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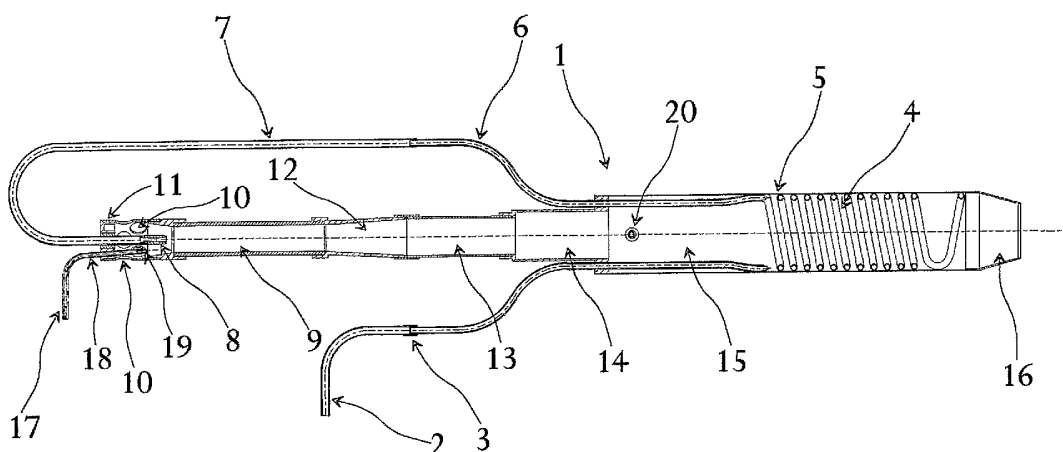
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(54) Title: AIR BREATHING REACTION PROPULSION ENGINES WITH EJECTORS



(57) **Abstract:** An air breathing reaction propulsion engine (1) comprises an open-ended cylindrical structure consisting of an ejector system into which, in operation, air is drawn by means of a pressure differential established by a supply of fuel expelled under pressure through a primary fuel nozzle (8) into the cylindrical structure. The resulting fuel/air mixture passes into the combustion chamber (5) through open communication with the ejector system at one end and which has at the opposite end an exhaust propulsion nozzle (16). A fuel heating coil (4) is disposed around the interior of the cylindrical wall of the combustion chamber (5) to heat and partially crack liquid fuel and to increase its pressure before it is supplied through the primary fuel nozzle (8) into the ejector system. For the purposes of starting the engine a supplementary start fuel nozzle (19) in the ejector system is supplied with gaseous fuel until the liquid fuel system becomes sufficiently pressurised to sustain combustion.

AIR BREATHING REACTION PROPULSION ENGINES WITH EJECTORS

The invention relates to air breathing reaction propulsion engines.

These engines are normally based around a rocket engine primary in which there are no moving parts in the main gas path. In particular they are capable of producing thrust at zero forward speed and operate in an essentially steady flow condition. Variously they are also known as 'ducted rockets', 'air breathing rockets', 'rocket based combined cycle engines', or 'ejector ramjet engines'.

The present invention, which I prefer to call an ejector jet engine, is not based upon a *rocket engine primary*. *It was conceived as a simple, cheap, lightweight and relatively safe means of jet propulsion that could be applied to high performance small scale or model aircraft. It was specifically designed to avoid the burst hazard of high speed rotating machinery, the explosion hazard of liquid fuel rocket engines in general, and the detonation hazard of potentially detonable fuel mixtures. Thus, the invention should be safer for use by amateur engineers.*

According to the present invention there is provided an air breathing reaction propulsion engine comprising an open-ended cylindrical combustion chamber which has at one end an exhaust propulsion nozzle, and which at the other end is in the form of an ejector system, which, in operation, feeds a fuel/air mixture into the combustion chamber.

Preferably there is provided an air breathing reaction propulsion engine comprising an open-ended cylindrical combustion chamber having an upstream end and a downstream end, an exhaust propulsion nozzle located at the downstream end of the combustion chamber, and an ejector system located at the upstream end of the combustion chamber, the ejector system comprising an open-ended cylindrical structure having an upstream end through which air is drawn into its interior, and a downstream end in open communication with the combustion chamber, a primary fuel

nozzle and a supplementary start fuel nozzle located within the ejector system, such that, in operation, for engine starting a supply of fuel under pressure is provided to the supplementary start fuel nozzle and the fuel is expelled into the cylindrical structure thereby establishing a pressure differential to draw air into the ejector system to form a combustible fuel/air mixture, and for normal running a supply of fuel under pressure is provided to the primary fuel nozzle, and the fuel/air mixture thereby formed is supplied to the combustion chamber.

The invention and how it may be carried into practice will now be described in greater detail with reference to the accompanying drawings in which:

Figure 1 is an overall view of an ejector jet engine shown in a section along its longitudinal axis;

Figure 2 shows detail of the engine inlet geometry and starting means of the engine of Figure 1;

Figure 3 shows a graph of thrust against fuel-air ratio;

Figure 4 shows a more detailed view of the fuel heating coil in Figure 1;

Figure 5 shows a graph of pressure against time to illustrate the effect of unsteady flow in the main gas path;

Figure 6 shows a graph of fuel pressure against time to illustrate the effect of unsteady flow in the fuel system;

Figure 7 shows alternative nozzle arrangements;

Figure 8 shows a Helmholtz resonator to suppress instabilities in the main gas path;

Figure 9 shows the ejector jet engine of Figure 1 together with a suitable control system;

Figure 10 shows in schematic form a diagram illustrating part of the operation of the control means for the engine of Figure 1;

Figure 11 shows an alternative inlet geometry for subsonic flight; and

Figure 12 shows an alternative inlet geometry for supersonic flight.

Referring now to the accompanying drawings; the air breathing reaction propulsion engine or ejector jet engine (1) shown in sectional view in Figure 1 uses a liquid fuel pumped under high pressure through the fuel inlet pipe (2), preferably up to a maximum pressure of the order of 20 bar from a fuel source (not shown) by a fuel pump (also not shown). The liquid fuel is pumped under pressure through a restrictor (3), which produces sufficient pressure drop to avoid instability in the downstream fuel heating equipment, into the fuel heating coil (4) located in the wall of open-ended cylindrical combustion chamber (5). The fuel is strongly heated, vaporised and partly cracked by heat from the combustion gases before leaving the fuel heating coil (4) through the fuel delivery tube (6), a nozzle feed tube (7) and into a primary nozzle (8) located towards the upstream end of an ejector system comprising mixer duct (9) and an air inlet duct (11). The duct (11) is disposed at the upstream end of the combustion chamber (5) and co-axially therewith. Further cracking of the fuel may take place in the nozzle feed tube (7). The high-speed jet of fuel from the primary nozzle (8) entrains air into a mixing section in the interior of the inlet duct (11) of the ejector system. A plume of fuel/air mixture exits the ejector system in a downstream direction through various stages of diffusion before the mixed flow enters the combustion chamber (5). The burned mixture gives up some heat to the fuel-heating coil (4), and then exhausts through a propulsion nozzle (16) to provide the engine thrust.

Preferably the liquid fuel is methanol with a small percentage of nitromethane added. Methanol is preferred due to its relatively low molecular weight and high stoichiometric

fuel-air ratio. The low molecular weight increases the exhaust velocity from the Primary Nozzle (8). The high stoichiometric fuel-air ratio allows a larger pressure rise and hence thrust to be obtained at maximum power. The nitromethane additive is beneficial because it has a low autoignition temperature, and allows an immediate 'quick relight' to be obtained in the event of flameout. High fuel pump pressures allow the use of smaller and lighter fuel heating equipment, and give a higher exhaust velocity from the primary nozzle (8).

The construction of the fuel heating coil (4) shown in Figure 4 is designed to maximise heat transfer whilst preserving a high flow area for the combustion gas stream. The coil (4) is located in the interior of the combustion chamber (5) and is wrapped around the periphery of the cylindrical combustion chamber preferably in physical contact with the walls of the chamber (5) to further increase heat input by conduction from the walls. The contact may be improved by selecting materials for the fuel heating coil (4) and combustor (5) with different coefficients of thermal expansion, such that the coil (4) tends to expand more than the combustor (5) when heated. Alternatively, the internal pressure acting on the fuel heating coil (4) will cause it to expand and contact the internal wall of the combustor (5). Such improved heat transfer not only improves the heat flux to the fuel; it has the benefit of cooling the walls of the combustor (5). That is during engine operation the fuel heating coil is urged into physical contact with the internal surface of the wall of the combustion chamber. The fuel heating coil (4) is preferably made with a rough external surface to further improve heat transfer from the combustion gases. This may be achieved by exposing the coil (4) to repeated oxidation and reduction cycles at sufficiently elevated temperature.

The fuel is strongly heated, vapourised, and partly cracked in the fuel heating coil (4), before leaving the combustor (5) through the fuel delivery tube (6). The fuel then flows into the nozzle feed tube (7) which supplies the primary nozzle (8). Further cracking of the fuel may take place in the nozzle feed tube (7). The fuel heating coil (4), fuel delivery tube (6), and nozzle feed tube (7) are preferably constructed from or contain materials to enhance cracking reactions. These cracking reactions are preferably energetically neutral, so that the molecular weight of the fuel is reduced without

substantial heat absorption. Any reduction in molecular weight due to cracking of the fuel leads to an increase in exhaust velocity from the primary nozzle (8), provided that there is not a corresponding drop in temperature of the fuel.

The vapourised and partly cracked fuel exhausts at high velocity through the primary nozzle (8) into the mixer duct (9). As shown in Figure 2 the primary nozzle (8) is preferably a convergent-divergent nozzle with a substantial ratio of exit area to throat area. High area ratio convergent-divergent nozzles have extremely poor thrust coefficients at low expansion ratios. The area ratio of the primary nozzle (8) is chosen not only for its good performance at design power, but also for its poor performance at low power. At low power it allows the fuel-air mixture to be sufficiently enriched to maintain stable burning. An area ratio of about three for the primary fuel nozzle is found to produce good results. Figure 3 illustrates the effect of different fuel-air ratios. At too low an area ratio primary nozzle (8), flameouts can be experienced at part power conditions.

