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(71) **Applicant: AIRBUS OPERATIONS LIMITED** [GB/GB]; Pegasus House, Aerospace Avenue, Filton, Bristol, BS34 7PA (GB).

(72) **Inventors: JAMES, Dylan**; c/o Airbus Operations Ltd., UK IP Dept., Pegasus House, Aerospace Avenue, Filton, Bristol, BS34 7PA (GB). **SANDIFORD, James-Patrick**; c/o Airbus Operations Ltd., UK IP Dept., Pegasus House, Aerospace Avenue, Filton, Bristol, BS34 7PA (GB).

(74) **Agent: LERWILL, Jonathan**; c/o Airbus Operations Ltd., UK IP Dept., Pegasus House, Aerospace Avenue, Filton, Bristol, BS34 7PA (GB).

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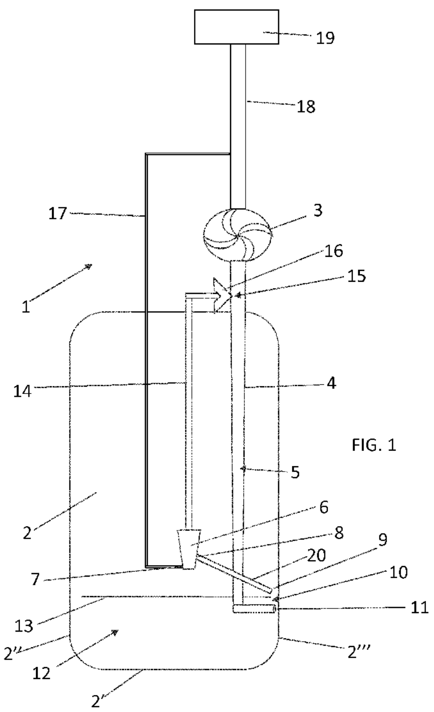

FIG. 1

(57) **Abstract:** The invention provides an aircraft fuel supply arrangement for delivering liquid hydrogen to an aircraft engine (19), the arrangement comprising: a fuel tank (2) for the storage of liquid hydrogen; an aircraft engine (19) configured to be powered by liquid hydrogen; a primary pump (3) for delivering liquid hydrogen fuel from the fuel tank (2) to the aircraft engine; one or more fuel delivery conduits (4,5) for carrying fuel from the fuel tank to the primary pump (3), one or more fuel delivery conduits (18) providing a fuel supply volume for carrying fuel; and a secondary pump (6) for delivering liquid hydrogen fuel to the primary pump (3). An aircraft comprising such an aircraft fuel supply arrangement, and a method of supplying liquid hydrogen to an aircraft engine are also provided.

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SUPPLY OF LIQUID HYDROGEN TO AIRCRAFT ENGINES

BACKGROUND OF THE INVENTION

[0001] The present disclosure relates to the supply of liquid hydrogen to aircraft engines.

[0002] The present invention concerns the supply of liquid hydrogen to aircraft engines. More particularly, but not exclusively, this invention concerns an aircraft fuel supply arrangement. The invention also concerns an aircraft comprising an aircraft system comprising an aircraft fuel supply arrangement, an aircraft and a method of supplying liquid hydrogen to an aircraft engine.

[0003] Conventional aircraft engines are powered by liquid kerosene fuel, but it has been proposed for aircraft engine to use other fuels, such as liquid hydrogen. Irrespective of the liquid fuel type, when an aircraft undertakes certain manoeuvres (such as manoeuvres that subject the aircraft to negative gravitational forces) gas may be taken into the engine fuel supply system because the inlet to the engine fuel supply system is in gas, and not liquid. It is generally undesirable for gas to be delivered to the aircraft engine because the aircraft engines are designed to run on liquid fuel, as opposed to gas. In conventional kerosene-fuelled aircraft measures are taken to remove the gas from the engine fuel supply system and/or to reduce the risk of gas entering the engine fuel supply system. For example, the gas may be vented from a fuel line between the engine and a fuel pump that is used to supply fuel to the engine. Alternatively, the fuel pump may be located in a collector box with a fuel intake at the bottom of the fuel tank, the intake being configured so that there is sufficient fuel below the intake to sustain the engine for a given period (usually 5 seconds). It is understood, however, that it may not be practical to provide a liquid hydrogen fuel delivery system with a gas release valve or vent. Furthermore, it is also understood that it may be difficult to arrange the fuel intake so that there is sufficient liquid hydrogen fuel below the intake for the desired period of time. Alternative ways of inhibiting gas from entering an aircraft engine fuelled by liquid hydrogen are therefore desired.

[0004] The present invention seeks to mitigate the above-mentioned problems. Alternatively or additionally, the present invention seeks to provide an improved aircraft fuel supply arrangement.

SUMMARY OF THE INVENTION

[0005] The present invention provides, according to a first aspect, an aircraft fuel supply arrangement configured to supply liquid hydrogen to an aircraft engine configured to be powered by liquid hydrogen, the aircraft fuel supply comprising:

a fuel tank for the storage of liquid hydrogen;

a primary pump for delivering liquid hydrogen fuel from the fuel tank to the aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the primary pump; and

a secondary pump configured to deliver liquid hydrogen into one or more of the fuel delivery conduits at a position between (i) one or more fuel inlets to one or more of the fuel delivery conduits and (ii) the primary pump, and thereby deliver liquid hydrogen to the primary pump.

[0006] It will be appreciated that the fuel inlets are the fuel inlets through which the fuel delivery conduit(s) draw fuel from the fuel tank. The applicant has discovered that it is possible to use a secondary pump to supply liquid hydrogen fuel to the primary pump, which may be of benefit if one or more fuel delivery conduits upstream of the primary pump contain gas for some reason, for example, if the aircraft has undertaken a manoeuvre that causes gas to be taken into one or more fuel delivery conduits, such as a turn, bank or manoeuvre (such as a climb or descent) that subjects the aircraft to negative gravitational forces (referred to hereinafter as a “negative-g event”).

[0007] One or more fuel delivery conduits may provide a fuel supply volume for accommodating fuel.

[0008] The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits at a point proximate one or more fuel inlets for one or more fuel delivery conduits. This may allow liquid hydrogen fuel to be delivered upstream of gas that may have been introduced to one or more fuel delivery conduits, for example, as a result of a negative-g event. The introduction of fuel upstream of the gas may cause that gas to be compressed, inhibiting further expansion of the gas and inhibiting evaporation or boiling of the remaining liquid hydrogen, thereby reducing the volume of gas delivered to the primary pump and therefore to the aircraft engine.

[0009] The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of (and optionally proximate to) the primary pump, and optionally downstream of the fuel supply volume provided by one or more fuel delivery conduits. The fuel supply volume may, in use, accommodate gas, for example, if the inlets to one or more fuel delivery conduits have been located in gas while the primary pump has been operating. This may happen, for example, during a negative-g event. The secondary pump may be configured to deliver liquid hydrogen to the primary pump, reducing the risk of gas being fed to the aircraft engine. The secondary pump may be configured to deliver liquid hydrogen to urge gas present in the fuel supply volume out of one or more fuel delivery conduits, reducing the risk of gas being fed to the aircraft engine.

[0010] The fuel supply volume may be sufficiently large to accommodate the volume of fuel used by the aircraft engine over a pre-determined period of time, such as at least 1 second, optionally at least 3 seconds, optionally at least 5 second, optionally no more than 10 seconds, optionally no more than 8 seconds and optionally no more than 6 seconds. The fuel supply volume may therefore be sufficiently large to accommodate gas that has been drawn into one or more fuel supply conduits over a sustained period for which the aircraft has undertaken a manoeuvre which has causes gas to be taken into the fuel delivery conduit(s), for example, a negative-g event lasting 5 seconds.

[0011] The aircraft fuel supply arrangement may comprise an engine supply conduit for supplying fuel from the primary pump to the aircraft engine. The engine supply conduit may be contiguous with a fuel delivery conduit for supplying fuel from the fuel tank to the primary pump.

