. The bend can have any suitable radius of curvature. Based on experience with cylindrical pipe elbows, the centerline radius of curvature (CLR) for a suitable bend is generally in the range from 1 to 2 times the pipe hydraulic diameter and is preferably be from 1.0 to 1.5 diameters, more preferably 1.3 diameters or less. Tighter bends are difficult to form and may not have good flow characteristics. More gradual bends may not effectively facilitate forming Venturi.

[0101] Within an exhaust conduit bend, the momentum of the exhaust flow concentrates the exhaust on the outer portion of the bend. The purpose of the constriction zone 111 is to concentrate and thereby accelerate the exhaust flow. The bend therefore, achieves a similar effect to the constriction zone 111. A bend can be used as a constriction zone 111 without physically narrowing the flow channel or in addition to a constriction zone 111 that narrows the flow channel.

[0102] A narrowing conduit can preserve the accelerated flow condition created by a conduit bend beyond the bend. Without narrowing the conduit, the flow will expand downstream from the bend away from the side of the conduit on which the flow has become concentrated. By having the conduit narrow through the bend, the distance over which the flow is accelerated and its pressure reduced can be extended. The air intake 114 is generally placed to admit air into the bend, but if the cross-sectional area available for the flow narrows through the bend, the intake can be placed further downstream and still effectively utilize the bend's flow concentration.

[0103] Figures 2-8, 19-21, and 25-27 provide examples of Venturi formed into exhaust conduit bends. Venturi 200, which is illustrated by Figure 2, is formed into a bend 201 of a conduit 207. The Venturi 200 comprises a constriction zone 214 through which the mean flow direction changes and through which the area available for flow 202 narrow. Other examples show Venturi formed in conduit bends of uniform cross-section, through which the area available for flow remains constant. The Venturi 200 further comprises a neck zone 203 through which the flow 202 is most tightly constricted and an expansion zone 206. The outer wall 204 of the pipe bend 201 has the shape that would be expected for a 90° pipe bend having an outer radius twice its inner radius. The flow is constricted by shifting the inner wall 214 from location 211, which would be the inner wall location if the bend 201 did not constrict the flow.

[0104] The air intake 114 for the Venturi 200 comprises openings 209 formed in the outer wall 204 of the pipe bend 201. These openings are formed by cutting and bending tabs 210 in the wall 204. The tabs 210 bend into the exhaust flow 202 and divert the flow away from the openings 209. Comparatively high pressure regions form behind the tabs 210, with the result that air flows from these regions into the low pressure exhaust racing past the tabs 210. Air is drawn from an air intake manifold 212 through the openings 209 and into the conduit 207.

[0105] Figure 21 illustrates Venturi 1000, which is another example of a Venturi formed into a conduit bend. The Venturi 1000 comprises a 90° exhaust pipe elbow 1012, a constriction zone 1011, and an expansion zone 1013. A cold chute 1014 admits ambient air into the elbow 1012 as exhaust flows from the constriction zone 1011 to the expansion zone 1013. The constriction zone 1011 and the expansion zone 1013 are designed to couple to catalysts. For example, the constriction zone 1011 can serve as the exit cone for DPF 108 and the expansion zone 1013 can serve as the entrance cone for the SCR catalyst 110. Alternatively, one or both of these zones can couple to exhaust pipes with cross-sections larger than that of the exhaust pipe elbow 1012.

[0106] For ease of construction, the Venturi 1000 preferably maintains a uniform cross section within the neck region 112 formed by the elbow 1012. The constriction zone 1011 provides a smoothly and continuously decreasing cross-sectional area for the exhaust flow, decreasing the area available for flow from that at the exit of the diesel particulate filter 108, or other exhaust treatment device immediately upstream from the Venturi 109, to the cross sectional area of the elbow 1012. Alternatively, the constriction zone 1011 can couple to an exhaust pipes having a diameter larger than that of the exhaust pipe elbow 1012 and can constrict the flow down just from that comparatively smaller area. Likewise expansion zone 1013 provides a smoothly and continuously increasing cross-sectional area for the exhaust flow, increasing from the cross-sectional area of the flow as it leaves the elbow 1012 to the frontal area of an ammonia SCR reactor 110, or alternatively just to the cross-sectional area of a larger exhaust pipe configured downstream from the Venturi (109).

[0107] The Venturi 1000 lends itself to a simple and cost-effective manner of construction. The neck region is formed from an exhaust pipe elbow, which in turn can be formed by bending a straight length of exhaust pipe. The cold chute 1014 can be formed of a simple tube inserted through a wall of the elbow. The elbow can be bent before or after connecting it to either the expansion zone 1013 or the constriction zone 1011. The constriction zone 1011 and the expansion zone 1013 are each axisymmetric, which simplifies their constructions.

[0108] The constriction zone 1011 has an S-shaped side wall, which provides a lower flow resistance than a cone occupying the same amount of space and providing the same reduction in area available for flow. The expansion zone 1013 has side walls angling 6 degrees from its central axis 1020. Equivalent length parabolic expansion zones, such as the expansions zones 1213 and 1113 of Figures 19 and 20, were found to provide an even lower flow resistance for an equivalent length and degree of flow expansion.

[0109] The amount of draw provided by the Venturi 1000 depends on the diameter of the cold chute 1014. Figure 22 plots calculated results for the Venturi draw as a function of the diameter of the elbow 1012 and the diameter of the cold chute 1014. The calculations are for an exemplary 350 kg/hr flow of exhaust at a temperature of 650 ºC and assume an SCR catalyst 110 exerting 1 kPa back pressure. Figure 23 plots corresponding back pressure calculations. These plots show the potential for obtaining substantial air dilution while exerting little back pressure.

[0110] The draw of Venturi 1000 can be increased by either reducing the diameter of the elbow 1012 or increasing the diameter of the cold chute 1014. Calculations suggested that the increase in back pressure for a given increase in air draw would be approximately the same regardless of which method was used to increase he air draw. Plastic parts testing, however, showed some significant differences so that the optimal elbow diameter-cold chute diameter pairing depends on the expected flow rate, the dilution fraction targeted, and other design details.

[0111] In terms of other design details, experiments have been conducted to determine the optimal position of the cold chute 1014. A first consideration is the positioning of the cold chute 1014 along the length of the bend 1012. For the 90º elbow, with a cold chute 1014 formed of a simple tube, the preferred positioning placed the outlet 1023 of the cold chute 1014 from 35 to 45° into the bend 1012, most preferably 40° into the bend 1012. This result can be extended to other geometries.

[0112] The angle of the cold chute 1014 also has an effect. Most preferably the cold chute 1014 is angled so as to be nearly parallel to the direction of the exhaust flow at the chute exit 1023. This direction can be assumed to be parallel to the elbow centerline 1020. Preferably, the cold chute 1020 is position within 30 degrees of this direction and more preferably within 15 degrees.

[0113] Another consideration is the position of the cold chute 1014 relative to the centerline 1020 of the bend 1012. Initially, it was expected that the cold chute 1014 would draw better if offset from the center line 1020 toward the outer side 1021 of the bend 1012. Experiments showed, however, that he cold chute 1014 draws best if offset from the centerline 1020 toward the inner side 1022 of the bend 1012. The center of the outlet 1023 is offset from the center line 1020 toward the outer portion of the bend. The offset is preferably 10 to 50% of the distance from the center line 1020 to the inner side 1022 of the bend 1012. These offsets cause most or all the cold air to enter the exhaust flow closer to the inner side 1022 of the bend 1012 rather than closer to the outer side 1021 of the bend 1012.

[0114] Some spacing of the outlet of the cold chute 1014 from the inner side 1022 of the bend 1012 is still desirable. The outer edge of the outlet 1023 is preferably offset from the inner side 1022 of the bend 1012 from 20-60% of the distance to the centerline 1020, more preferably 20-40%.

[0115] The results of plastic parts testing for three examples are plotted in Figure 24. For all cases, the elbow curvature was 1.16 times the tube diameter. The flow rates over which the data were generated were I the range from 350 to 900 kg/hr. The parameters that differentiated the three examples are given in Table 1. The data shows the potential for significantly improving the performance of a Venturi such as the Venturi 1000 by suitably positioning the cold chute 1014.

Design	Elbow diameter	Chute diameter	Offset from inner rim
Baseline	76 mm	34 mm	7 mm
Low Flow	79 mm	25 mm	7 mm
High Flow	76 mm	34 mm	12 mm

Table 1

[0116] Figures 25-27 illustrate a simple structure for effectively mounting the cold chute 1014 at a desired position within the elbow 1012. A slot 1043 is formed into the wall of the elbow 1012. The slot 1043 is sized to receive the cold chute 1014 to which is welded a dolphin fin 1041. The elbow 1012 and the dolphin fin 1041 fit tightly into the slot 1043 and can be welded to the wall of the elbow 1012, thereby sealing the gap and holding the cold chute 1014 firmly in position.

[0117] The Venturi 1000 provides a nearly constant flow area throughout the bend. In this example, the entire bend corresponds to the neck region 112. The diameter of the neck region provide a mass flux rate, averaged over the flow area and determined with the engine 101 at operating at it maximum rated power (torque-speed), in the range from 25 to 150 kg/m^{2}s, more preferably in the range from 50 to 75 kg/m^{2}s. These values are, on the whole, lower flux rates than would be preferred for a Venturi formed without a bend. The bend allows an effective Venturi to be formed with a larger neck area than would be required absent the bend.

[0118] Figures 19 and 20 illustrate Venturi 1100 and 1200, which are the same as the Venturi 1000 in most respects other than the way they are packaged into exhaust aftertreatment systems. The Venturi 1100 has a constriction zone 1111 that restricts the exhaust flow to the pipe diameter of the elbow 1012 and also provides the exit cone for a catalyst or other after treatment device such as the DPF 108. The Venturi 1100 has an elbow 1012 into which a cold chute 1014 is inserted, and a second elbow 1120 upstream from the elbow 1012. Together, the elbows 1120 and 1012 change the exhaust flow direction by 180º. The Venturi 1100 provides essentially the same performance as the Venturi 1000.

[0119] The cold chute for the Venturi 1100 can be placed in the elbow 1120 instead of the elbow 1012. This design, however, is inferior. The back pressure created by the downstream elbow 1012 causes pressures to be significantly higher within the elbow 1120 as compared to within the elbow 1012. As a result, the draw of a Venturi formed into the upstream elbow is significantly worse. On the other hand, providing cold chutes in both bends is a good alternative design.

[0120] The Venturi 1200 has a constriction zone 1211 that can provide the exit cone for an exhaust aftertreatment device such as the DPF 108. The constriction zone 1211 both restricts the exhaust flow to the pipe diameter of the elbow 1012 and changes the direction of the flow by 90º. The constriction zone 1211 is a side exiting nozzle that combines the functions of an exit cone, a constriction zone for a Venturi, and a 90º bend. The constriction zone 1211 replaces the constriction zone 1111 and the second elbow 1020. The inventors have found that integrating these components reduces back pressure as compared to providing the components separately as in the Venturi 1100.

[0121] The side exiting nozzle 1211 is shaped to smoothly constrict and redirect the exhaust flow exiting a catalyst or filter. The smoothly curving sides direct the exhaust flow toward the exit 1212. Preferably, the shape of the sides causes the flow streamlines to contract and curve steadily toward the exit 1212, minimizing the size and occurrence of re-circulation zones within the exhaust flow. The exit 1212 has a cross-section suitable to meet the Venturi flow rate requirement, which entails a cross-sectional area below that provided by the minimum exhaust pipe diameter for an exhaust system suitable for the engine 101.

[0122] The Venturi 1000, 1100, and 1200 have all been tested on a rig consistent with the system 100 illustrated by Figure 2. The tests spanned the speed-torque rang of the engine 101 and included denitration, desulfation, and DPF regeneration operations. The Venturi provided substantial draw which was evidenced by air to fuel ratio and temperature data. There was little or no backflow of exhaust from the cold chute 114 throughout the test cycles. When operations raised the temperature of the DPF 108 over 400 ºC, the Venturi cooled the exhaust, usually by at least 50 ºC. The Venturi cooled the SCR 110 even when the rate of fuel injection into the exhaust, in conjunction with throttling the air intake of the engine 101, prevented the Venturi from drawing sufficient air to keep the exhaust within the SCR 110 lean: the cooling effect of air dilution remained greater than the heating effect of reductants combusting in the SCR 110 with oxygen provided by the Venturi 109. Overall, the Venturi 109 protected the SCR 110 from excessive heating and increasing the air-fuel ratio of the exhaust entering the SCR 110. The operating temperatures to which the SCR 110 was reduced by the Venturi 109 were generally temperatures at which the SCR 110 had a higher efficiency as compared to the unreduced temperatures.

Exhaust sleeve and ram air intake

[0123] Another concept illustrated by Figure 2 is an air intake manifold formed by a sleeve that fits over an exhaust pipe. The intake manifold 212 is formed by a sleeve 208 that is shaped to slide over the exhaust pipe 207 downstream from the bend 201. A screen 215 filters the air flowing into the manifold 212. The sleeve 208 can be used to gather air and increase the draw of the Venturi 200.