In the ejector system, during operation, air is drawn through inlet holes (10) into the air inlet duct (11), and mixes with the high velocity fuel stream in the mixer duct (9). This inlet arrangement shown in Figures 1 and 2 is suitable for internal installation, or for bench running. For external installation, various conventional types of intakes known in the prior art could be used, although preferably fixed geometry intakes for reasons of cost and weight. Typical intake types are pitot for subsonic and low supersonic Mach numbers; cone and wedge intakes for higher supersonic Mach Numbers. Figure 11 shows an installation with a pitot type subsonic intake (111) connected to an external engine cowl (112) containing engine components substantially as shown in figures 1 and 2. The nozzle feed tube (7) and start fuel pipe (18) are now supported by a strut (113). The approaching airflow may decelerate even before reaching the intake (111). Further reduction in velocity and increase in static pressure occurs in the inlet diffuser (114) and the following sudden expansion into the cowl front cavity (115), from whence part of the flow continues into the engine via the pre-mixer duct (116) and mixer duct (9) where it is mixed with the high velocity fuel jet from the primary nozzle (8)

as previously described. Part of the flow may continue through the cowling rear cavity (117) to supply air to an ejector duct (75) illustrated in figure 7b and discussed below.

Figure 12 shows an installation with a conical centrebody type supersonic intake (121) connected to an external engine cowling (112) containing the same engine components as shown in Figure 11. The approaching airflow is decelerated through at least one oblique shock attached to the nose (122) of the conical forebody (123), and a normal shock attached to the lip (124) of the cowl (125). The flow entering the cowl (125) is now subsonic, and further reductions in velocity and increases in static pressure occur in the subsonic diffuser (126) and following sudden expansion into the cowling front cavity (115), from whence the flow continues into the engine as previously described

The mixing process transfers momentum from the high velocity fuel jet to the air causing a rise in static pressure and an increase in velocity in the mixer duct (9). Preferably the mixer duct (9) is parallel as shown in Figure 1. A parallel mixer duct (9) causes the static pressure to rise during the mixing process, but is also easier to manufacture. The mixed flow enters a diffuser (12) and tailpipe (13) where further rises in static pressure occur accompanied by reductions in average velocity.

The flow continues into a dump duct (14), intermediate the ejector system and the combustion system, where a sudden increase of area occurs, and then into the primary burning zone (15) of the combustor (5). Dump duct (14) has a twofold purpose. First, it acts as another stage in the diffusion process, increasing the static pressure and reducing the flow velocity, and second, it increases the turbulence in the flow immediately in front of the combustor (5) greatly improving the stability of burning therein.

The flow enters the combustor (5) where a flame is stabilised in the doughnut shaped vortex shed from the exit of the dump duct (14). Burning continues through the length of the combustor (5), and the highly turbulent burning flow supplies heat to the fuel heating coil (4) both directly by convection and radiation, and indirectly by conduction from the walls of the combustor (5). The total internal volume of the combustor (5) is

just sufficient that burning can be completed under the least favourable operational conditions. Minimising the volume of the combustor (5) is important in reducing the likelihood of instabilities in the main gas path caused by the coupling between fluctuations in heat release causing pressure changes in the combustor (5), leading to air flow and hence stoichiometry changes in the mixer duct (9).

Finally the burned flow leaves the propulsion nozzle (16) at high velocity to produce the engine thrust. The internal contour shape of the Nozzle (16) may depend on the application. For operation at low Mach Numbers only, a plain convergent nozzle as shown in Figure 1 will be most appropriate, whereas for operation at higher Mach Numbers, a convergent-divergent nozzle would be preferred (see below).

Figure 2 also shows details of the arrangement construction of the primary nozzle (8), a start fuel pipe (18) and start fuel nozzle (19). Engine starting is preferably accomplished by feeding a gaseous fuel into the start fuel inlet (17) from where it flows through the start fuel pipe (18) into the start fuel nozzle (19). The start fuel is preferably propane, which is easily stored as a liquid but is of lower molecular weight than butane, and also has a higher saturation pressure, both features allowing for a higher exhaust velocity from the start fuel nozzle (19).

The start fuel nozzle (19) is a convergent nozzle of relatively small throat diameter compared to that of the primary nozzle (8). This is necessary because the stoichiometric fuel-air ratio of the start fuel propane is substantially less than that of the primary fuel based on methanol, and the operating pressure ratio is lower. Also, the installation of the start fuel nozzle (19) is less favourable, being off the centre line of the mixer duct (9).

The start fuel flow entrains air in the manner previously described, and the start fuel / air mixture is ignited in the primary burning zone (15) by ignition means (20), preferably a glow plug. The detailed construction of the primary nozzle (8), start fuel pipe (18) and start fuel nozzle (19) is shown in Figure 2. When the fuel heating coil (4) has been raised to operating temperature, the liquid fuel can be introduced into the engine which

then operates in the previously described manner, and the start fuel flow can be shut off.

In an engine layout such as that shown in Figure 1, the nozzle (16) is not choked at zero forward speed. In a plain convergent nozzle (16), the airflow tends to rise markedly with increase in ram ratio from forward speed. This can lead to choking in the mixer duct (9), and hence low pressure rise. It also leads to unfavourable conditions in the combustor (5), giving high loading and weak fuel-air ratio, possibly leading to flameout. These difficulties can be avoided by the use of a convergent-divergent nozzle of appropriate area ratio.

Figure 7a shows a convergent-divergent (Con-Di) nozzle (71). At low forward speeds, when the Con-Di Nozzle (71) is unchoked, the area at the exhaust plane (72) controls the flow. At high forward speed, when the Con-Di nozzle (71) is choked, the area at the throat plane (73) controls the flow. The range of possible flows is thereby minimised. In an extreme case, the Throat Plane (73) could be designed to be near choking at zero forward speed conditions, effectively eliminating any change in matching due to forward speed effects.

The Con-Di nozzle (71) has an improved thrust coefficient at high flight Mach numbers arising from the ability to properly expand the flow to an appropriate low static pressure and supersonic exhaust velocity. However, a disadvantage is poor performance at intermediate flight speeds when shock systems in the divergent section (74) can give rise to reduced thrust coefficients.

Figure 7b illustrates an alternative approach to controlling the engine matching with forward speed using an ejector nozzle arrangement. Here the combustor (5) is surrounded by an ejector duct (75) through which air is drawn. The hot nozzle (76) exhausts into the ejector mixer (77) and then through the final nozzle (78). At low forward speeds, a small flow of auxiliary air is drawn through ejector duct (75), because the static pressure at the hot nozzle (76) is somewhat below atmospheric. At high forward speeds, a relatively large flow of auxiliary air flows through the ejector duct

(75). The static pressure at the hot nozzle is now substantially above atmospheric, and so the hot nozzle (76) never actually reaches choking conditions.

This arrangement has the additional advantage of providing extra wall cooling for the combustor (5). It has the disadvantage of reducing the specific thrust of the engine, since the auxiliary air flowing through the ejector duct (75) must be supplied by an intake arrangement, and it does not in itself contribute to a substantial increase in engine net thrust.

The ejector nozzle arrangement shown in Figure 7b may be preferred for high subsonic flight Mach numbers, whereas the convergent-divergent nozzle arrangement shown in Figure 7a may be preferred for supersonic flight Mach numbers.

Figure 8 shows a modified form of the intake arrangement incorporating a device designed to suppress instabilities in the main gas path. The instabilities are caused by changes in airflow without a corresponding change in fuel flow. This can happen in the arrangement shown in Figures 1 & 2 because the primary nozzle (8) carrying the main fuel flow is choked and the fuel flow is unaffected by airflow changes resulting from pressure fluctuations in the combustor (5). This type of instability is illustrated in Figure 5.

In the arrangement of Figure 8, the main fuel is supplied through nozzle feed tube (7) to the primary nozzle (8). An annular duct (81) carrying a small bleed flow of fuel exhausts through an annular nozzle (82) formed concentrically around the primary nozzle (8). The bleed flow of fuel is metered through a very small hole (83) in the nozzle feed tube (7). The pressure ratio across the annular nozzle (82) is very low, and a small increase in air static pressure at the exit of the annular nozzle (82) will result in a substantial drop in the bleed fuel flow in the annular duct (81). It is therefore possible in principle to match a small drop in airflow (and hence increase in static pressure) with an equal drop in total fuel flow, and thereby eliminate the basic feedback mechanism of the instability.

In order for this reduced bleed fuel flow to persist for long enough, some means of storing the excess bleed flow is required. This is provided by a resonator cavity (84), connected to the annular duct (81) by resonator pipe (85). The system of the resonator cavity (84), resonator pipe (85), annular duct (81) and annular nozzle (82) forms a Helmholtz resonator, whose natural resonant frequency is chosen to be the same as the instability needing to be attenuated. Adjustment of natural frequency is easily accomplished by variation of the volume of resonator cavity (84).

The Helmholtz resonator system may also be used as a flow path for start air and fuel flow in this arrangement. The area of the annular nozzle (82) is too large to allow starting using start fuel only as previously described, and a mixture of air and start fuel must be supplied if this nozzle is to be used for starting. Air and start fuel are supplied through start restrictor (86) located at the far end of the resonator cavity (84). The start restrictor (86) is of sufficiently small area as to have negligible effect on the operation of the Helmholtz resonator system during normal operation.

Practical tests of the arrangement of Figure 8 show a substantial reduction in amplitude of oscillations, by about a factor of 5 for the same geometry and operating conditions. A corollary of this improvement in unsteady behaviour was that an increase in range of operable fuel-air ratio was also obtained, at the lean limit, of the order of 5% of the stoichiometric value.