[0012] The primary pump may be located external to a fuel tank. This may facilitate ease of access to the primary pump. Also, if the primary pump generates heat, it may be desirable for the primary pump to be located external to the fuel tank, because it may not be desirable to heat the liquid hydrogen.

[0013] The secondary pump is optionally configured to draw liquid hydrogen from a fuel tank, optionally from a bottom region of a fuel tank (which may be the same fuel tank as the one or more fuel delivery conduits draw fuel from, or a different tank). In this context, "bottom" is determined when the aircraft is in a normal, level-flight orientation, with a flight path angle of zero, and optionally a pitch angle of less than 5 degrees.

[0014] The secondary pump may be located external to a fuel tank. This may facilitate ease of access to the secondary pump. Also, if the secondary pump generates heat, it may be desirable for the secondary pump to be located external to the fuel tank, because it may not be desirable to heat the liquid hydrogen.

[0015] The secondary pump may comprise an ejector pump (sometimes known as a vacuum ejector or jet pump). Such an ejector pump typically uses the Bernoulli effect or principle. The secondary pump may comprise a motive fluid inlet and a functional fluid inlet. The movement of motive fluid is used to convey a functional fluid through the pump. The motive fluid inlet is optionally configured to receive fluid, typically liquid hydrogen, moved by the primary pump. the motive fluid inlet is optionally configured to receive fluid from a motive fluid supply conduit, whose inlet is optionally located downstream of the primary pump. The motive fluid supply conduit may be in fluid communication with the engine supply conduit. Liquid hydrogen flowing in the engine supply conduit may be diverted to the motive fluid supply conduit, and then to the motive fluid inlet of the ejector pump. The functional fluid inlet is optionally configured to draw liquid hydrogen into the secondary pump, optionally from a bottom region of a fuel tank.

[0016] Optionally, the secondary pump may be configured to operate whenever the primary pump is operational. This is particularly the case if the secondary pump comprises an ejector pump. Alternatively or additionally, the secondary pump may be configured to deliver liquid hydrogen to the primary pump in response to a pre-determined event. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits, optionally proximate one or more fuel inlets for one or more fuel delivery conduits, in response to a pre-determined event. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits, in response to a pre-determined event. The pre-determined event may, for example, one of one or more pre-determined aircraft manoeuvres known to cause gas to enter one or more fuel delivery conduits, such as a turn, bank or a manoeuvre that causes the aircraft to experience negative gravitational forces. Typically, the secondary pump may be configured to deliver liquid hydrogen after the pre-determined event has been completed, for example, after a negative-g event has been completed. The secondary pump may be configured to deliver liquid hydrogen immediately after the pre-determined event has been completed (for example, within a second of the pre-determined event having been completed). This may reduce the likelihood of gas being delivered to the aircraft engine.

[0017] Optionally, the secondary pump may be configured to operate continuously, so long as the primary pump is operational. Alternatively, the secondary pump may be configured to deliver liquid hydrogen to the primary pump for a pre-determined period of time. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits, optionally proximate one or more fuel inlets for one or more fuel delivery conduits, for a pre-determined period of time. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits, for a pre-determined period of time. The pre-determined period of time may be determined based on one or more factors, such as the duration and/or magnitude of a pre-determined event, such as one of one or more pre-determined aircraft manoeuvres.

[0018] The secondary pump may be configured to deliver liquid hydrogen to the primary pump based on one or more sensed or measured parameters. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits, optionally proximate one or more fuel inlets for one or more fuel delivery conduits, based on one or more sensed or measured parameters. The secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits, based on one or more sensed or measured parameters. One or more sensed or measured parameters may comprise one or more of the presence of gas in one or more fuel delivery conduits, the amount of gas in one or more fuel delivery conduits, engine power, engine acceleration and engine speed.

[0019] As mentioned above, one or more fuel delivery conduits are provided with one or more fuel inlets. At least one, optionally more than one and optionally each of the fuel inlets may be located in a bottom region of a fuel tank. This reduces the likelihood of gas being taken-up into the fuel delivery conduits. One or more fuel inlets may be located in a fuel collector volume. A fuel collector volume may optionally be formed by one or more walls for inhibiting movement of liquid fuel. The wall(s) may inhibit the movement of liquid fuel, thereby reducing the risk of one or more fuel inlets being located in gas, as opposed to liquid. One or more of the walls may be provided by one or more fuel tank walls. At least one of the walls forming the collector volume may be inside the fuel tank.

[0020] An aircraft may comprise more than one aircraft engine configured to be powered by liquid hydrogen. Therefore, the aircraft fuel supply arrangement may comprise:

a first primary pump for delivering liquid hydrogen fuel from the fuel tank to a first aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the first primary pump, one or more fuel delivery conduits optionally providing a first fuel supply volume for accommodating fuel;

a first secondary pump for delivering liquid hydrogen fuel to one or more of the fuel delivery conduits and thereby deliver liquid hydrogen to the first primary pump;

a second primary pump for delivering liquid hydrogen fuel from the fuel tank to a second aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the second primary pump, one or more fuel delivery conduits optionally providing a second fuel supply volume for accommodating fuel;

a second secondary pump for delivering liquid hydrogen fuel to one of more of the fuel delivery conduits and thereby to deliver liquid hydrogen to the second primary pump.

[0021] The second secondary pump may be configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the second primary pump and downstream of the second fuel supply volume provided by one or more fuel delivery conduits.

[0022] According to a second aspect of the invention there is also provided an aircraft system comprising an aircraft fuel supply arrangement in accordance with the first aspect of the invention and one or more aircraft engines configured to be powered by liquid hydrogen, and configured to receive liquid hydrogen fuel from the aircraft fuel supply arrangement in accordance with the first aspect of the present invention.

[0023] According to a third aspect of the present invention, there is provided an aircraft comprising at least one aircraft fuel supply arrangement in accordance with the first aspect of the present invention and/or an aircraft system in accordance with the second aspect of the present invention. The aircraft of the third aspect of the present invention may comprise more than one aircraft fuel supply arrangement in accordance with the first aspect of the present invention. For example, the aircraft may comprise a first aircraft fuel supply arrangement in accordance with the first aspect of the invention associated with a first wing of the aircraft, and a second aircraft fuel supply arrangement in accordance with the first aspect of the invention associated with a second wing of the aircraft. Alternatively or additionally, the aircraft in accordance with the third aspect of the present invention may comprise more than one aircraft system in accordance with the second aspect of the present invention. For example, the aircraft may comprise one aircraft system in accordance with the second aspect of the invention associated with a first wing of the aircraft, and another aircraft system in accordance with the second aspect of the invention associated with a second wing of the aircraft.

[0024] The aircraft may be a rotary wing aircraft, but is preferably a fixed wing aircraft.

[0025] The aircraft may be a single aisle aircraft or a double aisle aircraft. The aircraft may be a passenger aircraft. The aircraft may have capacity for at least 50 passengers, optionally at least 70 passengers, optionally at least 100 passengers, optionally at least 120 passengers, optionally at least 150 passengers, optionally at least 200 passengers, optionally at least 250 passengers, optionally at least 300 passengers, optionally at least 350 passengers and optionally at least 400 passengers.

[0026] The aircraft may have a length of at least 25m, optionally at least 30m, optionally at least 35m, optionally at least 40m, optionally at least 45m, optionally at least 50m, optionally at least 55m, optionally at least 60m, optionally at least 65m and optionally at least 70m.

[0027] The aircraft may have a wingspan of at least 25m, optionally at least 30m, optionally at least 35m, optionally at least 40m, optionally at least 45m, optionally at least 50m, optionally at least 55m, optionally at least 60m, optionally at least 65m and optionally at least 70m.

[0028] The aircraft may have a maximum take-off weight of at least 50,000kg, optionally at least 60,000kg, optionally at least 70,000kg, optionally at least 80,000kg, optionally at least 90,000kg, optionally at least 100,000kg, optionally at least 150,000kg, optionally at least 200,000kg, optionally at least 250,000kg, optionally at least 300,000kg, optionally at least 350,000kg, optionally at least 400,000kg, optionally at least 450,000kg and optionally at least 500,000kg.