[0124] Another concept is to use the flow of air past a vehicle, ram air, to enhance the intake of a Venturi. This concept is further illustrated by Figures 3-5. In these figures, a sleeve 302 gathers ram air into an intake manifold 312. From the intake manifold 312, the air is drawn through Venturi openings 309 formed in a pipe bend 301. Within the pipe 301, the air mixes with exhaust 303. Ram air 304 is air driven into the entrance of the manifold 312 by the normal forward movement of a vehicle on which is mounted the exhaust aftertreatment system employing the Venturi. The ram intake concept can be employed without a pipe bend, but the pipe bend facilitates a wide sweep for the ram intake, as best illustrated with sleeve 208 of Figure 2. As an alternative, or in addition, forced convection into a Venturi air inlet manifold can be produced by a fan. The lack of an energy requirement or moving parts is the particular advantage of the air intake manifold configuration providing vehicle motion induced ram assisted Venturi air intake.

Intake diffuser

[0125] For the benefit of air dilution by the Venturi 109 to be fully realized, the drawn air must effectively mix with the exhaust prior to reaching the catalyst of the ammonia-SCR device 110. If the intake air joins the exhaust flow exclusively at the flow perimeter, it may remain concentrated at the perimeter through the flow expansion in the zone 113.

[0126] One concept for achieving a well mixed flow is to configure the Venturi air intake 114 to admit air into the exhaust flow at distributed locations. This can be achieved by extending the intake manifold to intrude the exhaust flow area and admit the air into the exhaust through a plurality of small opening formed in the manifold. The plurality of openings are preferably spread evenly with respect to the exhaust flow.

[0127] Figures 6 and 7 illustrate an exemplary Venturi 400 similar in many respects to the Venturi 200, but including a diffuser pipe 414 that intrudes the exhaust flow area and admits air into the exhaust through a plurality of small openings formed about the diffuser pipe 404's perimeter. The shape of the diffuser pipe 414 and the distribution of its openings are similar to that shown in Figure 8 with the diffuser pipe 502. The diffuser pipe 502 intrudes a pipe bend 501 of a Venturi 500. The manifold 412, which requires an additional piece 415 to the pipe sleeve 208, channels the air into the diffuser pipe 414. The diffuser pipe 414 has openings distributed over a large number of radii and also over an extended axial length. The diffuser 414 can take on complex shapes that introduce air into the exhaust in a still more evenly distributed manner, but friction losses and resulting back pressure militate against excessively disrupting the exhaust flow within the neck region 112 with intruding passages.

Intake check valve

[0128] Another feature of the Venturi 400 is a hinged door 413 that provides a check valve for intake air. While the preferred embodiments generally avoid moving parts, a check valve for intake air can be desirable to prevent backflow of exhaust out the Venturi air intake 114. The door 413 is biased to a closed position in which the door seals against the stop 414 to close off the manifold 412 from the external environment. The door 414 is configured to open only when the pressure differential across the door 413 is great enough and in the direction that causes air to enter the Venturi 400.

[0129] A biasing force for a Venturi air inlet can be created in any suitable manner. Examples of potentially suitable means include a spring that biases the door 413 closed, a configuration where gravity tends to hold the door 413 closed, and a magnet that draws the door 413 closed. Figure 9 illustrates a Venturi 600 in which gravity biases to a closed position a door 615 that blocks exhaust from the Venturi neck 612 from escaping the exhaust line. The door 413 can be replaced by a plurality of doors that collectively close the intake 114. The doors can be placed at any suitable location through the intake 114. Figure 10 illustrates an exemplary Venturi 700 in which a plurality of spring-biased hinged plates 715 actuate to seal off air intakes 714 where they join the Venturi neck 712.

Cyclonic air filtration

[0130] Another concept is to prevent foreign manner from entering the exhaust line through the Venturi using cyclonic filtration. Foreign matter could clog air intake passages or damage the ammonia-SCR reactor 110. Figure 11 illustrates a Venturi 800 employing cyclonic air filtration. Cyclonic air filtration is achieved by imparting a rotation to the intake air flow. Centrifugal force drives particles away from the axis of rotation. Accordingly, the Venturi air is drawn from the flow area nearest the axis of rotation and thus away from the particulates.

[0131] The Venturi 800 comprises a contraction zone 811, a neck zone 812, and an expansion zone 813. A sleeve 818 held on mounts 819 forms intake manifold 817. Air enters the manifold through openings 815, preferably with a ram or fan flow assist. The intake air passes through vanes 816, guided entryways, or the like that impart a rotation to the entering flow about the axis of Venturi 800. From this rotating flow, air is drawn through openings 814, which are as close to the axis of air rotation as any part of the intake manifold 817. Particulates in the air are driven to the outer shell 818. The outer shell 818 may contain openings 820 to release the particles.

Venturi formed into an SCR entrance

[0132] Another concept is to form the Venturi 109 into the entrance region of the ammonia-SCR reactor 110. The advantages of this design include space savings and the possibility of utilizing an expanding exhaust system cross-section to facilitate ram assisted air intake. If ammonia-SCR reactor 110 is connected to upstream devices with a standard exhaust pipe, the open area around the comparatively narrow region upstream from the ammonia-SCR reactor 110 facilitates the flow of air into the opening of a Venturi formed into the entrance cone.

[0133] Figures 12-14 illustrate Venturi formed into the entrance cones of SCR reactors. The Venturi 900 comprises a structure 903 that narrows the exhaust flow from pipe 901 into an annular region of expanding radii formed by the structure 903 and the entrance cone 902 and a tubular region formed entirely by the structure 903. The Venturi 910 has substantially the same structure, but different dimensions.

[0134] The Venturi 900 comprises opening 904 in the entrance cone 902 and through the corresponding annular region. These openings admit ambient air into an intake manifold 906. Air from the intake manifold 906 joins the exhaust in the region 903. A mixing zone 905, optionally including guide vanes that facilitate mixing, is provided in the region 907 between the entrance cone 902 and the catalyst of the ammonia-SCR reactor 110. The Venturi 910 has a similar structure, which may be more easily appreciated through the illustrations of Figures 13 and 14.

Distributed neck flow

[0135] Figures 12-14 illustrate another concept, which is distributing the exhaust flow through the neck region by spatially spreading the flow area provided by the neck. The Venturi 200 and 400 restrict the neck flow to a substantially cylindrical shape. The Venturi 900 illustrates that the neck flow can be constricted without confining the flow to a small area. In the Venturi 900, the annular region can have an arbitrarily large diameter, provided the difference between the inner and outer radii of the annulus suitably limits the cross-sectional area of the annulus. The flow can be distributed through any number of conduit structures having any suitable cross-section. The principle limitations are manufacturing considerations and back pressure.

[0136] Normally, the friction induced by the neck 112 is not the principle source of Venturi back-pressure. Typically, the principle sources of back-pressure are from constricting the flow into and expanding the flow out of the neck 112. Where a high degree of flow dilution is required, another significant contribution to the back pressure is from forces associated with accelerating the intake air. However, as the surface area of the neck increases, friction from the neck itself will eventually become an important factor.

[0137] Aside from the length of the neck region 112, an important parameter correlating with the magnitude of friction losses in the neck area is the hydraulic diameter of the neck. The hydraulic diameter is the diameter of a tube having the same perimeter to cross-sectional area ratio (surface area to volume ratio for a short section) as the neck. For example, the hydraulic diameter for the neck region of the Venturi 900 will be much less than the minimum diameter of the neck 203 for Venturi sized to accommodate equivalent exhaust flows.

[0138] One advantage of distributing the exhaust flow with a non-circular cross-section neck region is facilitating a uniform distribution of air intake into the exhaust flow. Previously, an intake air manifold was described for improving the distribution of air intake through the exhaust volume. Instead of, or in addition to an air intake manifold, a convoluted neck flow region can be used. The comparatively large surface area of a convoluted neck admits a wider distribution of air intake openings resulting in more intimate contact between Venturi air and exhaust even before the flows have had time to mix. The convolutions preferably reduce the hydraulic diameter of the neck region by at least a factor of four in comparison with a neck of circular cross section. A factor of four represents a very substantial increase in the flow perimeter.

[0139] Figures 15-18 illustrate a Venturi 950 that uses a lobed conduit 960 to provide a high surface area in a neck region 954. The Venturi 950 comprises a constriction zone 952, a neck zone 953 without openings for air intake, a neck zone 954 having openings to admit ambient air, and an expansion zone 955. In the region 951 upstream from the Venturi 950 and in the region 956 downstream from the Venturi 950, the exhaust line 104 has the circular profile illustrated in Figure 17. Within the constriction zone 952, the exhaust line cross-section smoothly transitions to the shape 960 illustrated in Figure 16. The shape 960 forces the exhaust 964 through a space 961 comprising eight lob-shaped protrusions. The profiles 951 and 960 are shown using the same scale for Figures 17 and 18. Accordingly, it can be seen that the flow area 961 is greatly less than that defined by passage 951 and that the flow will accordingly be accelerated and brought to a reduced pressure within the neck regions 953 and 954. Within the expansion zone 955, the exhaust line cross-section smoothly transitions back to its original circular shape.

Heat transfer using the neck region

[0140] Another concept is to systematically remove heat from the exhaust in the neck region of a Venturi.

Removing heat from exhaust requires overcoming a series of resistances. Those resistances include transfer of heat from the exhaust to a pipe wall, heat transfer through the pipe wall, and heat transfer away from the pipe wall, with the first and last being the most significant. A Venturi neck, particularly one having a convoluted cross-section, provides an excellent opportunity to carry out this heat transfer.

[0141] Figures 15-18 illustrate a Venturi 950 configured to transfer heat from the exhaust line 104 to the ambient. The Venturi 950 comprises neck regions 953 and 954 with the cross section 960 illustrated by Figure 18. As can be seen by comparing Figures 17 and 18 transition to the neck region 953 greatly reduces the mean distance between flowing exhaust and the conduit wall. Within the neck region 953, each portion of the exhaust is very near a wall in comparison with the conventional state shown in Figure 17. This greatly enhances the rate of heat transfer to the wall. The wall surface area is also increased, which makes for even faster heat transfer across the wall. More importantly, the shape 960 greatly increases the contact area between the conduit wall and ambient air when compared to the circular tube 951. To provide a substantially increased heat transfer rate in comparison with an equivalent length of ordinary exhaust pipe, the hydraulic diameter within the neck region 112 is preferably at least ten times less than that of adjacent pipe and the surface area per unit length (perimeter) is preferably at least two times greater. The eight lobs of Figure 18 provide approximately 2.5 times the perimeter of the straight pipe of Figure 17.

[0142] Heat loss from to the ambient can be further enhances with heat radiating vanes attached to the neck region. In this example, heat radiating vanes 959 are provided. Heat transfer from the exhaust to the external environment is particularly desirable during desulfation of the LNT 107 and when soot is combusting in the DPF 108.

[0143] The invention as delineated by the following claims has been shown and/or described in terms of certain concepts, components, and features. While a particular component or feature may have been disclosed herein with respect to only one of several concepts or examples or in both broad and narrow terms, the components or features in their broad or narrow conceptions may be combined with one or more other components or features in their broad or narrow conceptions wherein such a combination would be recognized as logical by one of ordinary skill in the art. Also, this one specification may describe more than one invention and the following claims do not necessarily encompass every concept, aspect, embodiment, or example described herein.

Industrial Applicability

[0144] The present invention is useful in making pollution control devices for vehicles.

The claims are:

1. An exhaust aftertreatment system (103) comprising:

an exhaust conduit (104) having a bend (201,301,1012), the exhaust conduit (104) being structured to channel an exhaust flow and to alter its direction as it passes through the bend (1012);

an air intake (114, 1012) having an inlet (1024) and an outlet (1023), the inlet (1024) being configured to admit ambient air, the outlet (1023) being configure to let the air out within the bend (201,301,1012) of the conduit (104);

wherein the air intake (114,1012) and conduit (104) provide a Venturi (109) that is functional to draw ambient air into an exhaust flow though the conduit (1014).

2. The exhaust aftertreatment system (103) of claim 1 wherein the conduit (104) further comprises:

a constriction zone (111, 1011, 1111, 1211) immediately upstream from the bend (1012) and through which the cross-sectional area available for the exhaust flow decreases; and

an expansion zone (113, 1013, 1113, 1213) immediately downstream from the bend (1012) and through which the cross-sectional area available for the exhaust flow increase.

3. The exhaust aftertreatment system of claim 2, wherein the expansion zone (113, 1013, 1113, 1213) continuously increases the area available for the exhaust flow from the cross-sectional area of the flow as it leaves the bend (1012) to the frontal area of an ammonia SCR reactor (110) configured downstream from the Venturi (109).

4. The exhaust aftertreatment system of claim 2, wherein the constriction zone (111, 1011, 1111, 1211) continuously decreases the area available for the exhaust flow from the area of the flow as it exits a diesel particulate filter (108) or other exhaust treatment device immediately upstream from the Venturi (109) to the cross sectional area of the flow as it enters the bend (1012).

5. The exhaust aftertreatment system (103) of claim 1 wherein the air intake (114, 1012) comprises a cold chute (1012)).

6. The exhaust aftertreatment system (103) of claim 5 wherein the outlet (1023) of the cold chute (1014) is offset from a central axis (1020) of the bend (1012) to the inner side (1022) of the bend (1012).

7. The exhaust aftertreatment system (103) of claim 5 wherein the outlet (1023) of the cold chute (1014) is offset from the inner side (1022) of the bend (1012) by at least 20% of the distance from the inner side (1022) of the bend (1012) to the central axis (1020) of the bend (1012).