This Helmholtz resonator system has the disadvantage of increasing the engine fuel consumption by the quantity of bleed flow being used, typically about 5%, and at the same time reducing the maximum specific thrust obtainable at the rich stability limit. However, it is preferred to avoid the need to employ such a resonator to suppress engine gas path instabilities. The engine can tend to be unstable if the combustor volume is too large. Preferably the combustion chamber volume is kept small by using features which enhance the fuel burning rate, and those which increase the rate of heat transfer through the fuel heating coil. Thus, important features include the abrupt enlargement in the flow path between the tailpipe 13 and dump duct 14 which causes a high turbulence level in the flow entering the combustor and greatly enhancing the

burning rate therein. (Tests have shown that a smoothly diverging section upstream of the combustor results in poor burning characteristics and lower engine power.) The spacing of the windings of the fuel heating coil greatly increases local turbulence and hence produces an improved heat transfer coefficient for the external flow. (Such a coil absorbs more heat than one with twice the number of turns in the same length and no gaps.) The physical contact between the fuel heating coil and the combustor casing increases heat flow by conduction from the casing. Positive contact due to internal pressure in the heating coil during operation is an advantage.

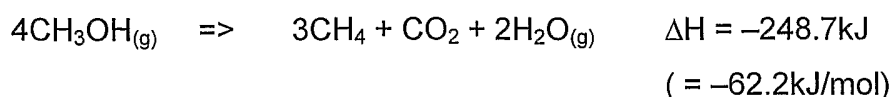
Since the engine uses the fuel as a working fluid, a relatively high proportion of fuel to air is required in order to obtain a high pressure rise at maximum power. This favours the use of oxygen bearing fuels such as methanol which has a high stoichiometric fuel – air ratio of 0.1545 compared to normal hydrocarbon fuels such as kerosene at 0.068.

The enthalpy input required to vaporise the fuel in the Fuel Heating Coil (4) should be low to reduce the heat transfer requirements. This tends to fundamentally conflict with the requirement for low molecular weight (see below) since liquids with low molecular weights tend to have a high latent heat. However, water, with a latent heat of evaporation of 2443kJ/kg stands out as being very undesirable on this count and should be avoided in fuel mixtures – for comparison the value for methanol is 1100kJ/kg.

Figure 3 illustrates the variation of fuel – air ratio with engine power level. The normal matching of the engine with a fixed nozzle (16) and convergent primary nozzle (8) is shown as line 31. High power operation is limited by the rich burning limit (32). More importantly, low power operation is prevented by the lean burning limit (33). Operation with a convergent – divergent primary nozzle (8) is shown as lines 34, 35, and 36. In addition to the normal range denoted by line 34, operation is now possible at low power in the range denoted by line 36. There is also a range where operation is still not possible denoted by line dashed line 35.

Increasing the area ratio of the primary nozzle (8) produces the characteristic line 37 which now lies entirely in the stable burning range. The area ratio of the primary nozzle (8) is selected to ensure this type of stable operation. In addition, it is desirable for the basic burning limits to be wide, and for this purpose a small fraction of nitromethane may be added to the fuel. This has the additional benefit of lowering the autoignition temperature so that immediate relight is possible from the hot combustor (5) in the event of flameout. Addition of water to the fuel has the opposite effect and should be avoided.

It is desirable for the molecular weight (mw) of the fuel to be low to increase the jet velocity from the primary nozzle (8). This tends to favour fuels such as methanol (mw 32) over liquid hydrocarbon fuels such as gasoline (average mw around 100). Cracking can be used to reduce the molecular weight of the fuel. It is desirable that this does not result in an increase in the heat transfer requirements to the fuel heating coil (4). It is also desirable that no solid products are formed which could be deposited in the fuel heating coil (4), fuel delivery tube (6), nozzle feed tube (7) or primary nozzle (8). Use of appropriate catalysts in the construction of the nozzle feed tube (7) should be considered to allow some cracking of the fuel, preferably in an energetically neutral net reaction. For example, in the case of methanol fuel the following two decomposition reactions are known in the prior art:



The former is catalysed by reduced copper and the latter by reduced nickel. The primary nozzle feed tube could be constructed to contain both catalysts on its inner surface. Only a moderate conversion is possible with the limited surface area and high flow velocities. The product molecular weight may for example be reduced by 20% by cracking about 20% of the fuel. Incorporation of a highly efficient catalytic converter is impractical due to size and weight considerations. Cracking reactions involving water

tend to be highly endothermic and so water should be avoided in fuel mixtures from this perspective.

The weight of the heat transfer equipment relative to the engine thrust must be minimised, this means that high heat transfer coefficients are required, favouring fast flowing and highly turbulent flow over the fuel heating coil (4). This requirement is compatible with the desired small cross – sectional area of the combustor (5) in ramjet engines.

The spacing of the coils in the fuel heating coil (4) should minimise the total weight of the fuel heating coil (4) and combustor (5) for the required heat flux. Heat transfer to the fuel heating coil (4) from the walls of the combustor (5) can be obtained by conduction between these two adjacent surfaces. High internal heat transfer coefficients are obtained in the fuel heating coil (4) due to the dense high pressure flow. These are further improved by the use of a small cross – sectional area, typically only two to three times that of the primary nozzle (8), although this is primarily to reduce the metal temperature in the fuel heating coil (4). Also it has been found advantageous if the spacing or pitch of the coils is sufficiently large to produce highly turbulent flow in the gas path through the combustion chamber.

The fuel heating coil (4) as illustrated in Figure 4 comprises a plurality of “double” turns. In the embodiment shown the coil has $2\frac{1}{2}$ ‘double’ turns of tube. Fuel is admitted through tube 41 and leaves through tube 42. Adjacent coils 43 and 44 carry fuel travelling in opposite directions. Coil 43 carries fuel anticlockwise from tube 41, whilst coil 44 carries fuel clockwise towards tube 42. The change of direction is accomplished by the return bend 45 at the mid point of the fuel heating coil (4). This method of construction allows the minimum obstruction to the flow of gases in the combustor (5) whilst allowing the fuel heating coil (4) inlet and outlet to be routed through the ‘cold’ or relatively cooler end of the combustor (5) as shown in Figure 1. The ratio of maximum engine thrust to the weight of fuel heating coil (4) can exceed 30 even in a small engine of this type.

The engine should be free from undesirable unsteady burning phenomena across the operating range. These tend to be most evident near the extremes of stoichiometry, and if present at large amplitude can have a marked effect on the achievable burning range. These effects tend to be worst on the lean side, and in extreme cases operation lean of stoichiometric may not be possible. The most basic and troublesome mode of instability involves a coupling between changes in heat release causing pressure changes in the combustor (5), leading to airflow and hence stoichiometry changes in the mixer duct (9).

A small rise in pressure in the combustor (5) causes the flow to decelerate in the dump duct (14), tailpipe (13), diffuser (12) and mixer duct (9). The air mass flow into the engine is therefore temporarily reduced. The fuel flow through the choked primary nozzle (8) is essentially constant during this time, and so a region of locally rich mixture is produced in the mixer duct (9). This then convects downstream, and when it reaches the combustor (5), it results in a temporary increase in heat release and therefore pressure, causing the cycle to repeat.

Figure 5 shows an example of the worst form of this instability, where the unsteady heat release couples with the Helmholtz mode of the engine (1) to produce massive changes in pressure and flow. The mixer entry static pressure (51) and combustor entry static pressure (52) are shown over a 0.2 second time period. The peaks in mixer entry static pressure (51) corresponding to the minimum mass flow rate occur about 90 degrees later than the peaks in combustor entry static pressure (52). The instability tends to grow with time (53), and results in peak pressures opposite in sense to the average flow conditions, with the combustor entry static pressure (52) falling below atmospheric (54), and the mixer entry static pressure (51) rising above atmospheric (55).

It is important to avoid this type of instability by ensuring that the Helmholtz frequency of the engine (1) is sufficiently high compared to the frequency associated with the convectively coupled instability described. In practical terms, this means minimising the volume of the combustor (5) compared to the flow area of the mixer duct (9).

The mixing length between the primary flow and air must be adequate to produce a suitable velocity profile at diffuser entry, and maximise momentum transfer from the energetic primary flow. Failure to do this results in an energetic core of the primary jet travelling unhindered down the diffuser whilst the bulk flow remains stalled and sees little rise in static pressure. A ratio of length to diameter of mixer duct (9) between about 5 and 8 is optimum for the arrangement shown in Figure 1.

In order to start the engine reliably, the fuel heating coil (4) needs to be raised to operating temperature before operation on liquid fuel can take place. An appropriate small supplementary start fuel nozzle (19) providing gaseous starting fuel to the ejector can accomplish this. The throat diameter of the start fuel nozzle (19) needs to be smaller than that of the primary nozzle (8) approximately in proportion to the stoichiometric Fuel – Air Ratio of the gaseous start fuel compared to that of the liquid main fuel. Using the primary nozzle (8) to introduce gaseous start fuel typically results in a mixture too rich to burn.

Flow instabilities in the liquid fuel heating equipment should be avoided. These can be very severe, although of longer time period than the main gas path instabilities. A typical sequence is illustrated in Figure 6, which shows traces of three pressures:

is the liquid pressure upstream of restrictor (3)

is the liquid pressure downstream of restrictor (3)

is the hot gas pressure at entry to the primary nozzle (8)

At the time denoted by line 64, the pressures 61 and 62 are almost equal, and so there is no net fuel flow into the engine (1). Since there is a flow out of the primary nozzle (8) proportional to the absolute pressure there, the stored mass of fuel in the engine is falling. As a consequence, the system pressures are falling at this time.

At the time denoted by line 65, there is a substantial flow of fuel into the engine indicated by the pressure drop between the pressures upstream (61) and downstream (62) of the restrictor (3). Now the fuel flow entering the engine (1) is greater than that

leaving it through the primary nozzle (8), and so the stored mass of fuel in the engine (1) is rising. As a consequence, the system pressures are rising at this time.

There is a delay before line 64 between the fuel flow into the engine (1) reaching zero and the system pressures starting to fall. During this time the proportion of liquid in the fuel heating coil (4) must be falling, and there may even be some reverse flow through the restrictor (3). A corollary is that between lines 64 and 65 there is a large fuel flow into the engine (1), but the system pressures are still falling. During this time the proportion of liquid in the fuel heating coil (4) must be rising.