[0029] In accordance with a fourth aspect of the present invention, there is provided a method of providing liquid hydrogen fuel to an aircraft engine in an aircraft comprising a primary pump for delivering liquid hydrogen fuel from a fuel tank to the aircraft engine, the method comprising causing a secondary pump to provide liquid hydrogen to the primary pump via one or more fuel delivery conduits for supplying liquid hydrogen from the fuel tank to the primary pump.

[0030] The applicant has discovered that it may be beneficial to use a secondary pump to deliver liquid hydrogen fuel to a primary pump. For example, if gas becomes present in the fuel lines that are used to deliver liquid hydrogen to the primary pump, then it may be desirable to deliver liquid hydrogen to the primary pump using a secondary pump in order to reduce the risk of gas being delivered to the aircraft engine.

[0031] The method may comprise causing the secondary pump to deliver liquid hydrogen to compress hydrogen gas and/or inhibit evaporation of liquid hydrogen. The method may comprise causing the secondary pump to deliver liquid hydrogen to one or more fuel delivery conduits, optionally to deliver liquid hydrogen proximate one or more fuel inlets for one or more fuel delivery conduits. The method may comprise causing the secondary pump to deliver liquid hydrogen to one or more fuel delivery conduits, thereby compressing gas present in one or more fuel delivery conduit. Causing the secondary pump to deliver liquid hydrogen to one or more fuel delivery conduits may comprise operating the primary fuel pump. In this connection, the secondary pump may be operated whenever the primary fuel pump is operational. This ensures continuous supply of liquid hydrogen by the secondary pump.

[0032] The method may comprise causing the secondary pump to deliver liquid hydrogen fuel so as to urge gas out of one or more fuel delivery conduits. One or more fuel delivery conduits may be configured to carry fuel to the primary pump. Gas may be located in one or more fuel delivery conduits for a variety of reasons, for example, if an aircraft has undertaken a negative-g event (such as an aircraft manoeuvre that subjects the aircraft to negative g). Causing gas to be removed from one or more fuel delivery conduits may reduce the likelihood of gas being delivered to the aircraft engine. The method may comprise causing the secondary pump to deliver liquid hydrogen to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits. The delivery of liquid hydrogen to one or more fuel delivery conduits upstream of the primary pump facilitates the delivery of liquid hydrogen to the primary pump. The delivery of liquid hydrogen to one or more fuel delivery conduits downstream of the fuel supply volume permits gas present in the fuel delivery volume to be urged out of, or purged from, the fuel delivery conduit(s).

[0033] The fuel supply volume may be sufficiently large to accommodate the volume of fuel used by the aircraft engine over a pre-determined period of time, such as at least 1 second, optionally at least 3 seconds, optionally at least 5 second, optionally no more than 10 seconds, optionally no more than 8 seconds and optionally no more than 6 seconds. The fuel supply volume may therefore be sufficient to accommodate gas that has been drawn into one or more fuel supply conduits as a result of the aircraft having undertaken a particular manoeuvre for a sustained period of time, for example, a negative-g event lasting for, say, 5 seconds.

[0034] The primary pump may be located external to a fuel tank. This may facilitate ease of access to the primary pump. Also, if the primary pump generates heat, it may be desirable for the primary pump to be located external to the fuel tank, because it may not be desirable to heat the liquid hydrogen.

[0035] The secondary pump is optionally configured to draw liquid hydrogen from a fuel tank, optionally from a bottom region of a fuel tank. The secondary pump may be located external to a fuel tank. This may facilitate ease of access to the secondary pump. Also, if the secondary pump generates heat, it may be desirable for the secondary pump to be located external to the fuel tank, because it may not be desirable to heat the liquid hydrogen.

[0036] As mentioned above, the secondary pump may optionally be operated whenever the primary pump is operated. Alternatively or additionally, the secondary pump is optionally caused to deliver liquid hydrogen to the primary pump in response to a pre-determined event. The secondary pump is optionally caused to deliver liquid hydrogen to one or more fuel delivery conduit, optionally to deliver liquid hydrogen proximate to one or more fuel tank inlet for one or more fuel delivery conduits, in response to a pre-determined event. The secondary pump is optionally caused to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits, in response to a pre-determined event. The pre-determined event may, for example, be one of one or more pre-determined aircraft manoeuvres known to cause gas to be taken into one or more fuel delivery conduits, such as a negative-g event. Optionally, the secondary pump is caused to deliver liquid hydrogen after the pre-determined event has been completed, for example, after a negative-g event has been completed. The secondary pump is optionally caused to deliver liquid hydrogen immediately after the pre-determined event has been completed, for example, within a second of the pre-determined event having been completed. This may reduce the likelihood of gas being delivered to the aircraft engine.

[0037] As mentioned above, the secondary pump may be configured to be operated whenever the primary pump is operated. Alternatively, the secondary pump may be caused to deliver liquid hydrogen to the primary pump for a pre-determined period of time. The secondary pump is optionally caused to deliver liquid hydrogen to one or more fuel delivery conduit, optionally proximate to one or more fuel tank inlet for one or more fuel delivery conduits, for a pre-determined period of time. The secondary pump may be caused to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits, for a pre-determined period of time. The pre-determined period of time may be determined based on one or more factors, such as the duration of a pre-determined event, such as the duration and/or magnitude of one of one or more pre-determined aircraft manoeuvres known to cause gas to be taken into one or more fuel delivery conduits, such as a negative-g event.

[0038] As mentioned above, the secondary pump may be configured to be operated whenever the primary pump is operated. Alternatively, the method may comprise sensing or measuring one or more parameters, and based on said sensing or measurement, deciding whether or not to cause the secondary pump to deliver liquid hydrogen. One or more sensed or measured parameters may comprise one or more of the presence of gas in one or more fuel delivery conduits, the amount of gas in one or more fuel delivery conduits, engine power, engine acceleration and engine speed. Based on the sensed or measured parameters, the secondary pump may be caused to deliver liquid hydrogen fuel to one or more fuel delivery conduits, optionally to deliver liquid hydrogen proximate to one or more fuel inlets for one or more fuel delivery conduits, or optionally upstream of the primary pump and downstream of the fuel supply volume provided by one or more fuel delivery conduits.

[0039] The primary pump may comprise any of the features described above in relation to the aircraft fuel supply arrangement of the first aspect of the present invention.

[0040] The secondary pump may comprise any of the features described above in relation to the aircraft fuel supply arrangement of the first aspect of the present invention.

[0041] One or more fuel delivery conduits may comprise any of the features described above in relation to the aircraft fuel supply arrangement of the first aspect of the present invention.

[0042] The method may comprise a method of providing liquid hydrogen fuel to a first aircraft engine in an aircraft comprising a first primary pump for delivering liquid hydrogen fuel from a fuel tank to the first aircraft engine, and to a second aircraft engine in an aircraft comprising a second primary pump for delivering liquid hydrogen fuel from a fuel tank to the second aircraft engine, the method comprising causing a first secondary pump to provide liquid hydrogen to the first primary pump, and causing a second secondary pump to provide liquid hydrogen to the second primary pump.

[0043] One or more fuel delivery conduits for carrying fuel from a fuel tank to the second primary pump may be provided. One or more fuel delivery conduits may provide a second fuel supply volume for accommodating fuel. The second secondary pump may be caused to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of the second primary pump and downstream of the second fuel supply volume provided by one or more fuel delivery conduits.

[0044] The method of the fourth aspect of the present invention may use the aircraft fuel supply arrangement of the first aspect of the present invention, the aircraft system of the second aspect of the present invention and/or the aircraft of the third aspect of the present invention.

[0045] It will, of course, be appreciated that features described in relation to one aspect of the present invention may be incorporated into other aspects of the present invention. For example, the method of the invention may incorporate any of the features described with reference to the aircraft fuel supply arrangement of the invention and *vice versa*.