8. The exhaust aftertreatment system (103) of claim 1 wherein the bend (1012) is an exhaust pipe elbow.

9. The exhaust aftertreatment system (103) of claim 8 wherein the bend (1012) comprises a 90 degree elbow of uniform pipe diameter.

10. The exhaust aftertreatment system (103) of claim 8 wherein the Venturi is the product of a process comprising inserting a cold chute (1014) through a wall of the exhaust pipe elbow.

11. A vehicle comprising:

an engine (101); and

the exhaust aftertreatment system (103) of claim 1;

wherein the exhaust aftertreatment system (103) comprises exhaust pipes that are of a standard diameter for the engine (101); and

the bend (1012) is formed of a pipe with a diameter less than the standard size.

12. A vehicle comprising:

an engine (101); and

the exhaust aftertreatment system (103) of 11;

the bend (1012) is formed of an exhaust pipe that is below a size range specified for the engine (101) by its manufacturer.

13. A vehicle comprising:

an engine (101) functional having a maximum rated power and producing an exhaust flow; and

the exhaust aftertreatment system (103) of claim 1 configured to receive the entire exhaust flow and channel the flow through the bend (1012);

wherein the dimensions of the bend (1012) cause the mass flux rate of the exhaust through the bend (1012) to be in the range from 25 to 150 kg/m^2s when the engine (101) is operating at the maximum rated power.

14. The vehicle of claim 13, wherein the dimensions of the bend (1012) cause the mass flux rate of the exhaust through the bend (1012) to be in the range from 50 to 75 kg/m^2s when the engine (101) is operating at the maximum rated power.

15. The exhaust aftertreatment system (103) of claim 1, further comprising:

a NO_X absorber-catalyst (107) having an exhaust inlet and an exhaust outlet and functional to absorb and store NO_X under lean conditions and reduce NO_X and regenerate its storage capacity under rich conditions; and

an ammonia-SCR reactor (110) having an exhaust inlet and an exhaust outlet and functional to reduce NO_X under lean conditions by catalyzing a reaction between NO_X and ammonia;

wherein the system (103) is configured to channel exhaust from the NO_X absorber-catalyst (107), through the conduit (104) comprising the bend (1012), and then to the inlet of the ammonia-SCR reactor (110).

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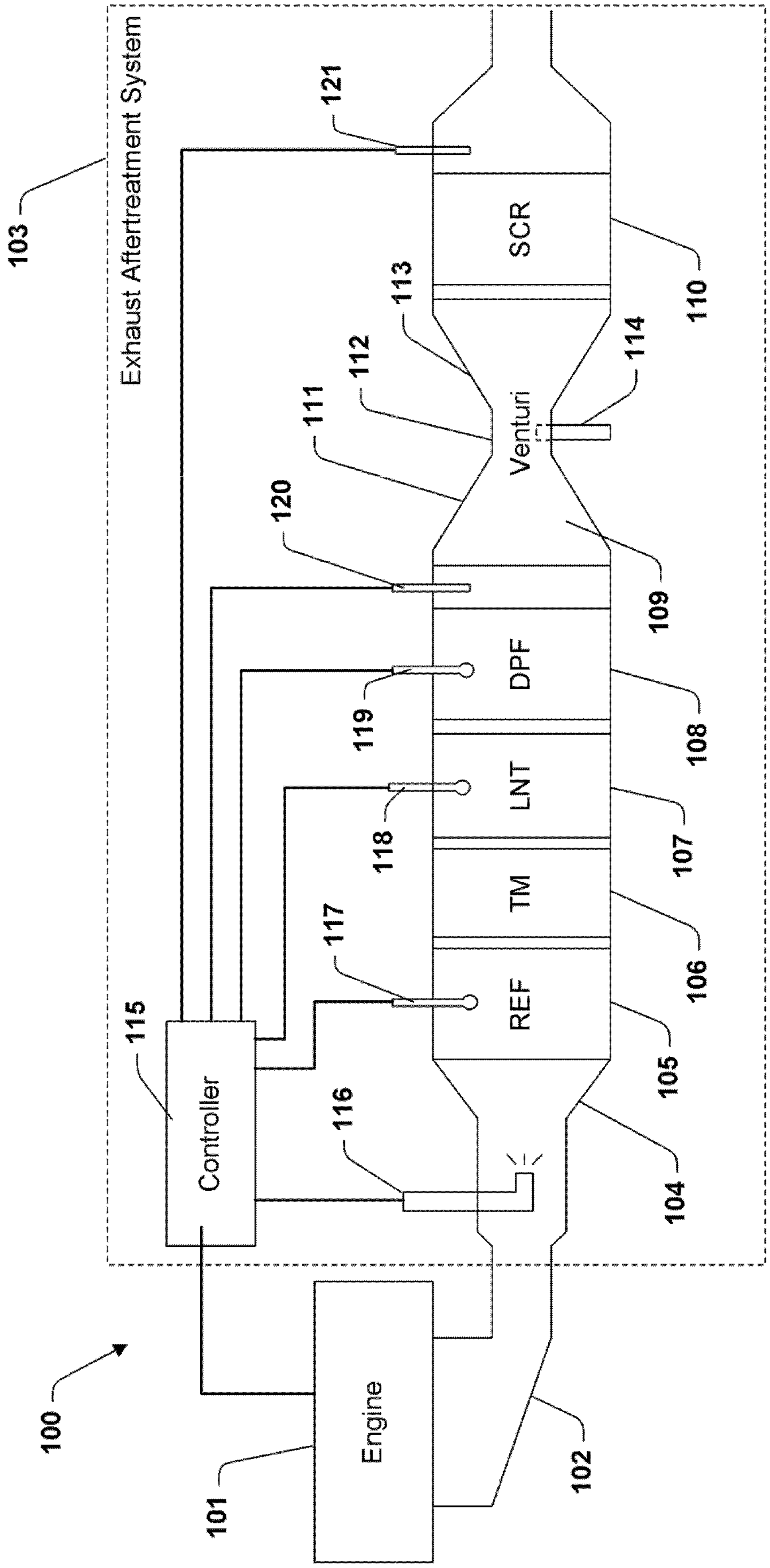
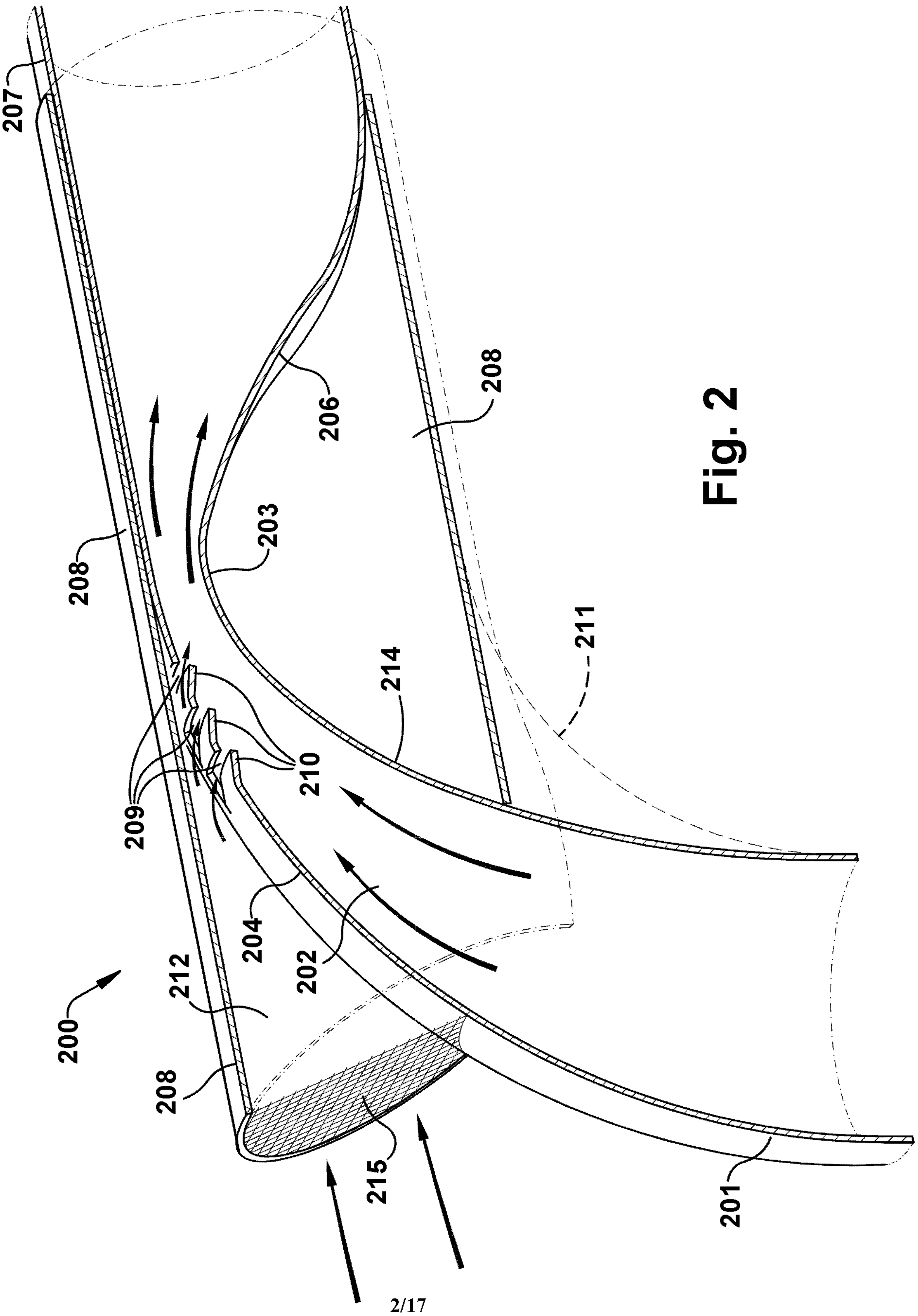


Fig. 1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215
201

Fig. 2

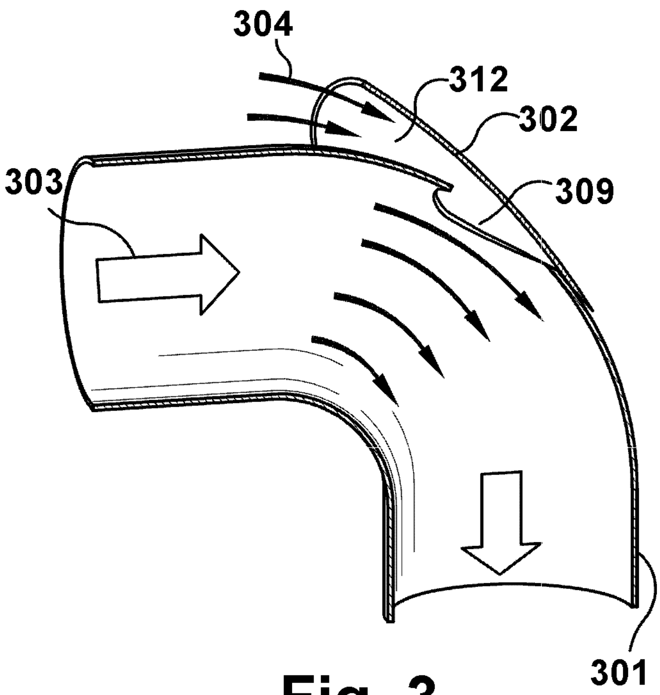

Fig. 3

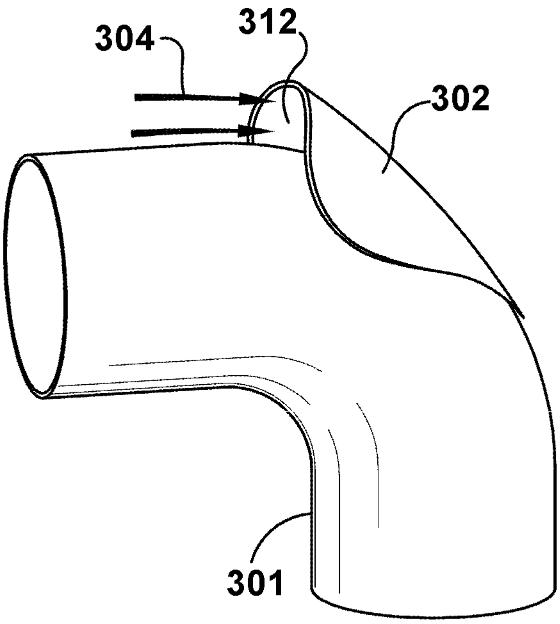

Fig. 4

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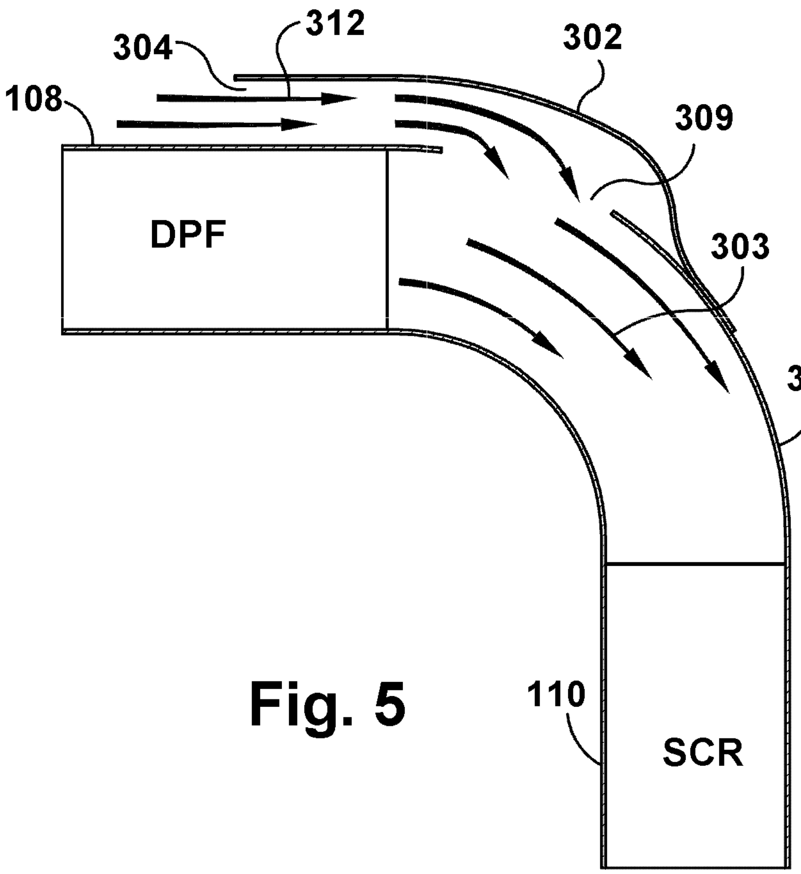