The system is dynamically unstable mainly because there is a portion of the fuel heating coil (4) that is alternately filled with liquid and vapour. It is the delays associated with emptying and filling this volume that give rise to the instability. The stability of the system can be improved by increasing the operating pressure, which reduces the difference in specific volume between liquid and vapour, and by introducing a pressure drop at entry to the fuel heating coil (4). This is the purpose of restrictor (3) shown in Figure 1. The pressure drop needs to be sufficient for stable fuel system behaviour and this is most easily determined by experiment.

Figure 9 shows an ejector jet engine 1 fitted with a fuel pump 91 and a control system 92. Probes measuring the inlet stagnation pressure P_2 (93) and exhaust static pressure P_0 (94) provide signals indicative of these pressures P_2 (95) and P_0 (96) to the control system (92). The control system (92) also receives a signal indicative of the engine power command WFDEM (97).

The control system (92) normally responds to changes in engine power command (97) by adjusting the quantity of fuel flow delivered by the fuel pump (92) to the engine (1). Control may be by means of adjusting the speed of the fuel pump (91) or the outlet pressure (99) of the fuel pump (91). Such control may be accomplished directly by modulating the voltage or current supplied to a motor (98) driving the fuel pump (91). Limits on the maximum and minimum allowable values of a parameter representative of

fuel flow are defined in the control system as a function of the sensed pressures P2 (95) and P0 (96).

A preferred implementation of these limitations in the control system (92) is illustrated in Figure 10. The exhaust static pressure P0 (96) is subtracted from the inlet stagnation pressure P2 (95) to provide a signal Delta P (101) indicative of airspeed. This Airspeed signal delta P (101) and the inlet stagnation pressure P2 (95) are used in a limit carpet (102) to determine values of maximum fuel flow WFMAX (103) and minimum fuel flow WFMIN (104). The limit carpet (102) has maximum lines (105) each representing a particular value of P2 (95). It also has equivalent minimum lines (106) each representing a particular value of P2 (95).

The power command (97) is compared with the minimum fuel flow WFMIN (104) in a high wins gate (107). The output (108) of this gate (107) is then compared with the maximum fuel flow WFMAX (103) in a low wins gate (109) to produce the final fuel flow command WFDEM (110). This fuel flow command WFDEM (110) is used to control the fuel pump (91) either directly through the voltage or current of the pump driving motor (98) or indirectly through a feedback signal indicative of the outlet pressure (99) of the pump (91).

CLAIMS

- 1 An air breathing reaction propulsion engine comprising

an open-ended cylindrical combustion chamber having an upstream end and a downstream end, an exhaust propulsion nozzle located at the downstream end of the combustion chamber, and an ejector system located at the upstream end of the combustion chamber,

the ejector system comprising an open-ended cylindrical structure having an upstream end through which air is drawn into its interior, and a downstream end in open communication with the combustion chamber, a primary fuel nozzle and a supplementary start fuel nozzle located within the ejector system,

such that, in operation, for engine starting a supply of fuel under pressure is provided to the supplementary start fuel nozzle and the fuel is expelled into the cylindrical structure thereby establishing a pressure differential to draw air into the ejector system to form a combustible fuel/air mixture, and for normal running a supply of fuel under pressure is provided to the primary fuel nozzle, and the fuel/air mixture thereby formed is supplied to the combustion chamber.
- 2 A propulsion engine as claimed in claim 1 wherein the supplementary start fuel nozzle is connected to a source of gaseous fuel used to start the engine, and during normal running the supply of gaseous fuel is discontinued.
- 3 A propulsion engine as claimed in claim 1 wherein the supplementary start fuel nozzle is located alongside the primary fuel nozzle.
- 4 A propulsion engine as claimed in claim 3 wherein the supplementary start fuel nozzle has a throat diameter smaller than a corresponding throat diameter of the primary nozzle.

- 5 A propulsion engine as claimed in claim 4 wherein the ratio of the throat diameter of the supplementary start fuel nozzle to the throat diameter of the primary nozzle is approximately in proportion to the stoichiometric fuel/air ratio of the start fuel relative to the primary fuel.
- 6 A propulsion engine as claimed in claim 1 wherein the primary fuel nozzle has an area ratio of about three
- 7 A propulsion engine as claimed in claim 1 further comprising a fuel heating coil disposed around the wall of the cylindrical combustion chamber through which the supply of fuel for normal running is supplied to the primary nozzle.
- 8 A propulsion engine as claimed in claim 7 wherein the fuel heating coil is located in the interior of the combustion chamber.
- 9 A propulsion engine as claimed in claim 8 wherein the pitch of the coils of the fuel heating coil is sufficiently large to produce, in operation, turbulent flow of the gas path through the combustion chamber.
- 10 A propulsion engine as claimed in claim 7 wherein the fuel heating coil comprises a plurality of double turns such that adjacent turns of the coil carry fuel in opposite directions and the inlet and outlet turns are located at the relatively cooler end of the combustion chamber.
- 11 A propulsion engine as claimed in claim 7 wherein during engine operation the fuel heating coil is urged into physical contact with the wall of the combustion chamber.
- 12 A propulsion engine as claimed in claim 1 further comprising a diffuser section located intermediate the ejector system and the combustion chamber and the diffuser section has a cross section the size of which has an abrupt enlargement in the downstream direction.

- 13 A propulsion engine as claimed in claim 12 wherein the abrupt enlargement of the cross section of the diffuser section comprises a step change in the cross section.
- 14 A propulsion engine as claimed in claim 1 further comprising an ejector duct surrounding the combustion chamber, and a second propulsion nozzle at the downstream end of the ejector duct disposed co-axially with the first propulsion nozzle at the downstream end of the combustion chamber, wherein the first and second propulsion nozzles form an ejector nozzle arrangement which during engine operation maintains the core engine operating point as forward speed is increased.
- 15 A propulsion engine as claimed in claim 1 further comprising a restrictor through which fuel is supplied to the primary fuel nozzle to prevent instabilities in the supply of fuel.