DESCRIPTION OF THE DRAWINGS

[0046] Embodiments of the present invention will now be described by way of example only with reference to the accompanying schematic drawings of which:

[0047] Figure 1 shows a schematic view of an aircraft fuel supply arrangement according to a first embodiment of the invention;

[0048] Figure 2 shows a schematic view of another aircraft fuel supply arrangement according to a second embodiment of the invention;

[0049] Figure 3 shows a schematic view of an aircraft according to an embodiment of the invention;

[0050] Figure 4 shows a schematic view of a method of supplying liquid hydrogen fuel to an aircraft engine according to an embodiment of the invention;

[0051] Figure 5 shows a schematic view of an alternative method of supplying liquid hydrogen fuel to an aircraft engine according to an embodiment of the invention; and

[0052] Figure 6 shows a schematic view of a method of supplying liquid hydrogen fuel to an aircraft engine according to another embodiment of the invention.

DETAILED DESCRIPTION

[0053] An example of an aircraft fuel supply arrangement for delivering liquid hydrogen to an aircraft engine according to an embodiment of the invention will now be described with reference to Figure 1. The aircraft fuel supply arrangement, denoted generally by reference numeral 1, is configured to deliver liquid hydrogen to an aircraft engine 19 configured to be powered by liquid hydrogen. The aircraft fuel supply arrangement 1 comprises a fuel tank 2 for the storage of liquid hydrogen, a primary pump 3 for delivering liquid hydrogen fuel from the fuel tank 2 to the aircraft engine 19, a fuel delivery conduit 4 for supplying fuel from the fuel tank 2 to the primary pump 3, the fuel delivery conduit 4 providing a fuel supply volume 5 for accommodating fuel, and a secondary pump 6 for delivering liquid hydrogen fuel to the primary pump 3. For the avoidance of doubt, it should be noted that the aircraft fuel supply arrangement 1 is shown in Figure 1 on its side; in this connection, the bottom of the fuel tank 2 is denoted by reference numeral 10. Fuel delivery conduit 4 is approximately horizontal. The applicant has discovered that it is advantageous to provide a secondary pump 6 that is able to provide liquid hydrogen fuel to the primary pump 3. This is advantageous when, for example, there is gas present in the fuel delivery conduit 4, as will now be explained.

[0054] Gas may become present in the fuel delivery conduit 4 as a result of certain aircraft manoeuvres, such as manoeuvres that subject the aircraft to negative gravitational forces, sometimes known as “negative-g events”. These negative-g events can include certain turns, banks, ascents and descents. In this connection, an inlet 11 to the fuel delivery conduit 4 is located in the bottom 10 portion of fuel tank 2 in order to decrease the likelihood of the inlet 11 being located in gas, as opposed to liquid. For most in-flight conditions, the inlet 11 will be immersed in liquid hydrogen and therefore liquid will be drawn by primary pump 3 through inlet 11, through fuel delivery conduit 4, through engine supply conduit 18 and into aircraft engine 19. During certain aircraft manoeuvres (such as a negative-g event), inlet 11 may not be immersed in liquid, and therefore gas will be drawn through inlet 11 and into fuel delivery conduit 4. If no remedial action is taken, the gas will be delivered to the primary pump 3 and to the aircraft engine 19, which is generally undesirable because neither the primary pump 3 nor the aircraft engine 19 is designed to work with gas, but rather liquid hydrogen. Prolonged delivery of gas to aircraft engine 19 may result in the engine not functioning. Delivery of gas to the primary pump3 may damage the primary pump 3 and/or lead to a reduction in lifespan of the primary pump 3. The aircraft fuel supply arrangement 1 is configured to deal with gas in the fuel delivery conduit 4, as will now be explained.

[0055] Fuel delivery conduit 4 provides a fuel supply volume 5 that is sufficiently large that a volume of gas taken into the fuel delivery conduit 4 by the primary pump 3 during a negative-g event that lasts five seconds can be accommodated in the fuel delivery conduit 4. The gas located in the fuel supply volume 5 therefore would not pass the primary pump 3 or enter the aircraft engine 19 during the negative-g event.

[0056] It should be noted that second pump 6 is operational so long as primary pump 3 is operational. In this connection, secondary pump 6 is an ejector pump that operates using the Bernouilli effect. In this connection, motive liquid is continuously fed through motive liquid supply conduit 17 from engine supply conduit 18 to the motive liquid inlet 7 of secondary pump 6. The inlet 9 of the secondary pump supply conduit 20 is located in liquid hydrogen. Movement of the motive liquid through motive liquid inlet 7 generates suction which causes liquid hydrogen to be drawn through inlet 9, through conduit 20 and into a functional fluid inlet 8 of the secondary pump 6. Liquid hydrogen is pumped through secondary pump outlet conduit 14 into the fuel delivery conduit 4 at a point 15 that is upstream of primary pump 3 but downstream of fuel supply volume 5. The liquid hydrogen from secondary pump 6 is therefore supplied to the fuel delivery conduit 4 downstream of the gas that is present in the fuel delivery conduit 4 as a result of the negative-g event. Some of the liquid hydrogen supplied by the secondary pump 6 is provided to the primary pump 3, and some of the liquid hydrogen supplied by the secondary pump 6 urges the gas out of the fuel delivery conduit 4 via inlet 11. Sufficient liquid hydrogen is supplied by the secondary pump 6 to meet the demands of the primary pump 3 (and therefore of the aircraft engine 19) and to ensure that gas is removed from the fuel delivery conduit 4. As mentioned above, secondary pump 6 is operated continuously, so long as primary pump 3 is operational. Alternatively, the secondary pump may be operated for a pre-determined amount of time (for example, 10 seconds). This may be achieved, for example, using a different type of secondary pump. Alternatively, the secondary pump may be operated to deliver a pre-determined and measured amount of liquid hydrogen, once again optionally using a different type of secondary pump. As a further alternative, the secondary pump may be operated based on a sensed or measured parameter, optionally using a different type of secondary pump. For example, one or more sensors (not shown) may be used to monitor for the presence of gas at various positions in the fuel delivery conduit 4. The secondary pump 6 may be operated, based on the output of one or more of those gas sensors. For example, the secondary pump 6 may be operated until there is no gas sensed in the fuel delivery conduit 4. This aircraft fuel supply arrangement therefore reduces the likelihood of gas being provided to the primary pump and/or aircraft engine.

[0057] A non-return valve 16 is provided to inhibit passage of gas from fuel delivery conduit 4 into the secondary pump outlet conduit 14, in the event that gas is present in the fuel delivery conduit 4 in the region of the secondary pump outlet conduit 14.

[0058] For the avoidance of doubt, primary pump 3 is located external to fuel tank 2 in order to reduce undesirable heating of the liquid hydrogen by the primary 3 pump. The secondary pump 6 may be located in the fuel tank as it does not generate heat.

[0059] Fuel inlet 11 to fuel delivery conduit 4 is located at the bottom of a fuel collector volume 12 formed by external tank walls 2’, 2’’ and 2’’’ and internal wall 13. The internal wall 13 inhibits movement of fuel out of the fuel collector volume 12, reducing the likelihood of the fuel inlet 11 being exposed to gas, as opposed to liquid.

[0060] As mentioned above, secondary pump 6 is an ejector pump. Ejector pumps have no electrical power requirements and generate little heat. They typically comprise a Venturi, which restricts a flow of a fluid and is configured to create suction and a pumping action. Ejector pumps may also be known as jet pumps.

[0061] An example of an embodiment of an aircraft in accordance with the present invention will now be described with reference to Figure 3. The aircraft is denoted generally by reference numeral 100 and comprises a first aircraft fuel supply arrangement 1A as described above with reference to Figure 1 used to provide liquid hydrogen to first, starboard aircraft engine 19A and a second aircraft fuel supply arrangement 1B as described above with reference to Figure 1 used to provide liquid hydrogen to second, port aircraft engine 19B. The starboard and port wings are denoted W1 and W2, respectively. The aircraft 100 is a single aisle passenger aircraft with a seating capacity of about 150 passengers.