Fig. 5

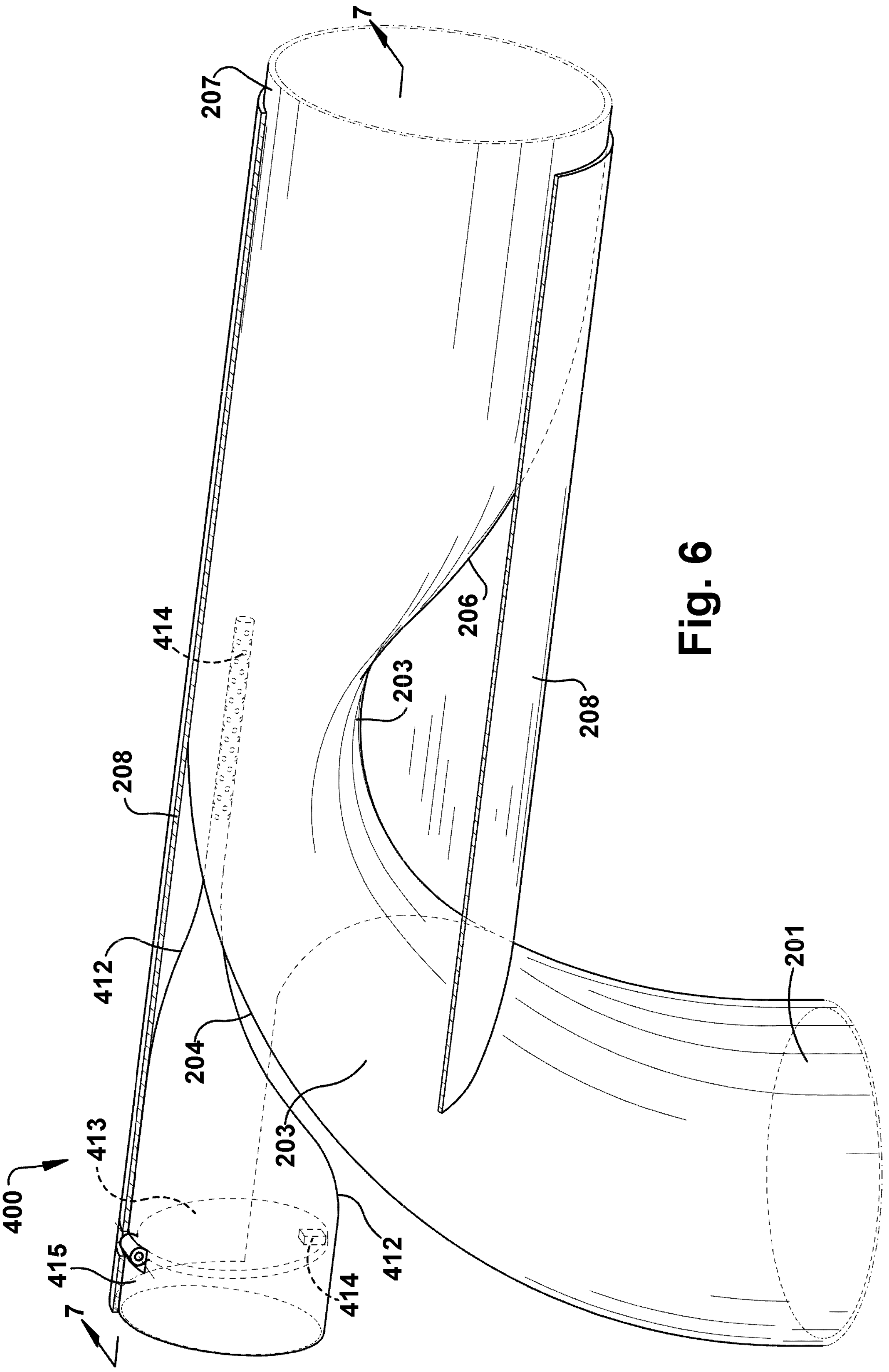


Fig. 6

Sheet 5/17

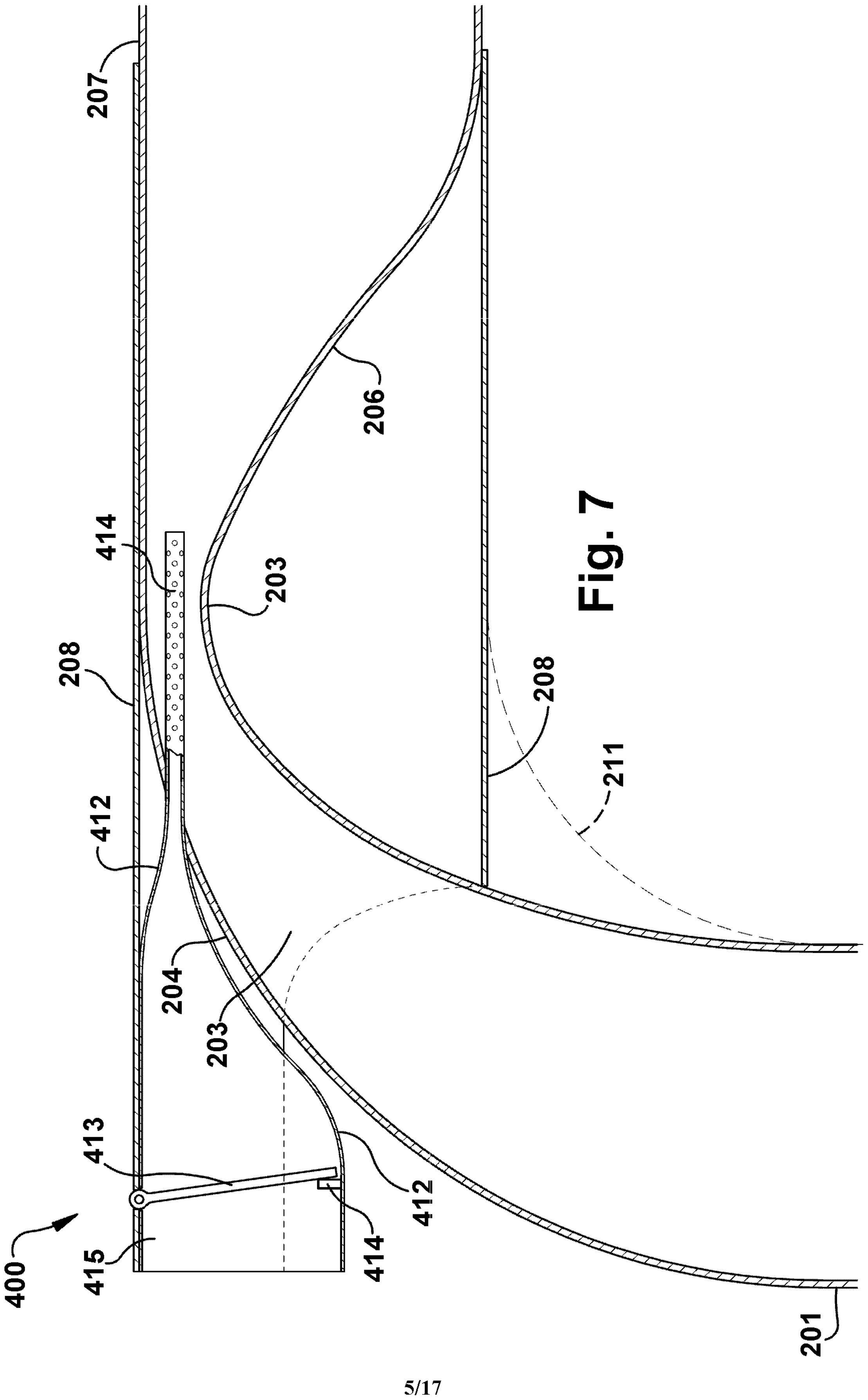


Fig. 7

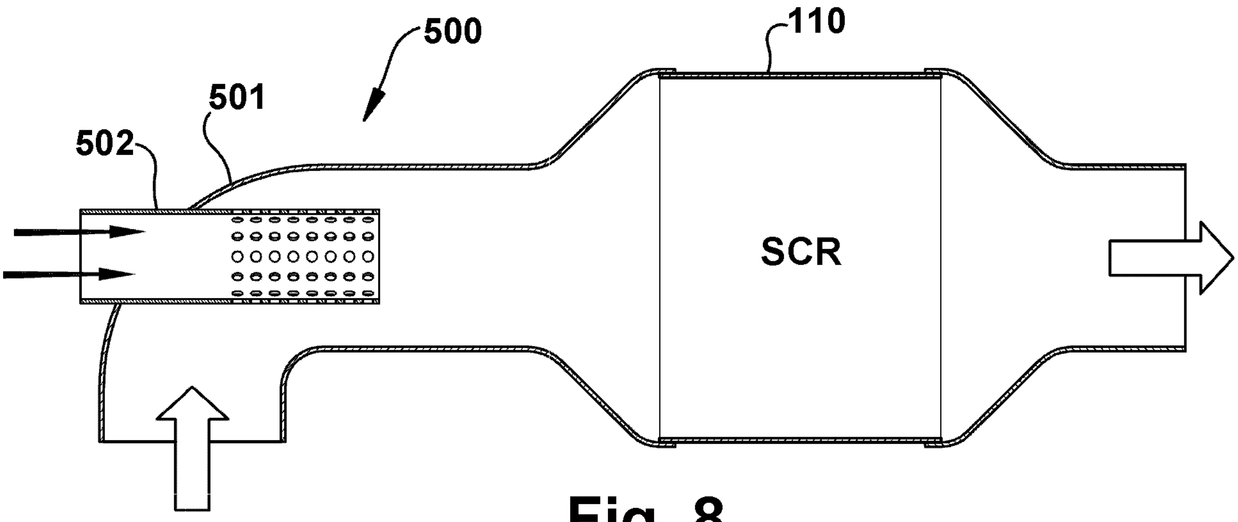


Fig. 8

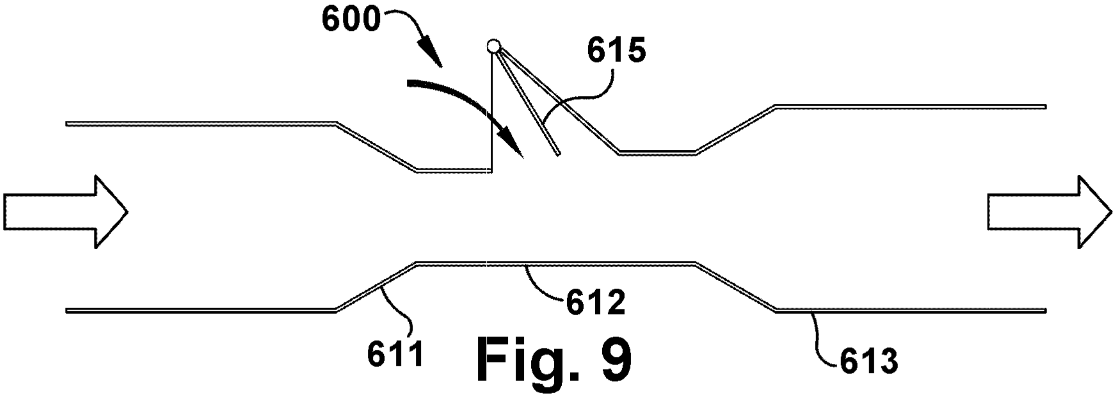


Fig. 9

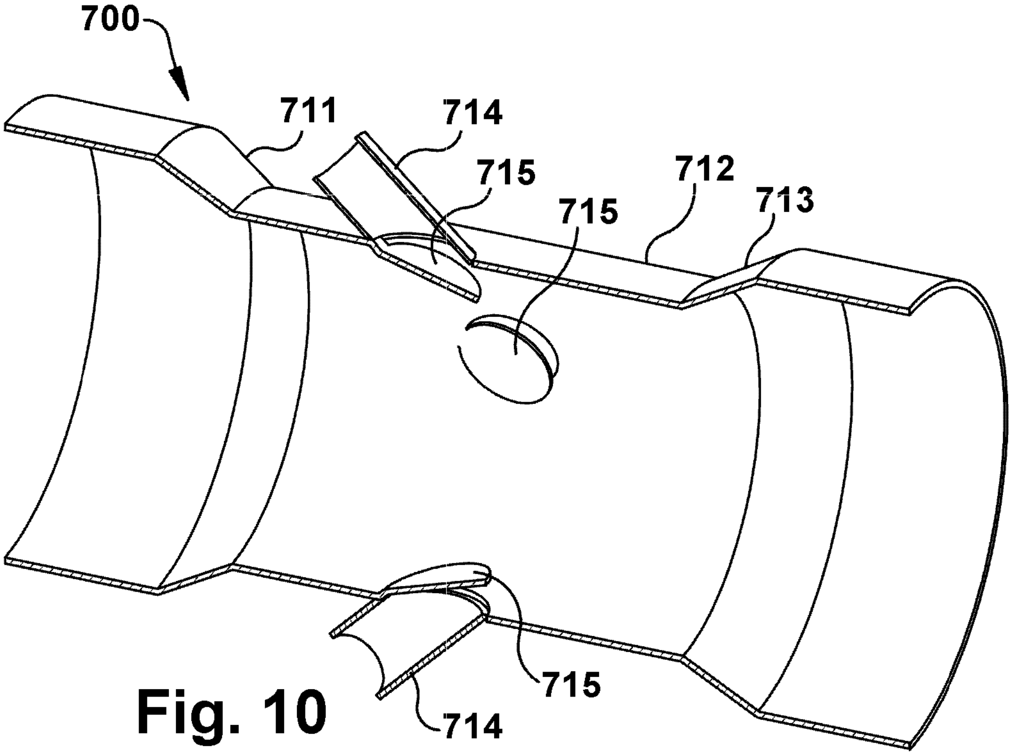


Fig. 10

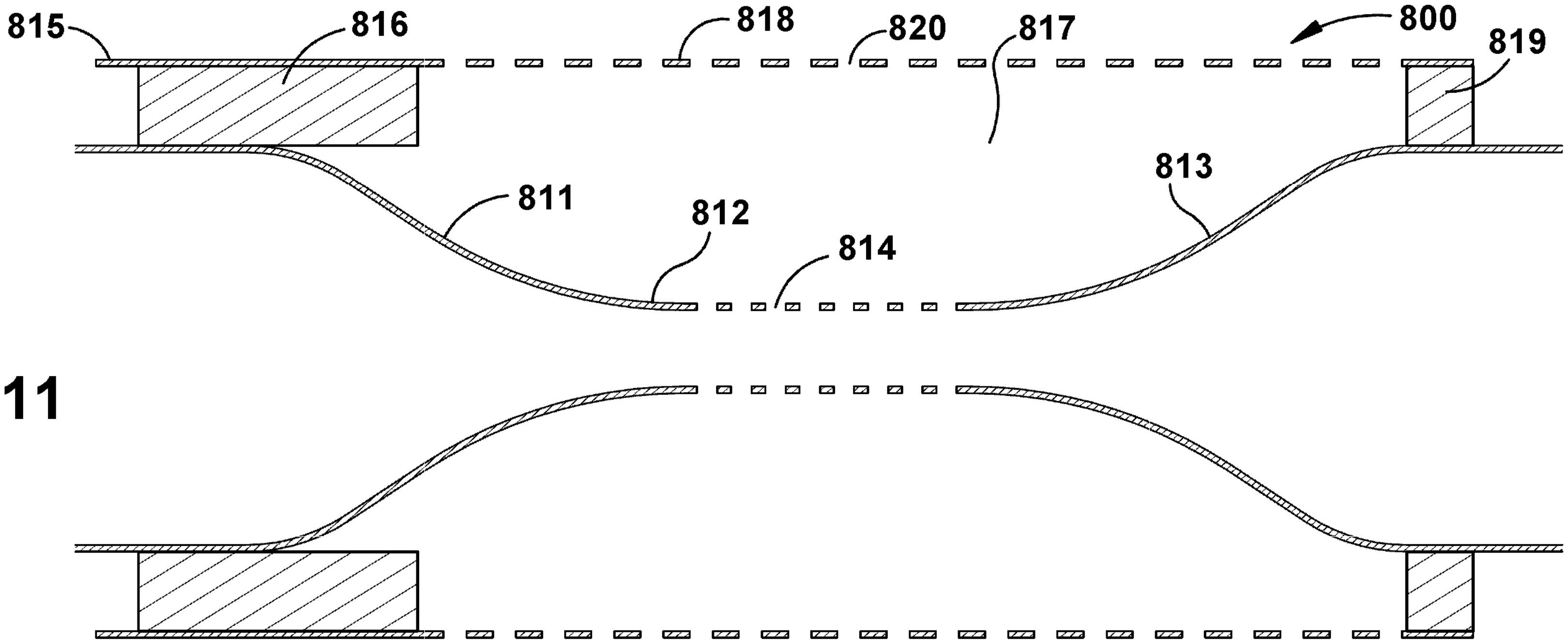