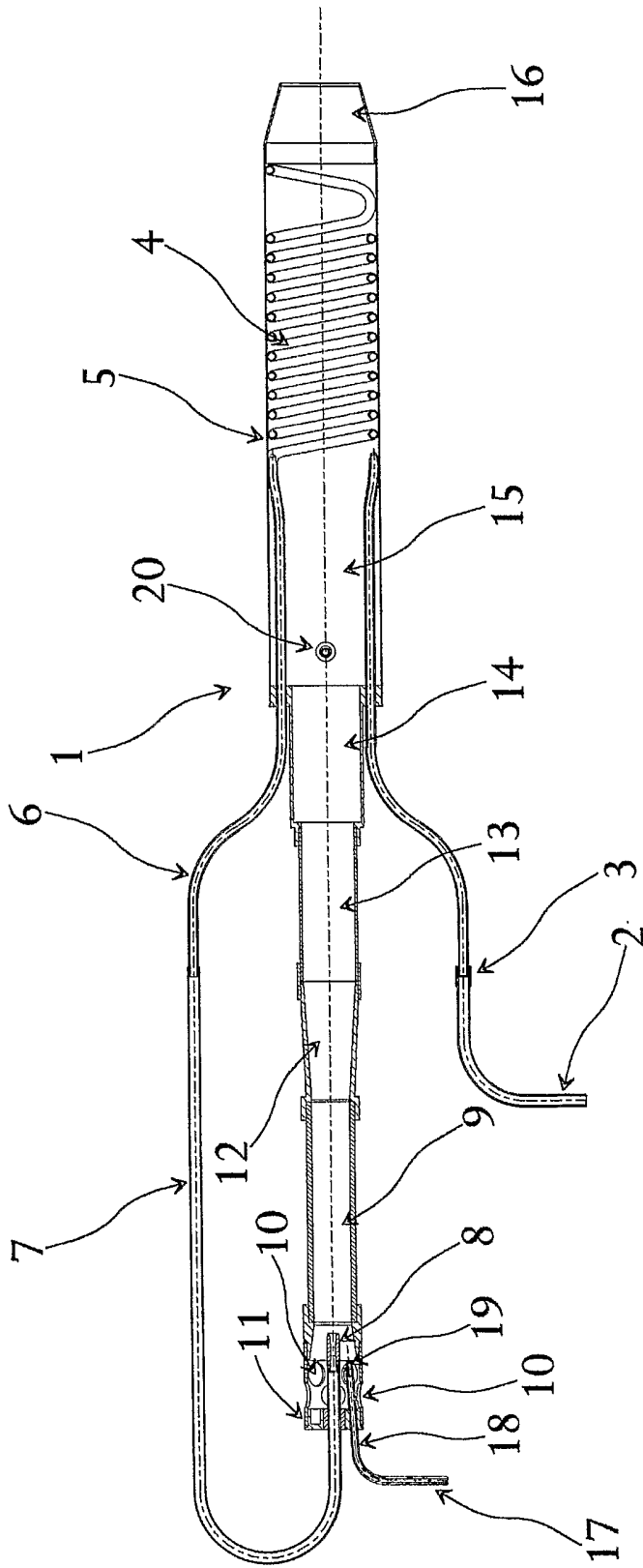


Figure 1

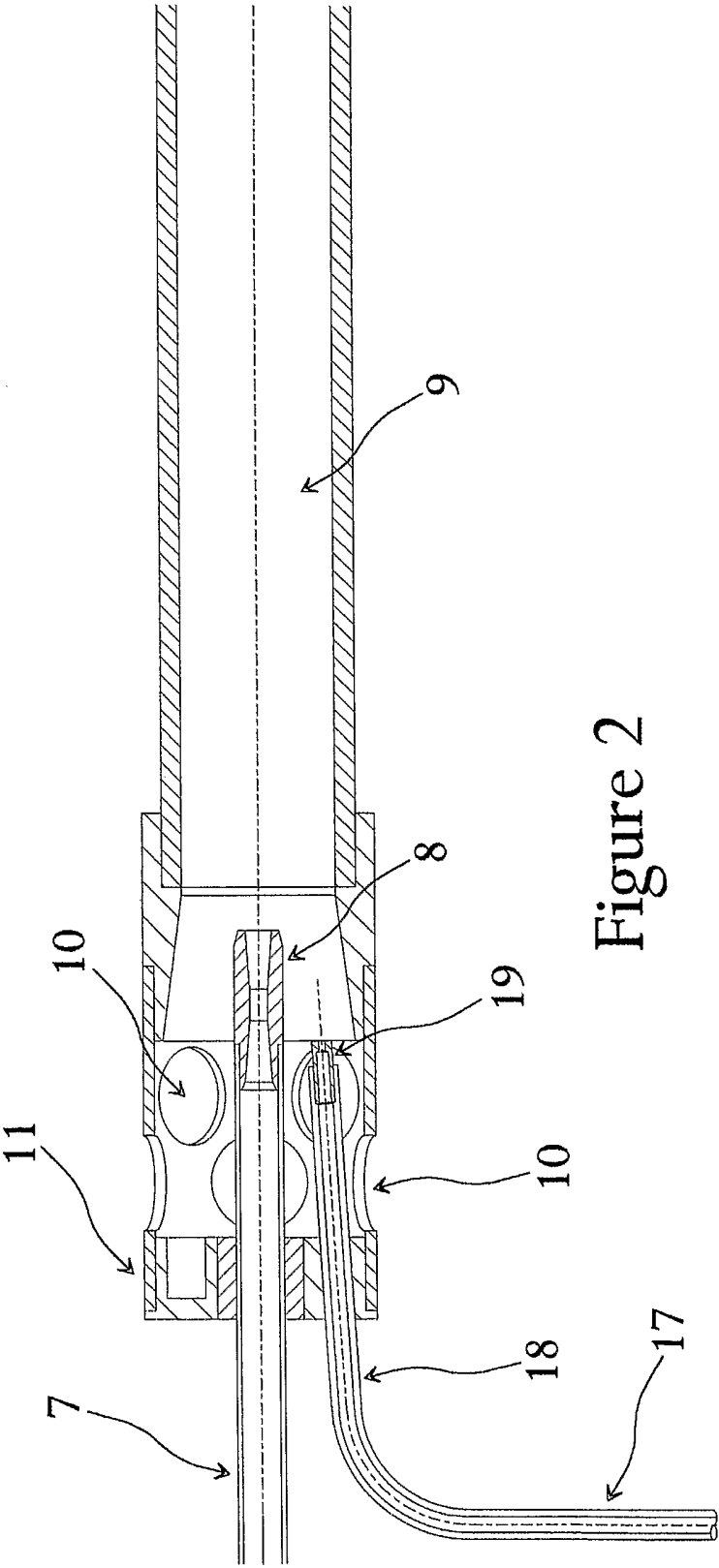


Figure 2

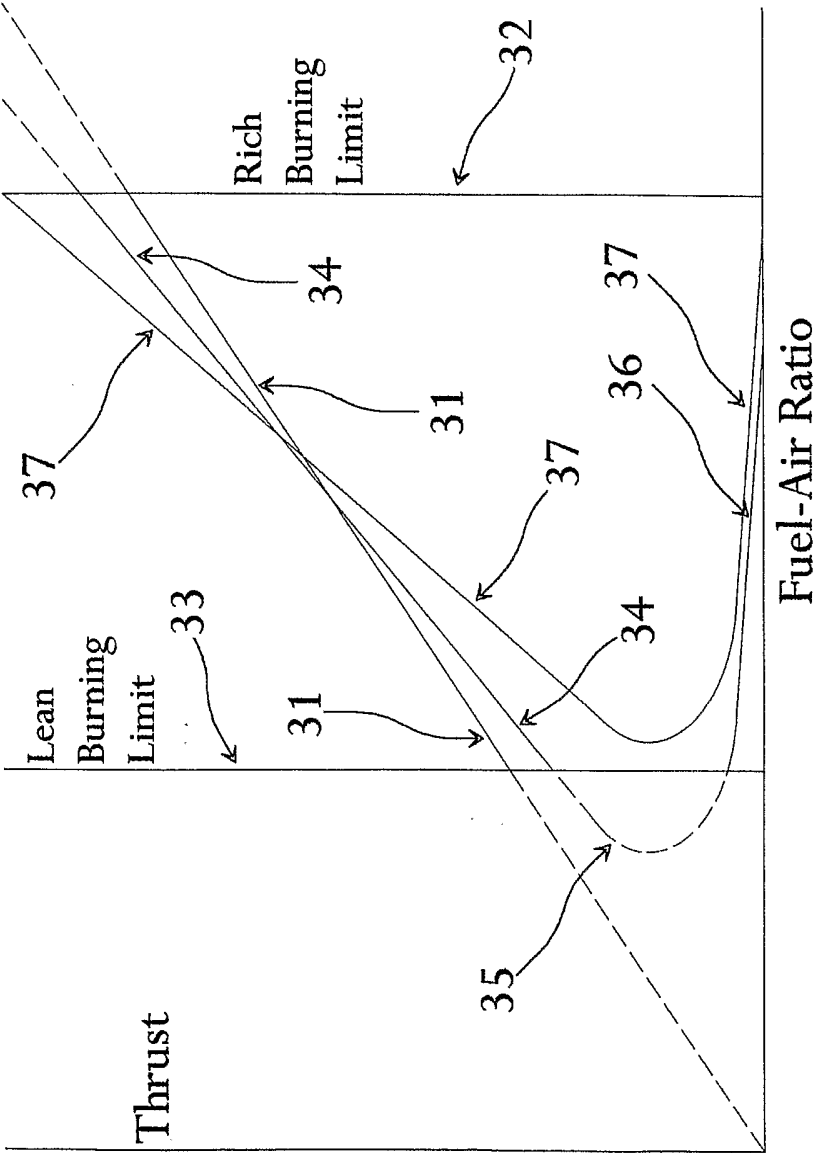


Figure 3

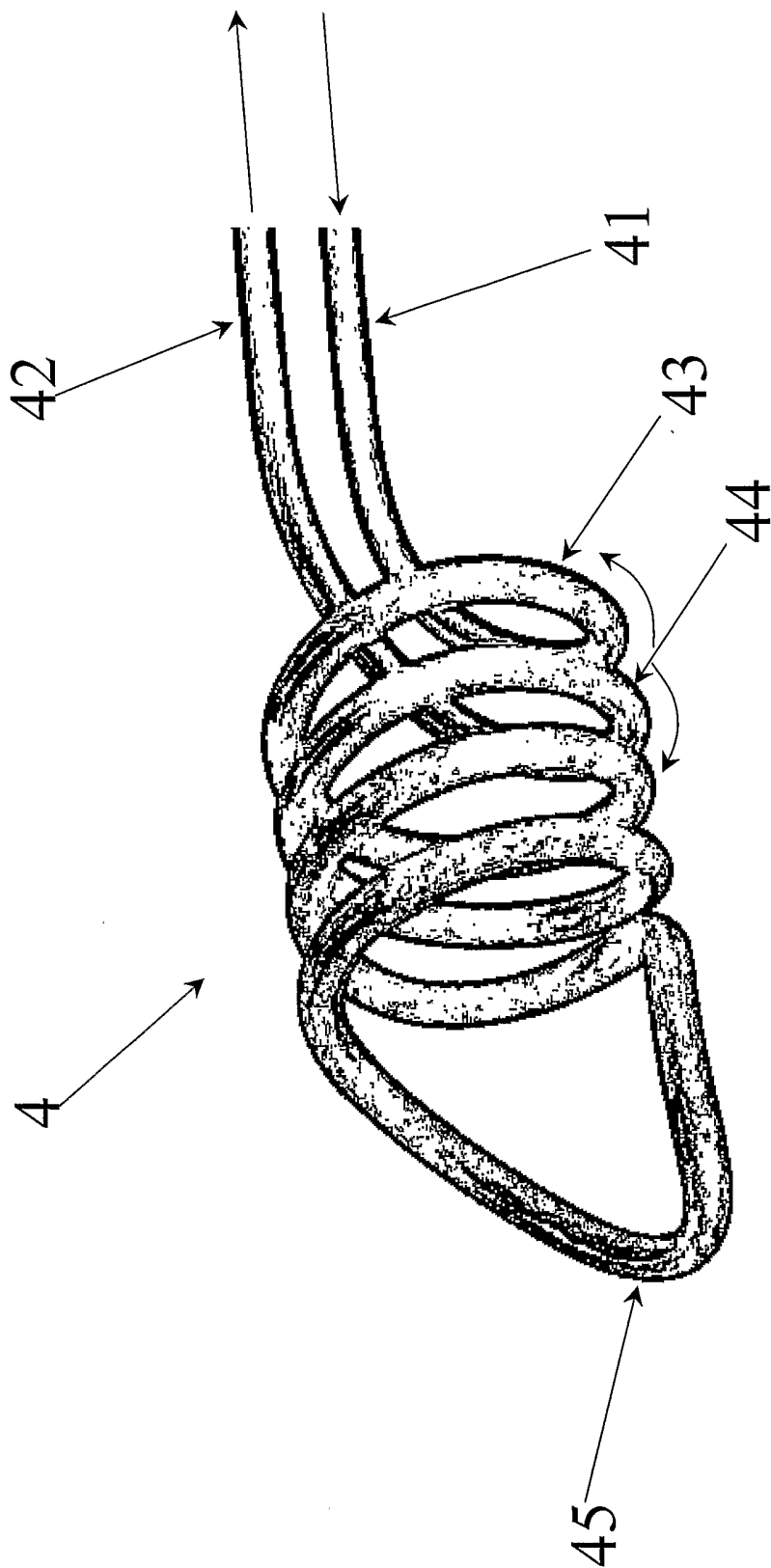