[0062] An example of a method of supplying liquid hydrogen fuel to an aircraft engine in accordance with an embodiment of the invention will now be described with reference to Figures 4 and 1. The method is denoted generally by reference numeral 200. The method 200 is a method of providing liquid hydrogen fuel to an aircraft engine 19 in an aircraft 100 comprising a primary pump 3 for delivering liquid hydrogen fuel from a fuel tank 2 to the aircraft engine 19. The method 200 comprises causing 201 the secondary pump 6 to deliver liquid hydrogen fuel to the fuel delivery conduit 4 upstream of the primary pump 3 and downstream of the fuel supply volume 5 provided by the fuel delivery conduit 4. This causes 202 liquid hydrogen to be delivered to the primary pump 3, and causes 203 liquid hydrogen to urge gas out of the fuel delivery conduit 4. Causing 201 the secondary pump 6 to deliver liquid hydrogen fuel to the fuel delivery conduit 4 comprises operating the primary pump 3, as described above.

[0063] A further, alternative example of a method of supplying liquid hydrogen fuel to an aircraft engine in accordance with an embodiment of the invention will now be described with reference to Figures 5. The method is denoted generally by reference numeral 300. The method 300 is a method of providing liquid hydrogen fuel to an aircraft engine 19 in an aircraft 100 comprising a primary pump 3 for delivering liquid hydrogen fuel from a fuel tank 2 to the aircraft engine 19. The method 300 comprises, in response to a pre-determined event 301 (in this case, the aircraft 100 performing a negative-g manoeuvre), causing 302 the secondary pump to deliver liquid hydrogen fuel to the fuel delivery conduit 4 upstream of the primary pump 3 and downstream of the fuel supply volume 5 provided by the fuel delivery conduit 4. This causes 303 liquid hydrogen to be delivered to the primary pump 3, and causes 304 liquid hydrogen to urge gas out of the fuel delivery conduit 4. In this case, the secondary pump may be a different type of pump to an ejector pump or jet pump.

[0064] A further example of an aircraft fuel supply arrangement in accordance with a further embodiment of the first aspect of the invention will now be described with reference to Figure 2. The aircraft fuel supply arrangement, denoted generally by reference numeral 51, is configured to deliver liquid hydrogen to an aircraft engine 19 configured to be powered by liquid hydrogen. The aircraft fuel supply arrangement 51 comprises a fuel tank 2 for the storage of liquid hydrogen, a primary pump 3 for delivering liquid hydrogen fuel from the fuel tank 2 to the aircraft engine 19, a fuel delivery conduit 4 for carrying fuel from the fuel tank 2 to the primary pump 3, the fuel delivery conduit 4 providing a fuel supply volume 5 for accommodating fuel, and a secondary pump 6 for delivering liquid hydrogen fuel to the primary pump 3. For the avoidance of doubt, it should be noted that the aircraft fuel supply arrangement 51 is shown in Figure 2 on its side; in this connection, a bottom of the fuel tank 2 is denoted by reference numeral 10. Fuel delivery conduit 4 is approximately horizontal. The applicant has discovered that it is advantageous to provide a secondary pump 6 that is able to provide liquid hydrogen fuel to the primary pump 3, albeit not directly to the primary pump 3. In the aircraft fuel supply arrangement of Figure 1, liquid hydrogen was provided by the secondary pump 6 to the fuel delivery conduit 4 adjacent to, and immediately upstream of, the primary pump 3, thereby providing liquid hydrogen to the primary pump 3 and expelling gas from the fuel delivery conduit 4. In the aircraft fuel supply arrangement 51 of Figure 2, the secondary pump 6 provides fuel to the fuel delivery conduit 4 remote from the primary pump 3, which fuel will be provided to the primary pump 3. The secondary pump 6 in the aircraft fuel supply arrangement of Figure 2 is configured not to remove the gas from the fuel delivery conduit 4, but rather to compress it, and inhibit further evaporation or boiling of liquid, limiting the amount of gas that is taken into the aircraft engine 19. This will now be described, with reference to Figure 2.

[0065] As mentioned above in relation to the aircraft fuel supply arrangement 1 of Figure 1, gas may become present in the fuel delivery conduit 4, for example, as a result of a manoeuvre of the aircraft.

[0066] As described above in relation to the aircraft fuel supply arrangement of Figure 1, fuel delivery conduit 4 provides a fuel supply volume 5 that is sufficiently large to accommodate a volume of gas urged into the fuel delivery conduit 4 by the primary pump 3 as the aircraft undertakes a certain manoeuvre (such as a negative-g manoeuvre) for a period of up to five seconds. The gas located in the fuel supply volume 5 has therefore not passed the primary pump 3 or entered the aircraft engine 19.

[0067] It should be noted that second pump 6 is operational so long as primary pump 3 is operational. In this connection, secondary pump 6 is an ejector pump that operates using the Bernouilli effect. In this connection, motive liquid is continuously fed through motive liquid supply conduit 17 from engine supply conduit 18 to the motive liquid inlet 7 of secondary pump 6. The inlet 9 of the secondary pump supply conduit 20 is located in liquid hydrogen. Movement of the motive liquid through motive liquid inlet 7 causes liquid hydrogen to be drawn through inlet 9, through conduit 20 and into a functional fluid inlet 8 of the secondary pump 6, and into fuel delivery conduit 4. Liquid hydrogen is pumped into the fuel delivery conduit 4 close to the inlet 11 to the fuel delivery conduit 4. The liquid hydrogen from secondary pump 6 is therefore supplied to the fuel delivery conduit 4 upstream of the majority of the gas that is present in the fuel delivery conduit 4 as a result of the negative-g event. The pumping of liquid hydrogen into the fuel delivery conduit 4 by secondary pump 6 will compress the gas in the fuel delivery conduit 4, and may inhibit further evaporation or boiling of liquid hydrogen. This will therefore limit the volume of gas that passes through the primary pump 3 and into the aircraft engine 19. For the avoidance of doubt, the liquid hydrogen provided by the secondary pump 6 will be delivered to the primary pump 3.

[0068] For the avoidance of doubt, primary pump 3 is located external to fuel tank 2 in order to reduce undesirable heating of the liquid hydrogen by the primary 3 pump. Secondary pump 6 may be located inside or outside of fuel tank 2.

[0069] Fuel inlet 11 is located at the bottom of a fuel collector volume 12 formed by external tank walls 2’, 2’’ and 2’’’ and internal wall 13. The internal wall 13 inhibits movement of fuel out of the fuel collector volume 12, reducing the likelihood of the fuel inlet 11 being exposed to gas, as opposed to liquid.

[0070] As mentioned above, secondary pump 6 is an ejector pump. Ejector pumps have no electrical power requirements and generate little heat.

[0071] A further example of a method of supplying liquid hydrogen fuel to an aircraft engine in accordance with another embodiment of the invention will now be described with reference to Figures 6 and 2. The method is denoted generally by reference numeral 400. The method 400 is a method of providing liquid hydrogen fuel to an aircraft engine 19 in an aircraft comprising a primary pump 3 for delivering liquid hydrogen fuel from a fuel tank 2 to the aircraft engine 19. The method 400 comprises causing 401 the secondary pump 6 to deliver liquid hydrogen to the fuel delivery conduit 4, proximate the fuel inlet 11 for the fuel delivery conduit 4. This causes 402 the compression of the hydrogen gas present in fuel delivery conduit 4 and/or inhibits further evaporation or boiling of liquid hydrogen.

[0072] Whilst the present invention has been described and illustrated with reference to particular embodiments, it will be appreciated by those of ordinary skill in the art that the invention lends itself to many different variations not specifically illustrated herein. By way of example only, certain possible variations will now be described.

[0073] The Examples above demonstrate the use of an ejector pump as a secondary pump to provide liquid hydrogen to the primary pump. Those skilled in the art will realise that other types of pump may be used.

[0074] The Examples above demonstrate an aircraft fuel supply arrangement and method that allow for a negative-g event of up to 5 seconds in duration. Those skilled in the art will realise that other durations may be used.

[0075] The Examples above demonstrate that the inlets for the fuel delivery conduits are located in a fuel collector volume (sometimes known as a collector box), formed by walls to inhibit the movement of liquid hydrogen therepast. Those skilled in the art will realise that the fuel tank need not comprise a collector box.