815
816
818
820
817
800
819
811
812
814
813

Fig. 11

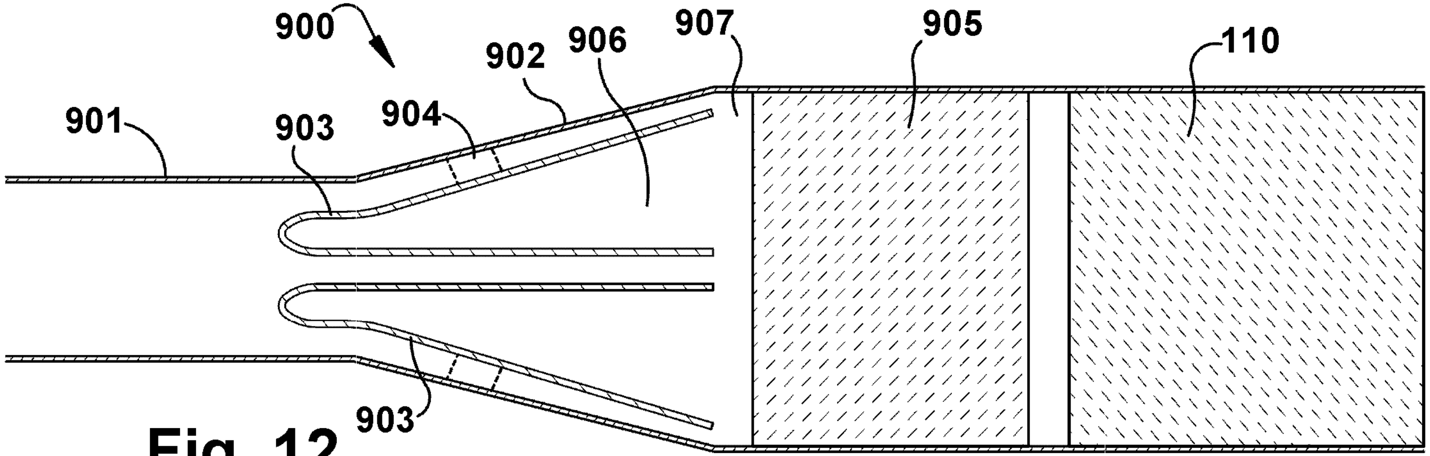
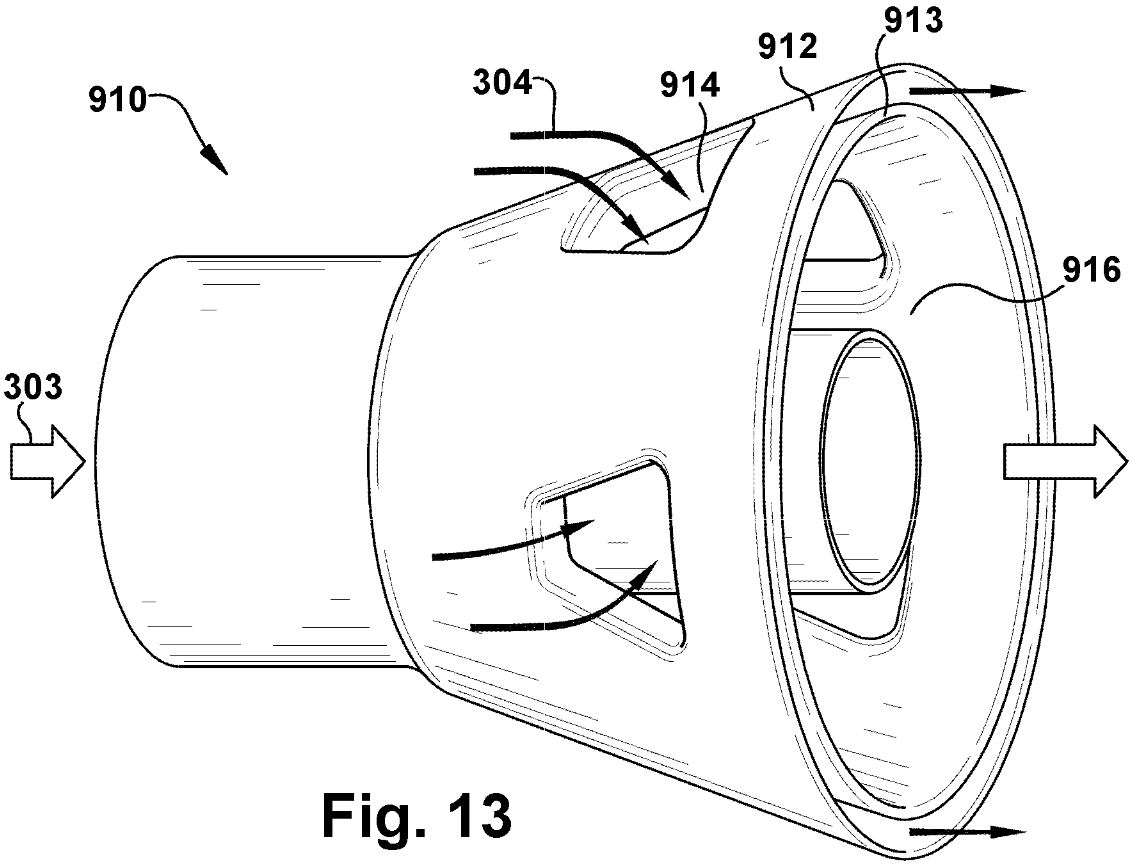

900
907
905
110
902
906
901
903
904
903

Fig. 12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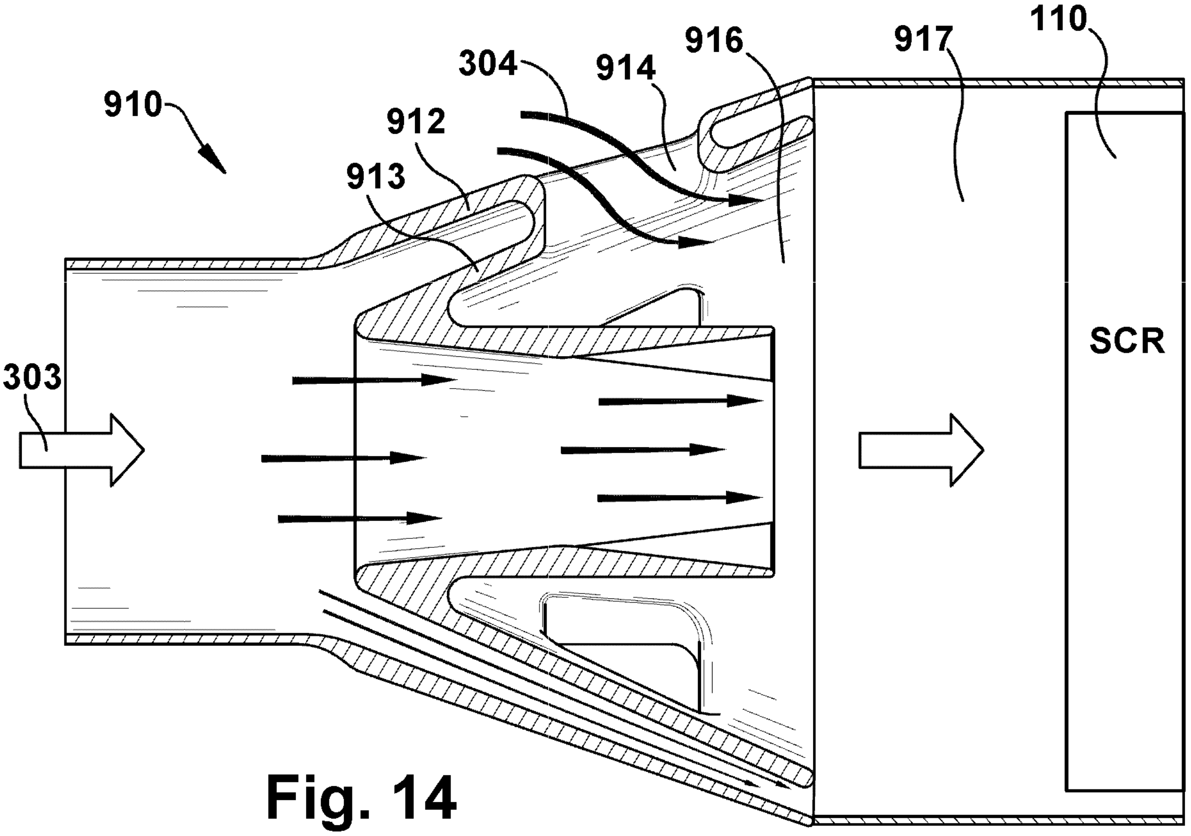
304
914
912
913
916
303