Figure 4

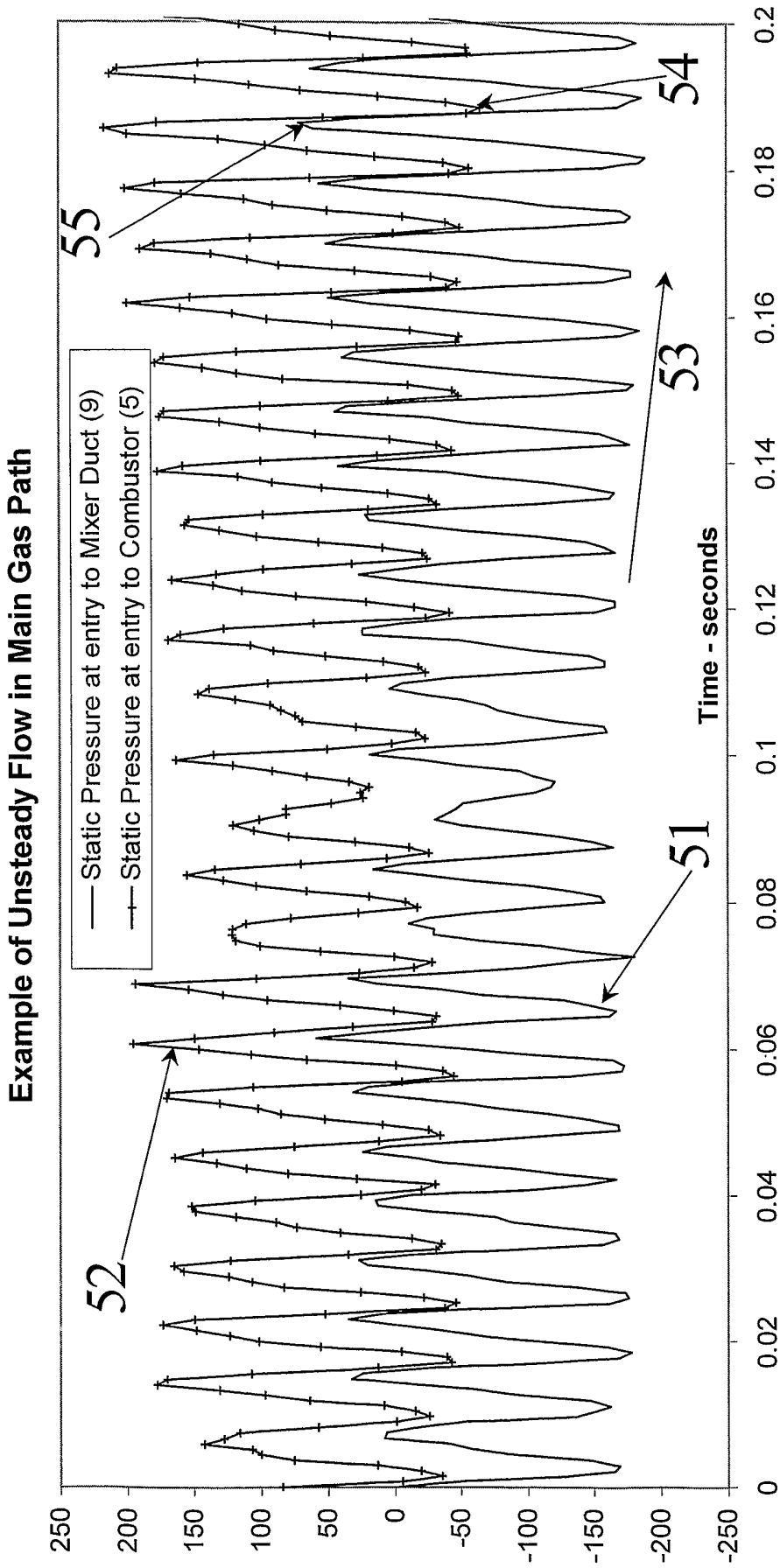


Figure 5

Example of Unsteady Flow in Fuel System

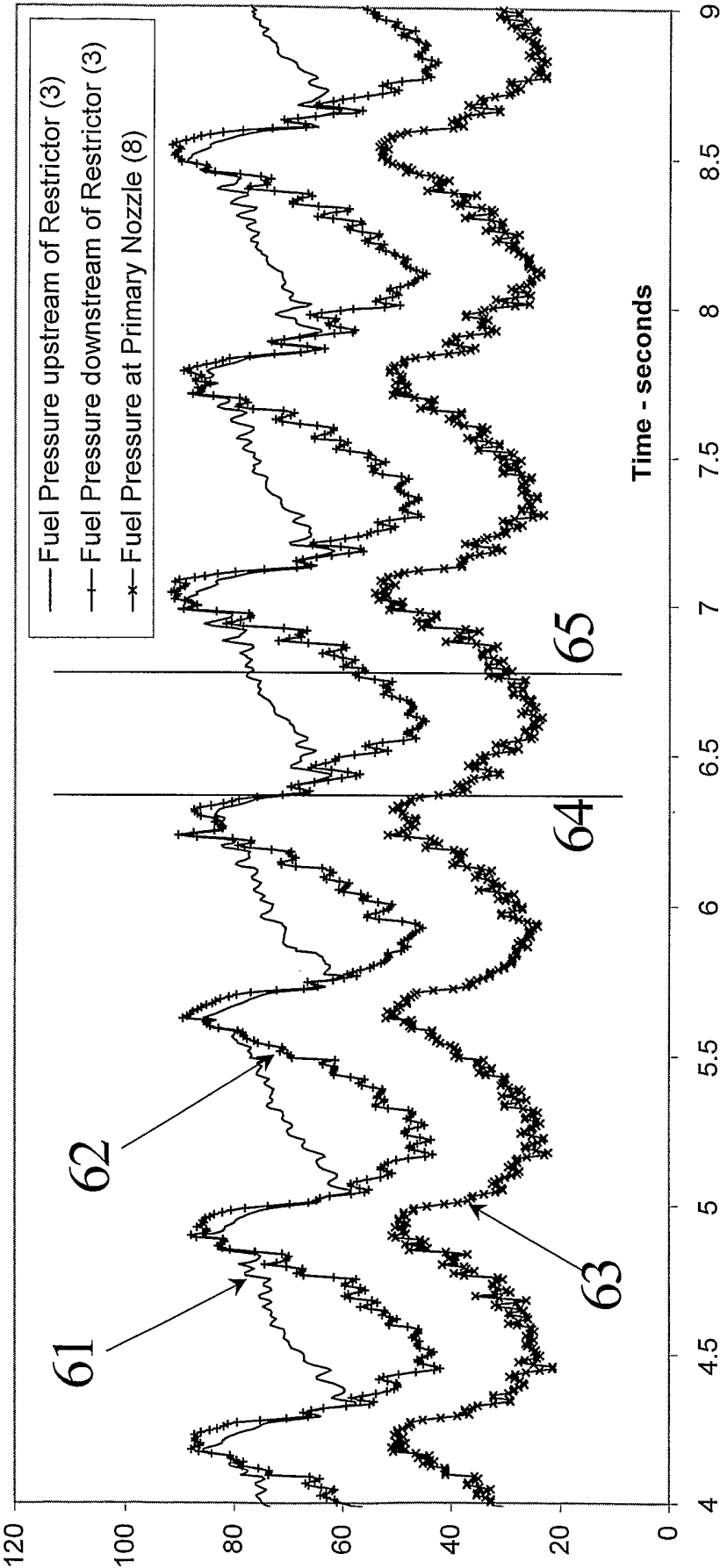


Figure 6

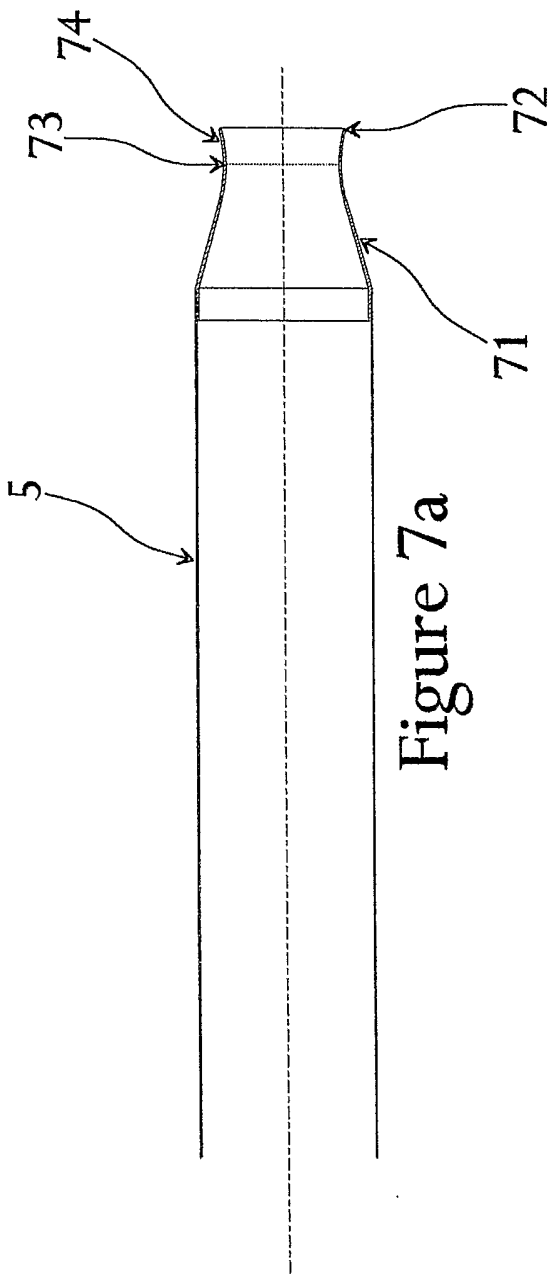