[0076] Where in the foregoing description, integers or elements are mentioned which have known, obvious or foreseeable equivalents, then such equivalents are herein incorporated as if individually set forth. Reference should be made to the claims for determining the true scope of the present invention, which should be construed so as to encompass any such equivalents. It will also be appreciated by the reader that integers or features of the invention that are described as preferable, advantageous, convenient or the like are optional and do not limit the scope of the independent claims. Moreover, it is to be understood that such optional integers or features, whilst of possible benefit in some embodiments of the invention, may not be desirable, and may therefore be absent, in other embodiments.

CLAIMS

1. An aircraft fuel supply arrangement configured to supply liquid hydrogen to an aircraft engine configured to be powered by liquid hydrogen, the aircraft fuel supply comprising:

a fuel tank for the storage of liquid hydrogen;

a primary pump for delivering liquid hydrogen fuel from the fuel tank to the aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the primary pump; and

a secondary pump configured to deliver liquid hydrogen into one or more of the fuel delivery conduits at a position between (i) one or more fuel inlets to one or more of the fuel delivery conduits and (ii) the primary pump, and thereby deliver liquid hydrogen to the primary pump.

2. The aircraft fuel supply arrangement according to claim 1, wherein the secondary pump is configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits at a point proximate to one or more fuel inlets for one or more fuel delivery conduits.

3. The aircraft fuel supply arrangement according to claim 1, wherein the secondary pump is configured to deliver liquid hydrogen fuel to one or more fuel delivery conduits upstream of, and optionally proximate to, the primary pump, and downstream of a fuel supply volume for accommodating fuel, the fuel supply volume being provided by one or more fuel delivery conduits.

4. The aircraft fuel supply arrangement of claim 3, wherein the secondary pump is configured to deliver liquid hydrogen to urge gas present in the fuel supply volume out of one or more fuel delivery conduits.

5. The aircraft fuel supply arrangement of claim 3 or claim 4, wherein the fuel supply volume is sufficiently large to accommodate the volume of fuel used by the aircraft engine over a pre-determined period of time, optionally at least 1 second, optionally at least 3 seconds, optionally at least 5 second, and optionally no more than 10 seconds, optionally no more than 8 seconds and optionally no more than 6 seconds.

6. The aircraft fuel supply arrangement according to any preceding claim comprising an engine supply conduit for supplying fuel from the primary pump to the aircraft engine.

7. The aircraft fuel supply arrangement according to any preceding claim, wherein one or both of the primary pump and the secondary pump are located external to a fuel tank.

8. The aircraft fuel supply arrangement according to any preceding claim, wherein the secondary pump comprises an ejector pump.

9. The aircraft fuel supply arrangement according to any preceding claim, wherein the secondary pump is configured to operate whenever the primary pump is operational.

10. The aircraft fuel supply arrangement according to any of claims 1 to 8, wherein the secondary pump is configured to deliver liquid hydrogen to the primary pump in response to a pre-determined event, wherein optionally the pre-determined event is one of a turn, bank or manoeuvre that causes the aircraft to cause gas to enter one or more fuel delivery conduits.

11. The aircraft fuel supply arrangement according to any of claims 1 to 8 and 10, wherein the secondary pump is configured to deliver liquid hydrogen to the primary pump for a pre-determined period of time.

12. The aircraft fuel supply arrangement according to any of claims 1 to 8, 10 or 11, wherein the secondary pump is configured to deliver liquid hydrogen to the primary pump based on one or more sensed or measured parameters.

13. The aircraft fuel supply arrangement according to any preceding claim, comprising:

a first primary pump for delivering liquid hydrogen fuel from the fuel tank to a first aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the first primary pump, one or more fuel delivery conduits optionally providing a first fuel supply volume for accommodating fuel;

a first secondary pump for delivering liquid hydrogen fuel to one or more of the fuel delivery conduits and thereby deliver liquid hydrogen to the first primary pump;

a second primary pump for delivering liquid hydrogen fuel from the fuel tank to a second aircraft engine;

one or more fuel delivery conduits for supplying fuel from the fuel tank to the second primary pump, one or more fuel delivery conduits optionally providing a second fuel supply volume for accommodating fuel;

a second secondary pump for delivering liquid hydrogen fuel to one of more of the fuel delivery conduits and thereby to deliver liquid hydrogen to the second primary pump.

14. An aircraft system comprising an aircraft fuel supply arrangement in accordance any preceding claim and one or more aircraft engines configured to be powered by liquid hydrogen, and configured to receive liquid hydrogen fuel from the aircraft fuel supply arrangement in accordance with any preceding claim.

15. An aircraft comprising at least one aircraft fuel supply arrangement in accordance with any of claims 1 to 13 and/or an aircraft system in accordance with claim 14.

16. A method of providing liquid hydrogen fuel to an aircraft engine in an aircraft comprising a primary pump for delivering liquid hydrogen fuel from a fuel tank to the aircraft engine, the method comprising causing a secondary pump to provide liquid hydrogen to the primary pump via one or more fuel delivery conduits for supplying liquid hydrogen from the fuel tank to the primary pump.

17. The method according to claim 16, comprising causing the secondary pump to deliver liquid hydrogen to one or more fuel delivery conduits, thereby compressing hydrogen gas and/or inhibit evaporation of liquid hydrogen.

18. The method according to claim 16 or claim 17, comprising causing the secondary pump to deliver liquid hydrogen fuel so as to urge gas out of one or more fuel delivery conduits.

19. The method according to any of claims 15 to 18, wherein the secondary pump is operational whenever the primary pump is operational.

20. The method according to any of claims 15 to 18, wherein the secondary pump is caused to deliver liquid hydrogen to the primary pump in response to a pre-determined event.

21. The method according to claim 20, wherein the pre-determined event is one of a bank, turn or an aircraft manoeuvre that subject the aircraft to negative gravitational forces.