Fig. 13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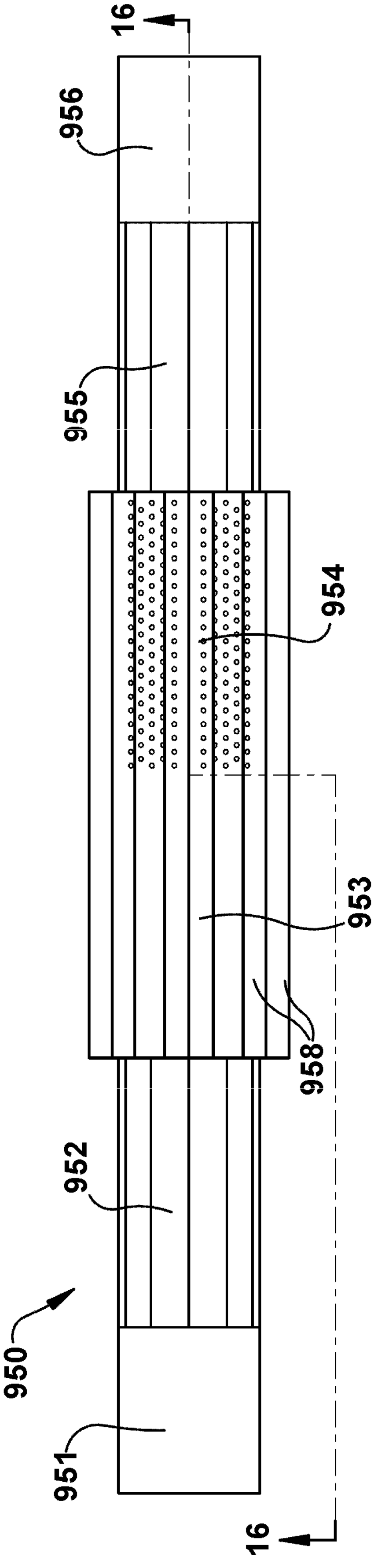
304
914
916
917
110
912
913
303
SCR

Fig. 14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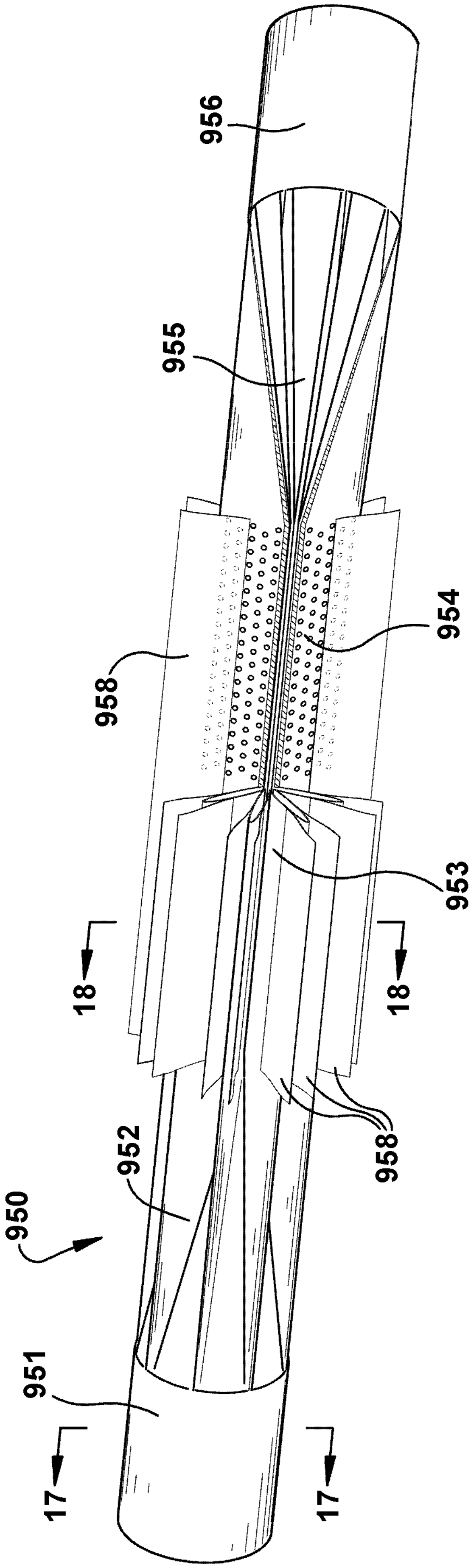
956
955
954
953
958
952
950
951
16