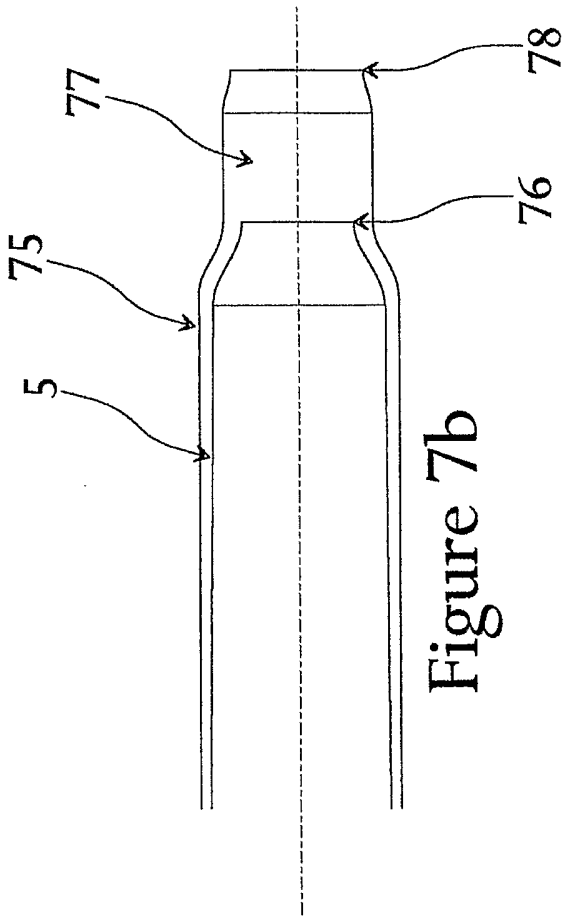
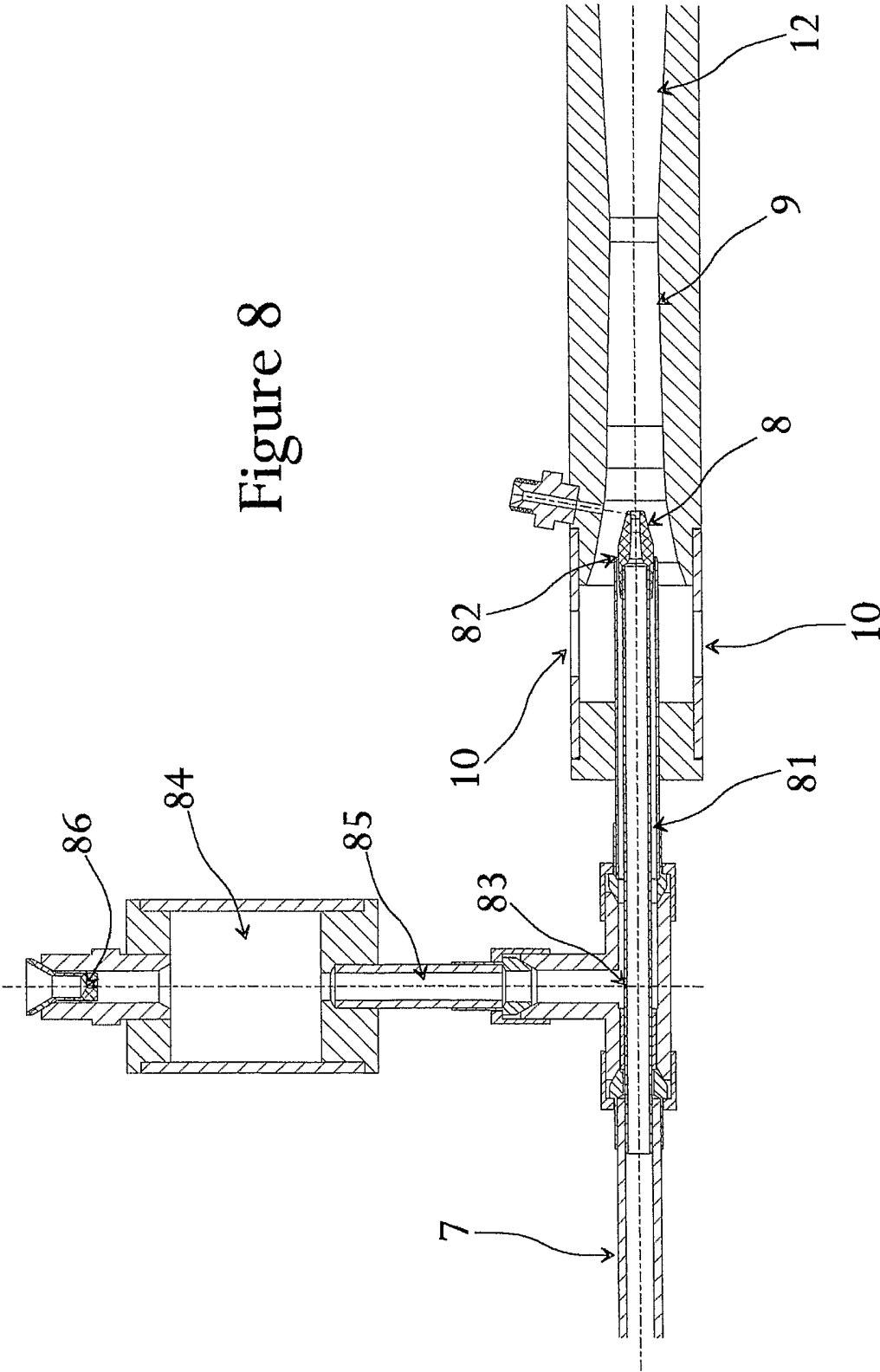


Figure 8



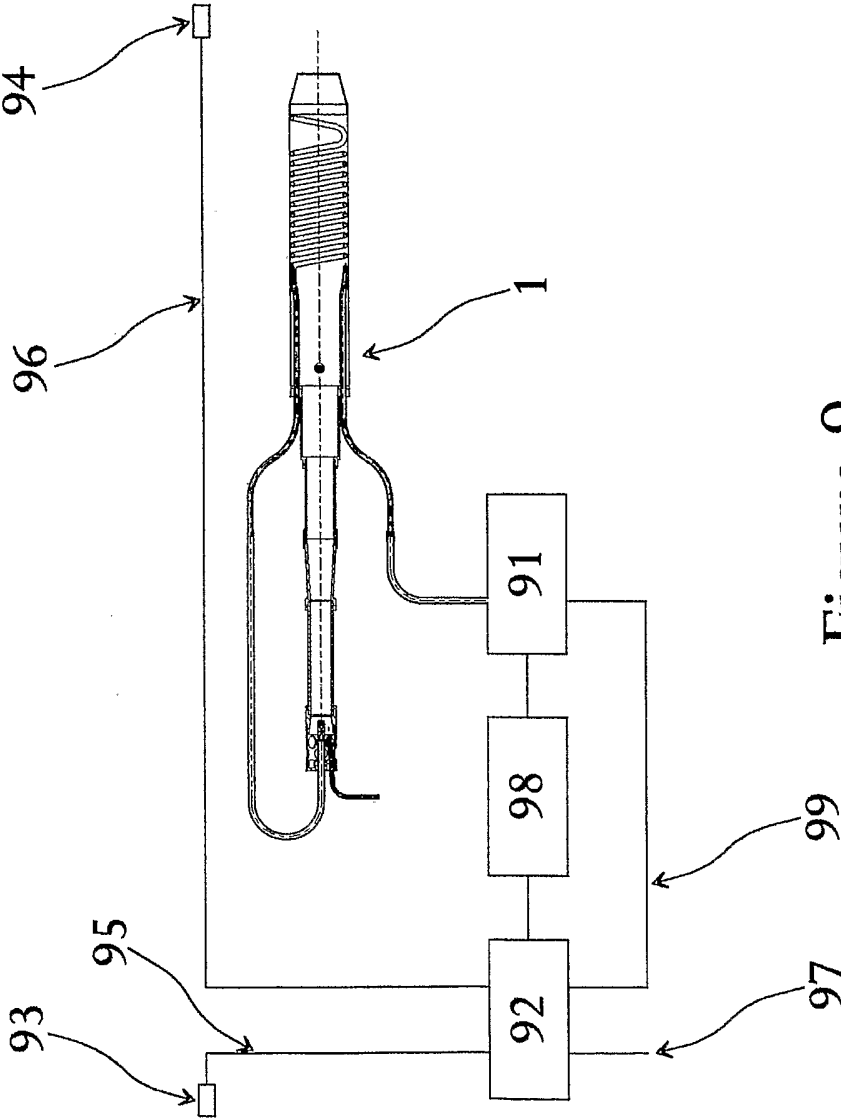
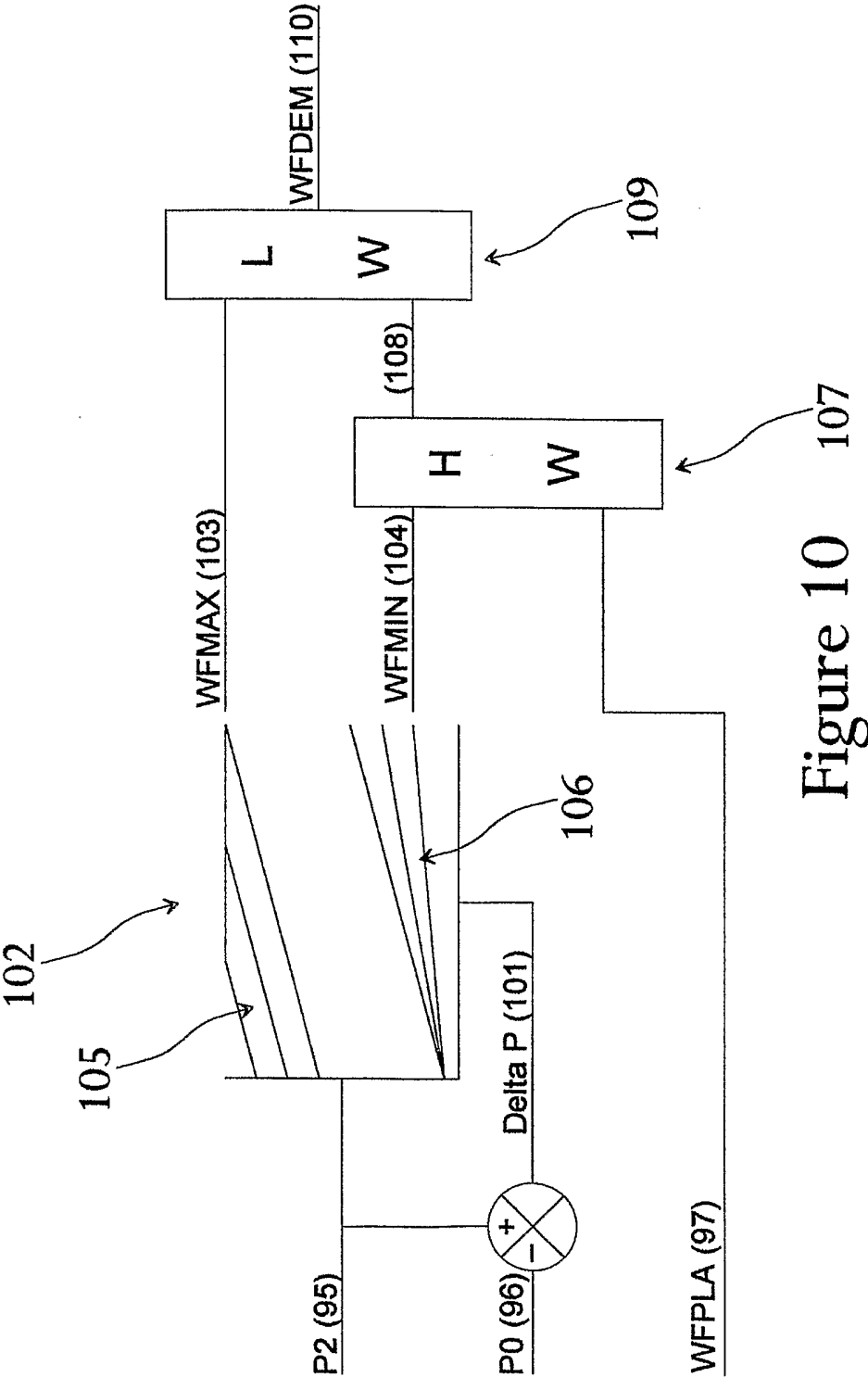