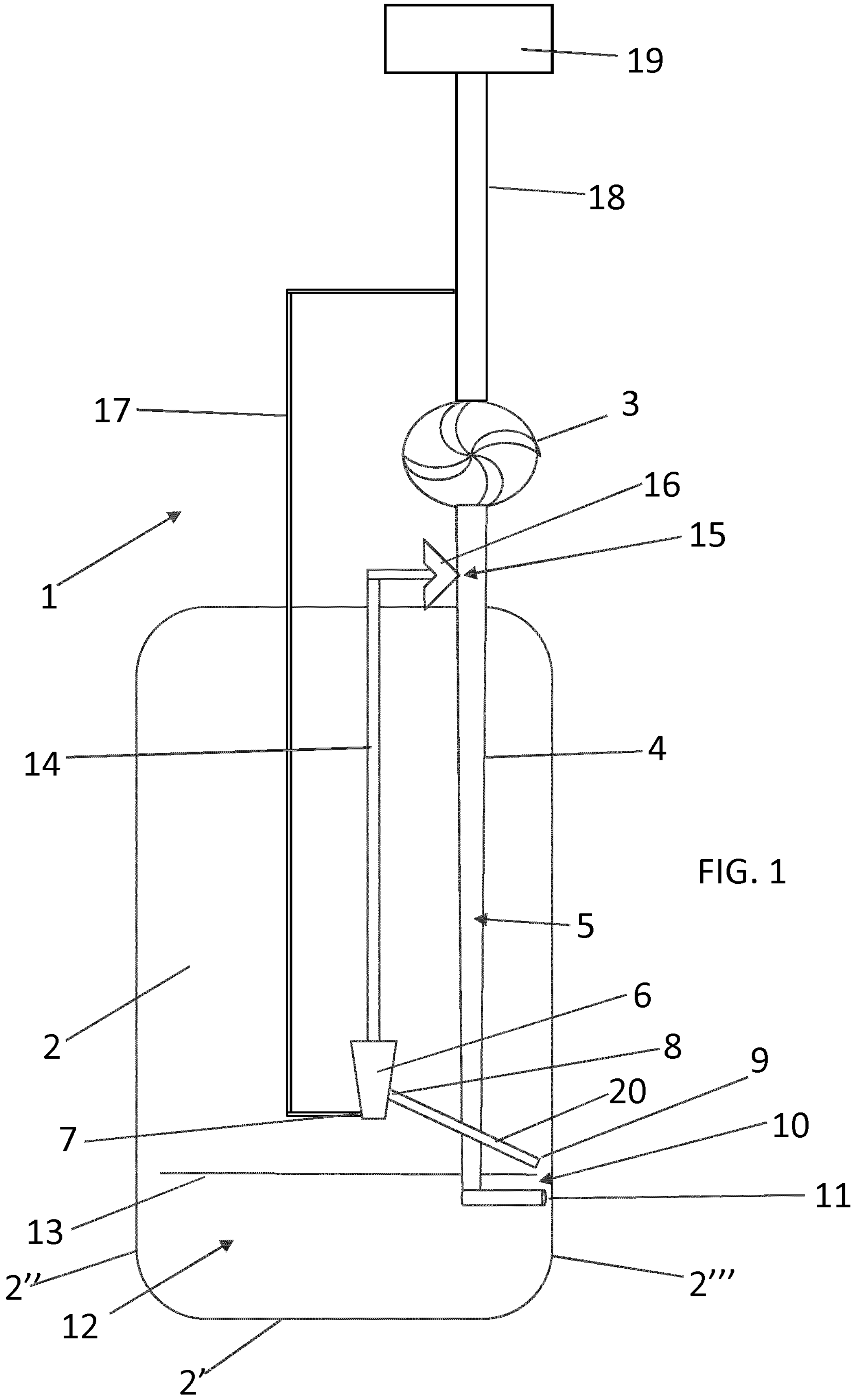

FIG. 1

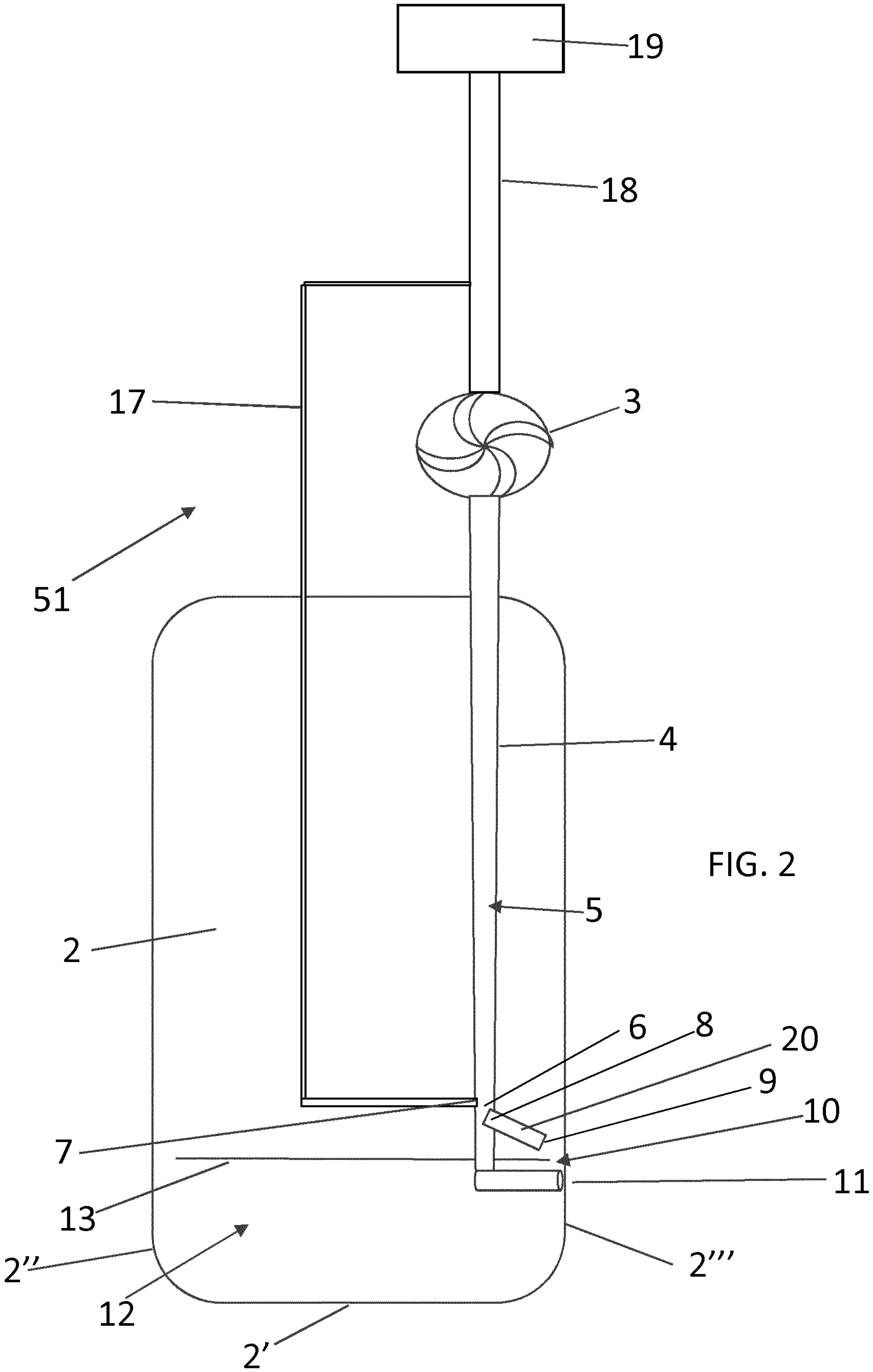

FIG. 2

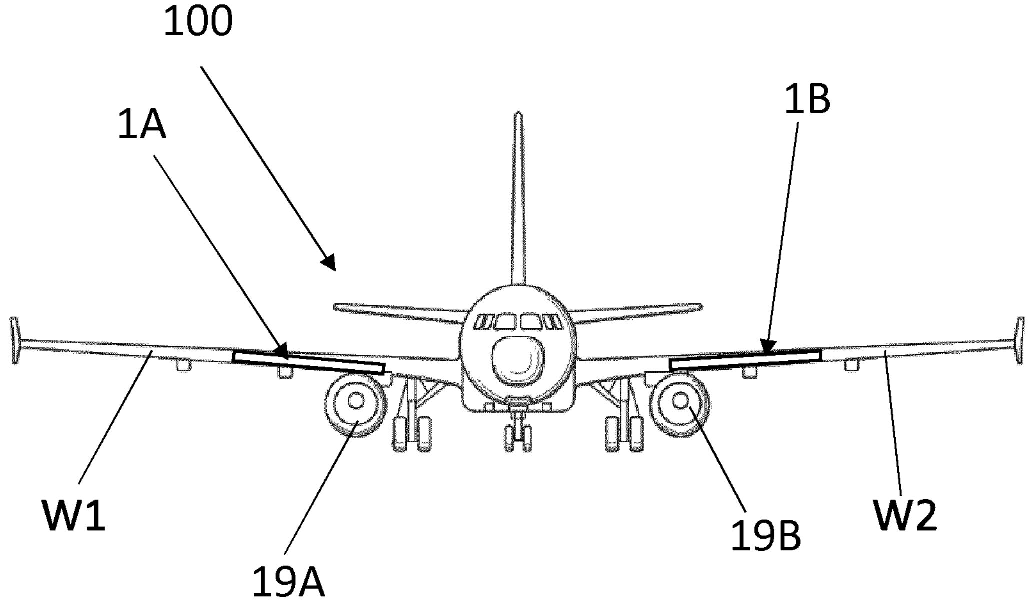

FIG. 3

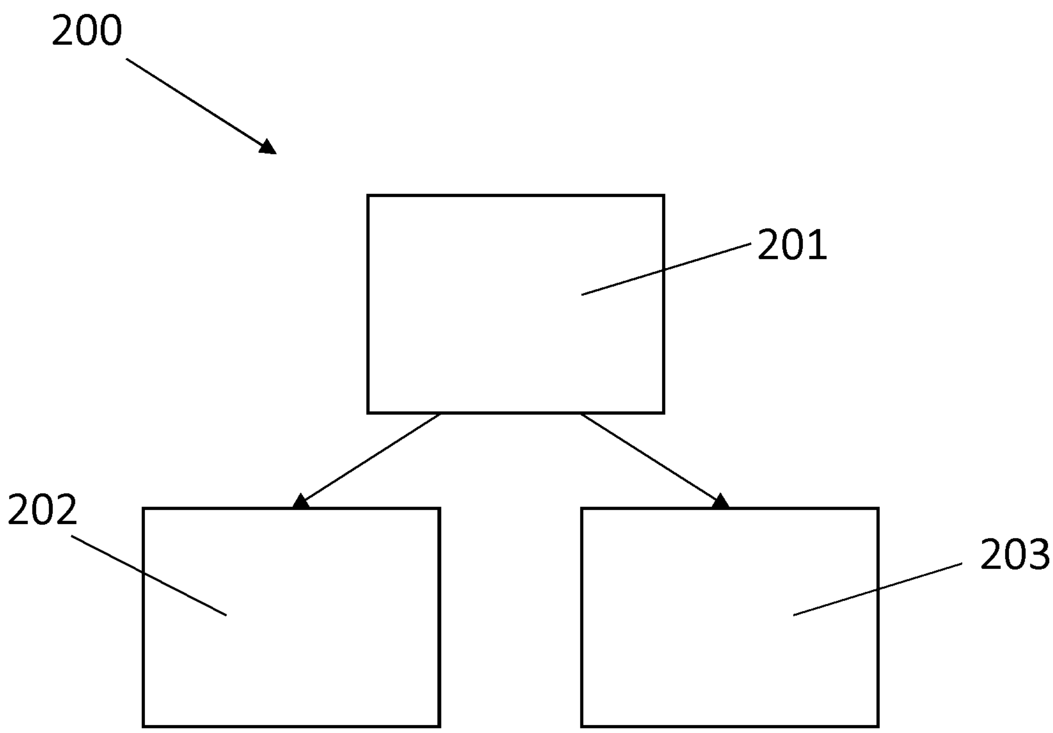

FIG. 4

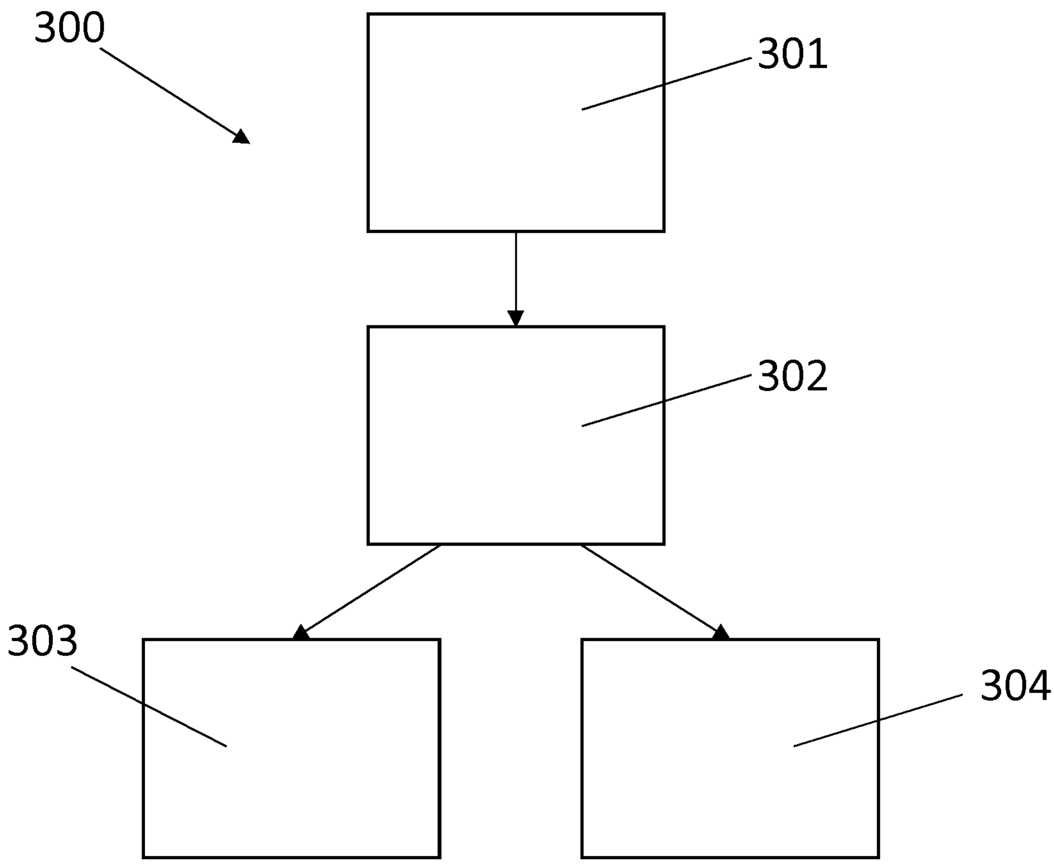

FIG. 5

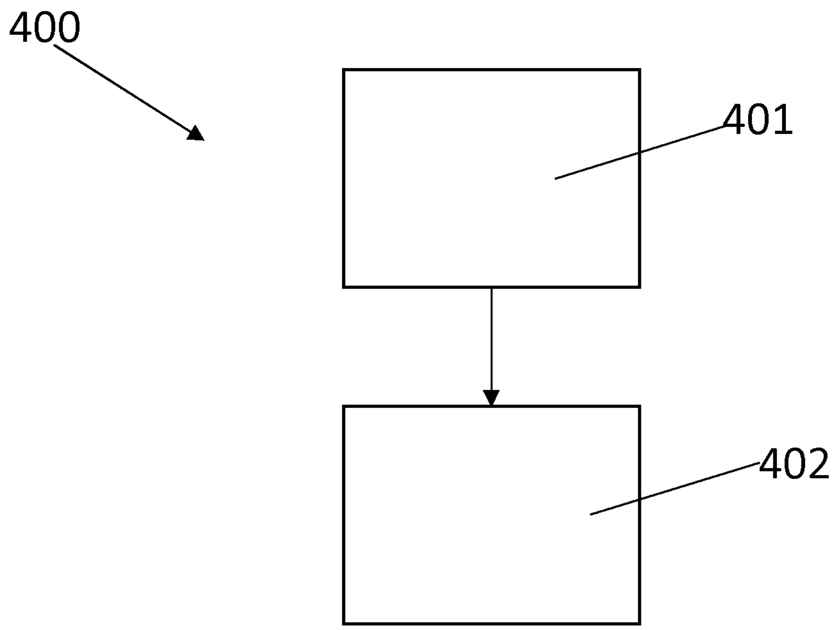

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/061434

A. CLASSIFICATION OF SUBJECT MATTER
INV. B64D37/30
ADD.

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)
B64D

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 practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 548 961 A (LUGER PETER DR [DE] ET AL) 27 August 1996 (1996-08-27)	1-9,11, 12,15-19
Y	column 1, lines 6-14 column 3, lines 1-16 column 4, line 29 - column 5, line 4; figure 2 -----	10,20,21
X	RU 2 702 454 C1 (SHISHKOV VLADIMIR ALEKSANDROVICH [RU]) 8 October 2019 (2019-10-08)	1-3,14, 16
A	the whole document -----	4-13
X	SU 1 795 139 A1 (SAMARSKIJ MOTORNYJ Z [SU]) 15 February 1993 (1993-02-15) the whole document -----	1-3,14, 16
	-/--	

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

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 July 2024	24/07/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Busto, Mario

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	column 1, lines 4-11 column 3, line 24 - column 4, line 4; figure 1 -----	4-12
Y	GB 851 428 A (UNITED AIRCRAFT CORP) 19 October 1960 (1960-10-19)	10,20,21
A	page 1, line 60 - page 2, line 125 page 3, lines 62-106; figures 2,3 -----	1-9,16

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/061434

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