Fig. 15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951
17
17

Fig. 16

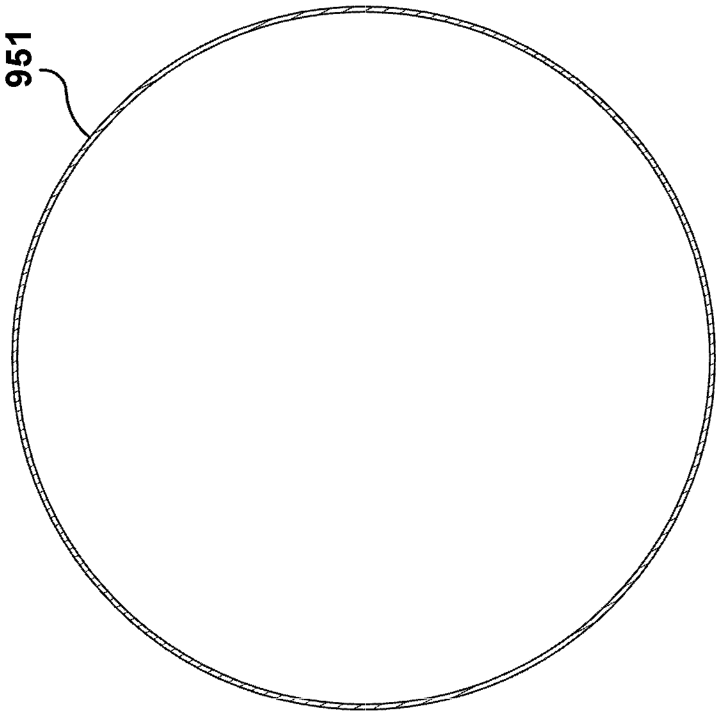


Fig. 17

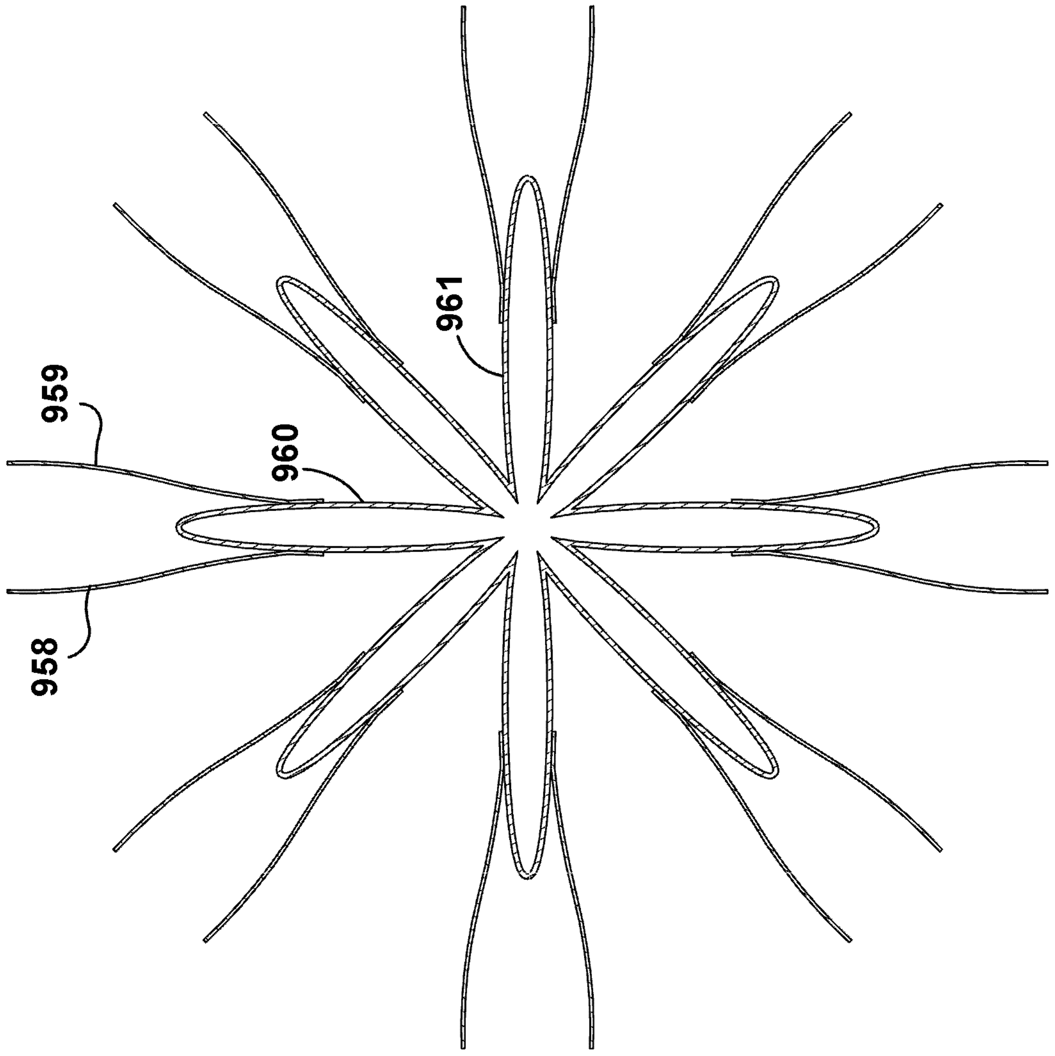


Fig. 18

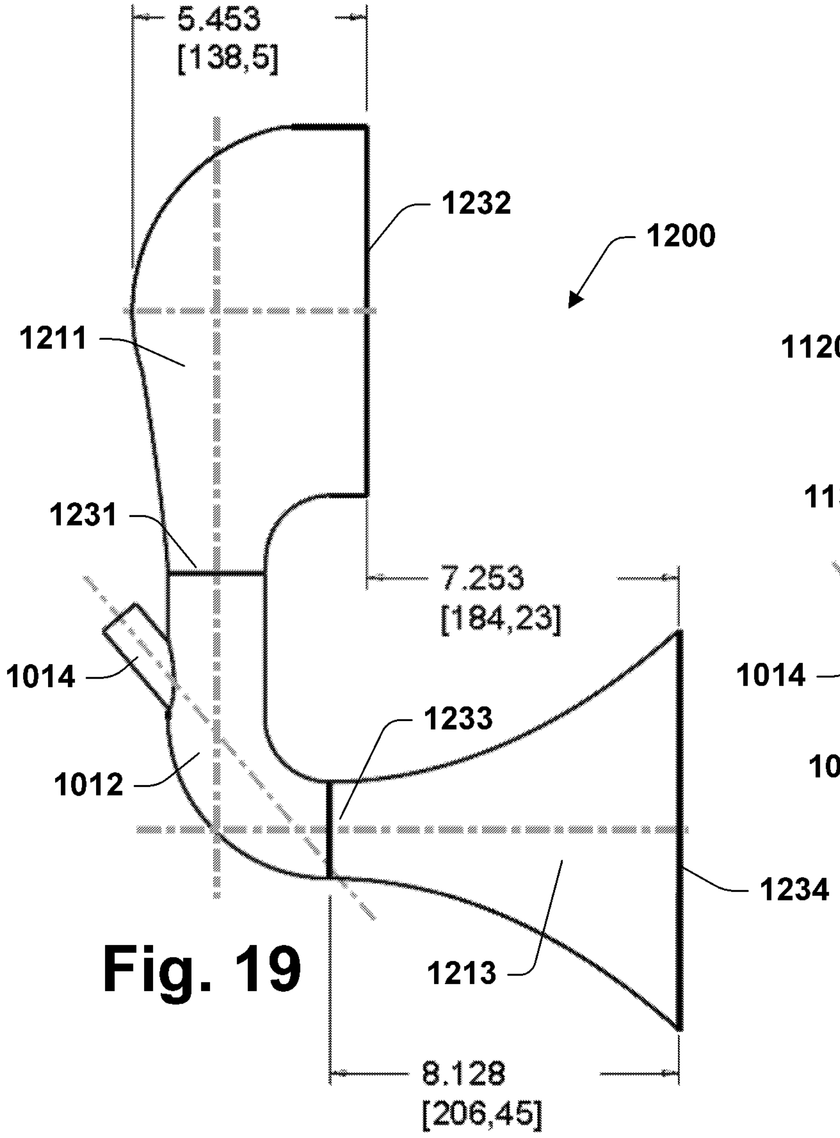
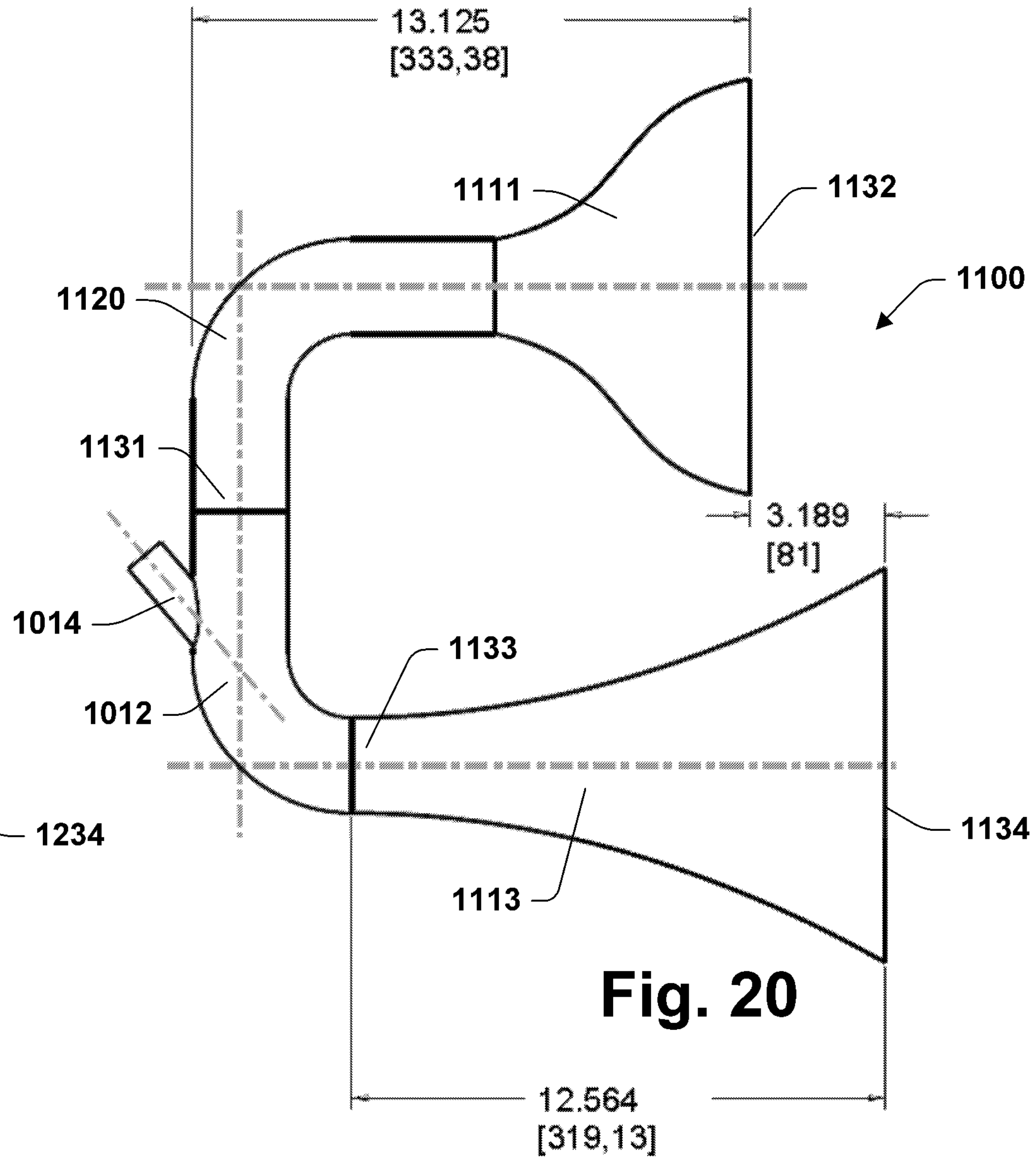

5.453
[138,5]
1232
1200
1211
1231
7.253
[184,23]
1014
1233
1012
1234
1213
8.128
[206,45]

Fig. 19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[333,38]
1111
1132
1100
1120
1131
3.189
[81]
1014
1133
1012
1134
1113
12.564
[319,13]

Fig. 20

Sheet 13/17

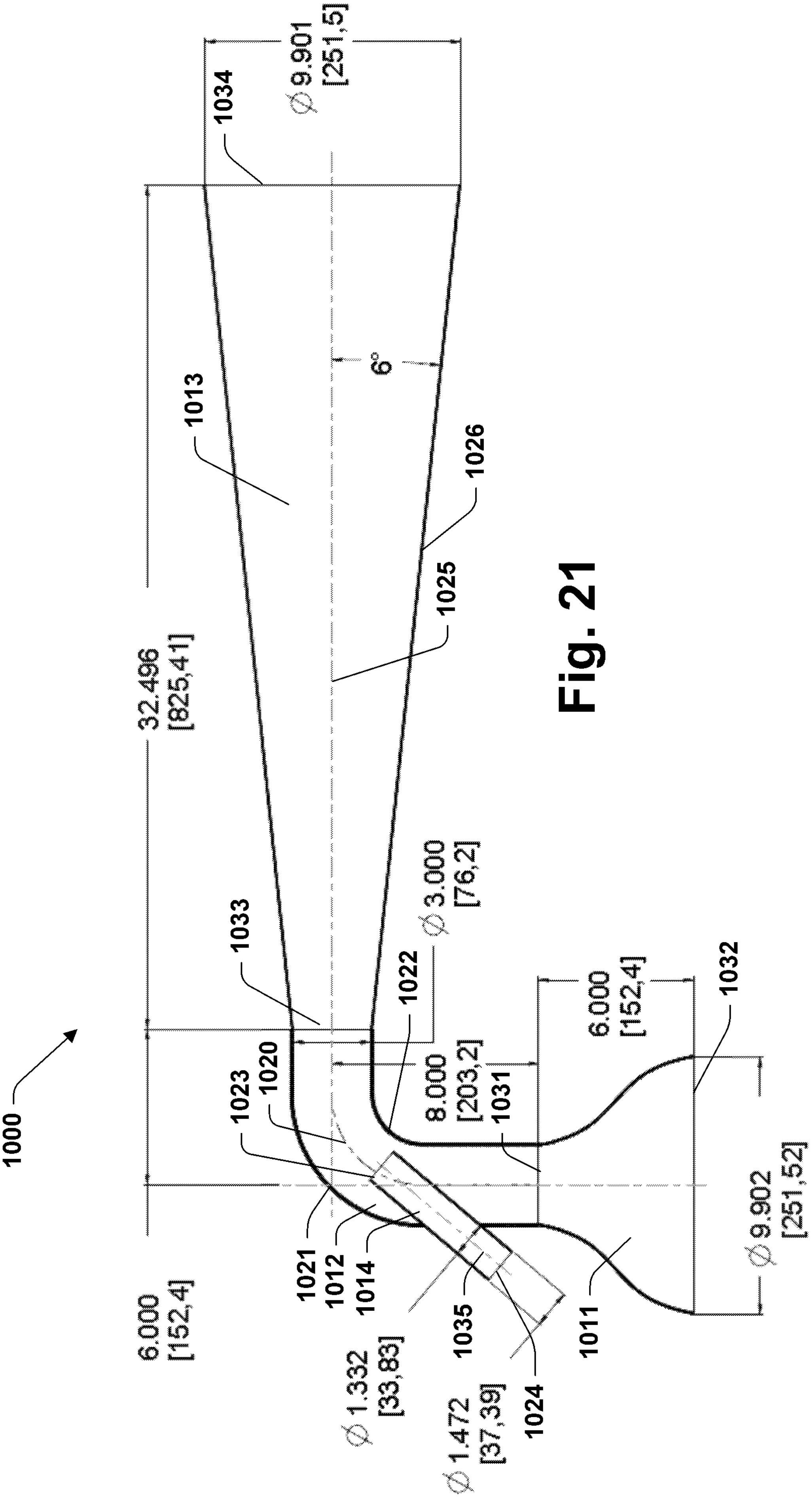

Fig. 21

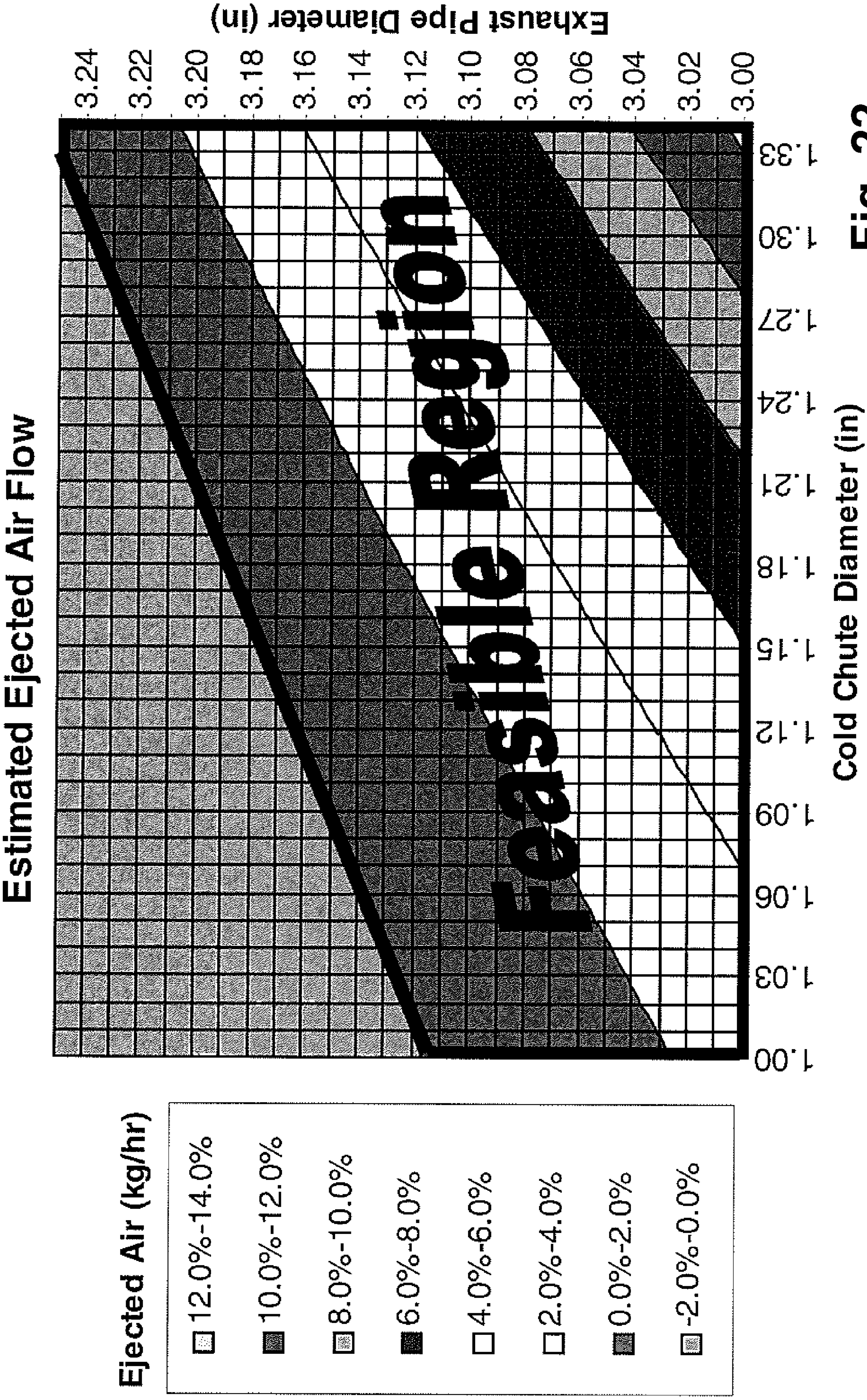
Estimated Ejected Air Flow
Exhaust Pipe Diameter (in)
3.24
3.22
3.20
3.18
3.16
3.14
3.12
3.10
3.08
3.06
3.04
3.02
3.00
Feasible Region
1.00
1.03
1.06
1.09
1.12
1.15
1.18
1.21
1.24
1.27
1.30
1.33
Cold Chute Diameter (in)
Ejected Air (kg/hr)
12.0%-14.0%
10.0%-12.0%
8.0%-10.0%
6.0%-8.0%
4.0%-6.0%
2.0%-4.0%
0.0%-2.0%
-2.0%-0.0%