Figure 9



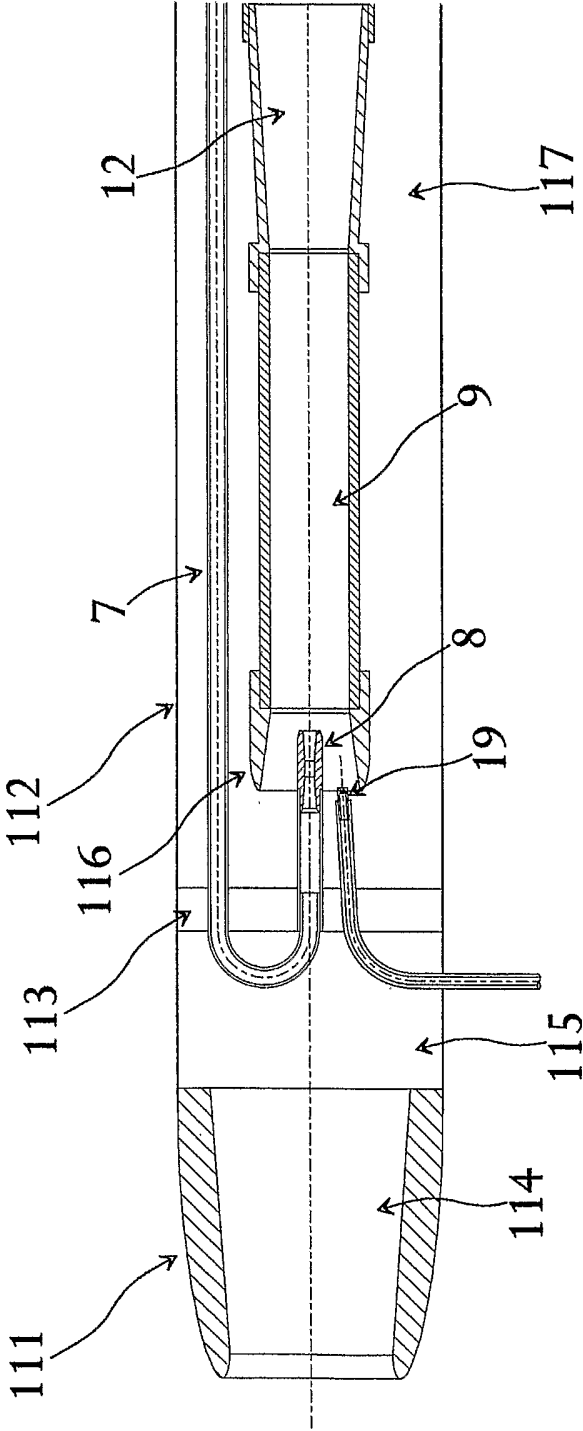


Figure 11

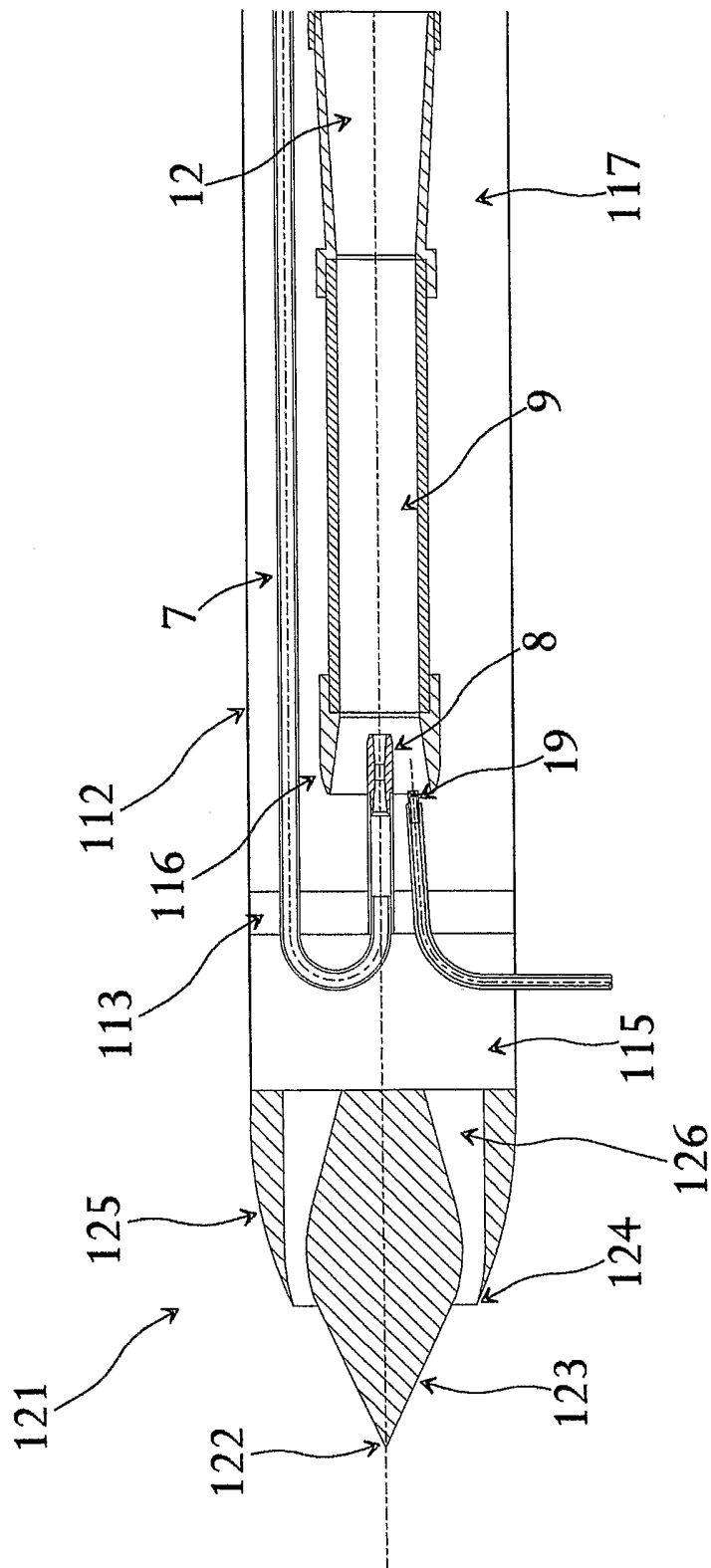


Figure 12

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB2004/003221

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F02K7/12

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 F02K

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

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

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 768 257 A (NEUFFER B) 30 October 1973 (1973-10-30) column 3, line 64 - column 4, line 68 column 7, line 49 - column 7, line 57; figures 1a,10,12,13 -----	1,3, 7-10, 12-14
X	GB 2 021 201 A (KERSHAW HA) 28 November 1979 (1979-11-28) page 1, line 56 - page 1, line 85 page 2, line 54 - page 2, line 78; figures 1-4 -----	1,3,7,8
X	US 5 946 904 A (BENDOT JOSEPH G ET AL) 7 September 1999 (1999-09-07) column 3, line 28 - column 3, line 65; figures 1-3 ----- -/--	1,3

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

29 October 2004

Date of mailing of the international search report

08/11/2004

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INTERNATIONAL SEARCH REPORT

Int ernational Application No
PCT/GB2004/003221

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CH 325 606 A (SNECMA) 15 November 1957 (1957-11-15) the whole document -----	1,7

INTERNATIONAL SEARCH REPORT

Information on patent family members

In tional Application No

PCT/GB2004/003221

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 3768257	A	30-10-1973	US 3861141 A	21-01-1975
GB 2021201	A	28-11-1979	NONE	
US 5946904	A	07-09-1999	AU 8696798 A	01-03-1999
			CN 1123687 B	08-10-2003
			DE 1009927 T1	14-09-2000
			EP 1009927 A1	21-06-2000
			RU 2195565 C2	27-12-2002
			WO 9907988 A1	18-02-1999
CH 325606	A	15-11-1957	NONE	