Fig. 22

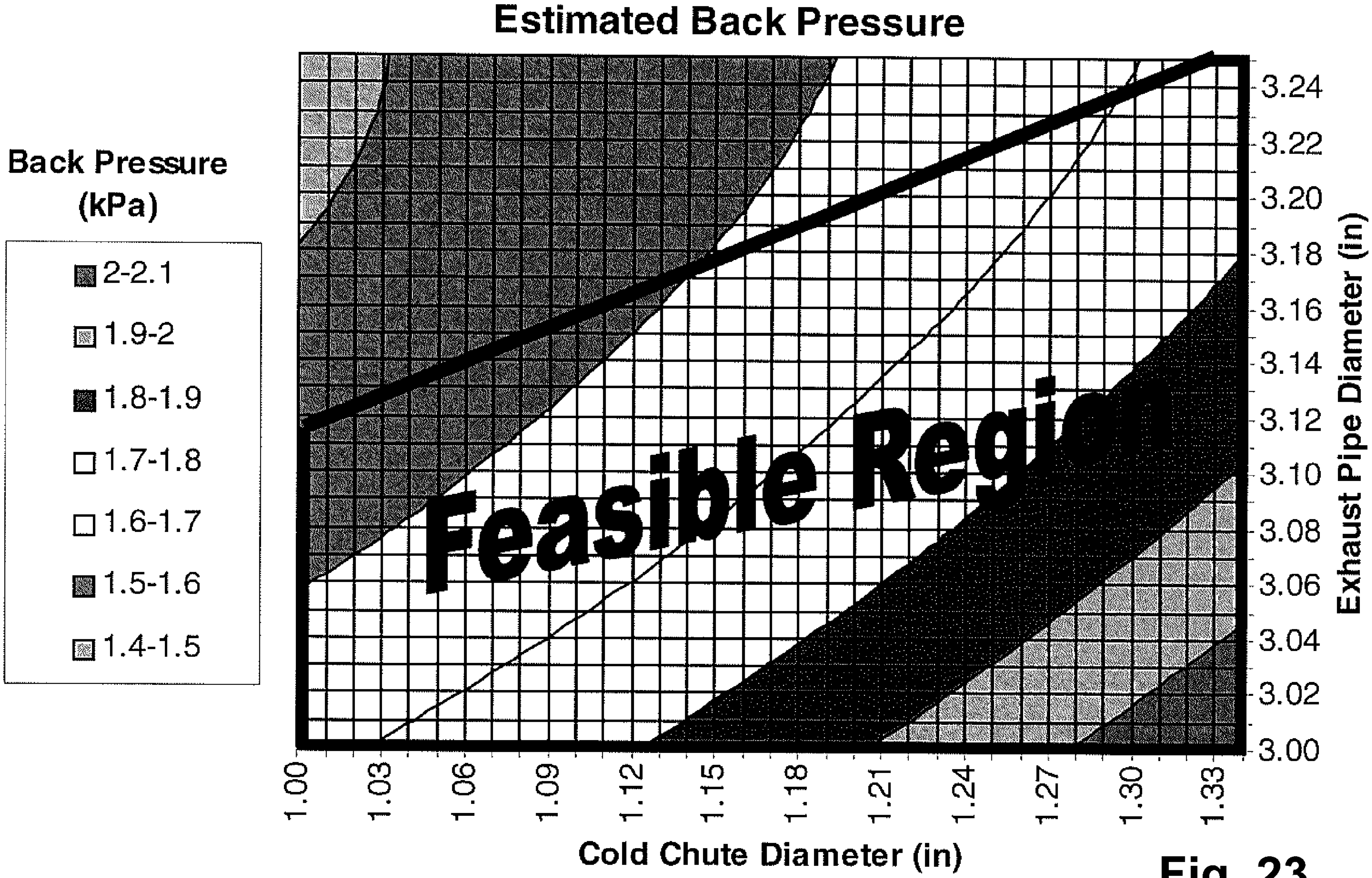
Estimated Back Pressure
Back Pressure (kPa)
▨ 2-2.1
▨ 1.9-2
■ 1.8-1.9
☐ 1.7-1.8
☐ 1.6-1.7
▨ 1.5-1.6
▨ 1.4-1.5
Feasible Region
1.00
1.03
1.06
1.09
1.12
1.15
1.18
1.21
1.24
1.27
1.30
1.33
Cold Chute Diameter (in)
3.24
3.22
3.20
3.18
3.16
3.14
3.12
3.10
3.08
3.06
3.04
3.02
3.00
Exhaust Pipe Diameter (in)

Fig. 23

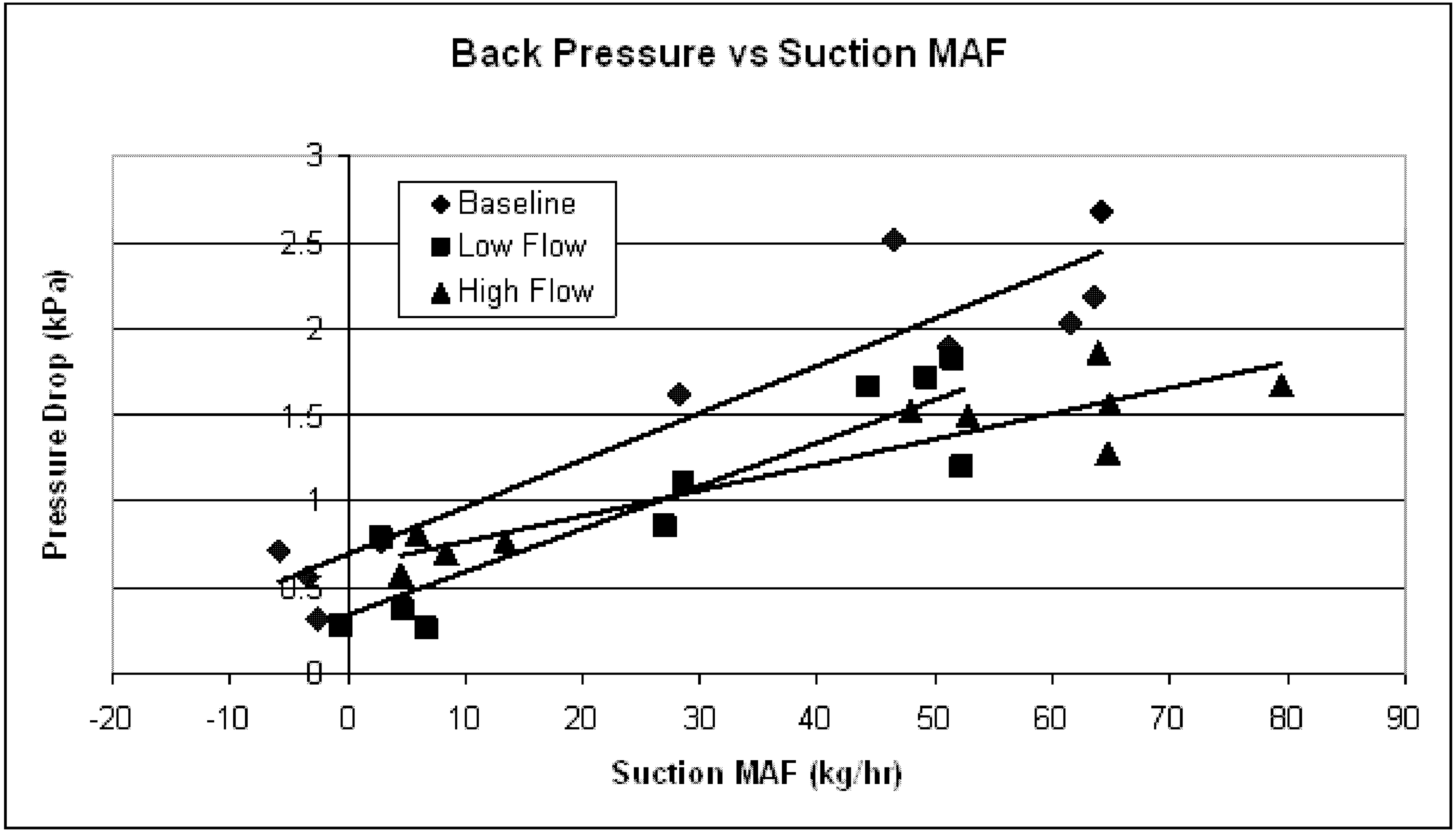
Back Pressure vs Suction MAF
Baseline
Low Flow
High Flow
Pressure Drop (kPa)
0
0.5
1
1.5
2
2.5
3
Suction MAF (kg/hr)
-20
-10
0
10
20
30
40
50
60
70
80
90

Fig. 24

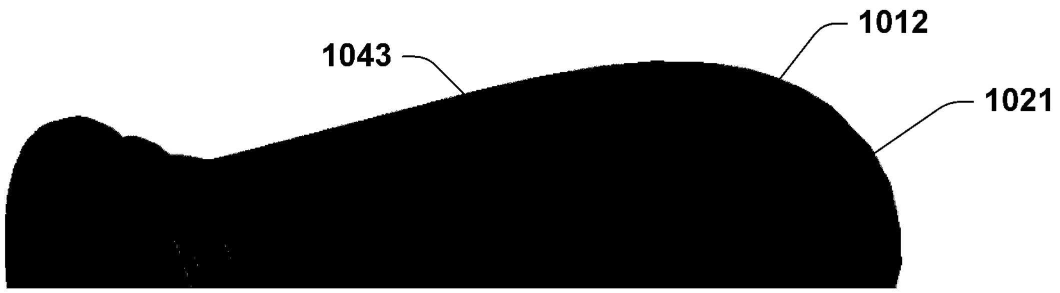

Fig. 25

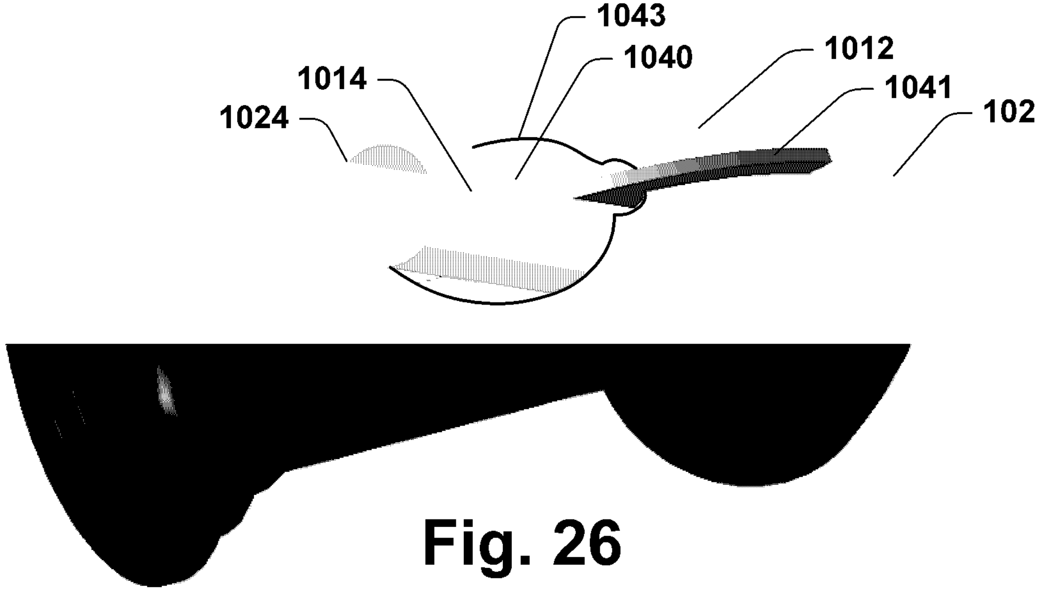

Fig. 26

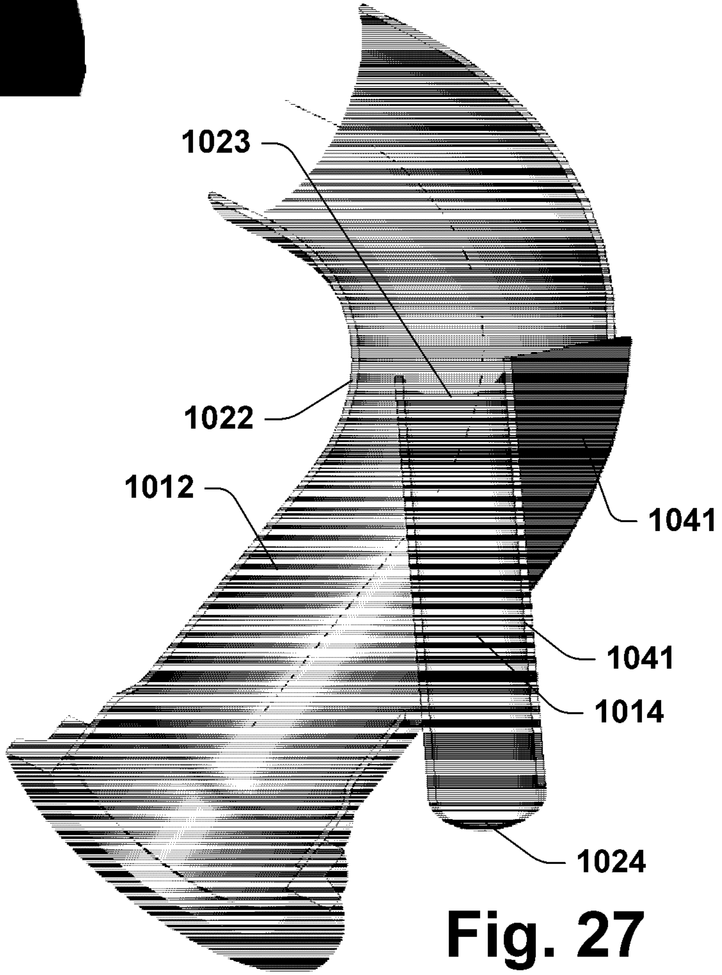

Fig. 27