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| United States Patent Application Publication | 20250264063 |
| Kind Code | A1 |
| Publication Date | August 21, 2025 |
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## AIRCRAFT COMPRISING A GAS TURBINE ENGINE HAVING PRIMARY AND SECONDARY FUEL-INJECTORS


### Abstract

An aircraft includes an engine system which includes a gas turbine engine and a fuel system. The engine has combustion apparatus having an annular array of alternating primary and secondary fuel-injectors. The fuel system includes a fuel store and a controller. The controller is arranged to receive one or more signals indicative of one or more of (i) starting of the gas turbine engine; (ii) flame-out of the combustion apparatus; and (ii) a manoeuvring of the aircraft associated with a risk of flame-out of the combustion apparatus or preparation for such manoeuvring; and in response thereto to control the fuel system to commence supply of fuel from the fuel store to the secondary fuel-injectors of the combustion apparatus. Compared to known aircraft, engine lighting and relighting are achieved for more rapidly and reliably and the aircraft is less susceptible to flame-out, especially where hydrogen fuel is used.



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**Appl. No.:** **19/038249**

**Filed:** **January 27, 2025**

### Foreign Application Priority Data

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|---|---|---|
| GB | 2402325.1 | Feb. 19, 2024 |

### Publication Classification

**Int. Cl.:** **F02C9/46** (20060101); **F02C7/22** (20060101); **F23R3/28** (20060101)

**U.S. Cl.:**

CPC **F02C9/46** (20130101); **F02C7/22** (20130101); **F02C7/228** (20130101); **F02C9/263** (20130101); **F02C9/28** (20130101); **F02C9/40** (20130101); **F23R3/28** (20130101); F05D2270/09 (20130101)

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## Background/Summary

TECHNICAL FIELD
[0001] The invention relates to aircraft comprising gas turbine engines.
BACKGROUND
[0002] Flameout-out of a gas turbine engine may have one of several possible causes, for example fuel starvation or compressor stall or, specifically in the case of an aero engine, excessive altitude, severe precipitation or foreign object damage. In the case of an aero engine, flame-out is more likely during certain aircraft manoeuvres, and efficient and reliable re-lighting is of key importance. However, lighting and relighting can be difficult and unreliable, especially for certain types of fuel, such as gaseous hydrogen. For aero engines in particular, resistance to flame-out and the ability to rapidly light, and re-light after a flame-out incident, are important objectives in the design of gas turbine engine systems.
BRIEF SUMMARY
[0003] A first aspect of the invention provides an aircraft comprising an engine system which includes: [0004] (i) a gas turbine engine including combustion apparatus having an annular array of alternating primary and secondary fuel-injectors each having a respective fuel-emitting face; and [0005] (ii) a fuel system comprising a fuel store and a controller;
[0006] wherein [0007] (a) the fuel system is arranged to provide fuel from the fuel store to the primary and secondary fuel-injectors; [0008] (b) each primary and secondary fuel-injector is arranged to emit fuel in a direction having a component normal to the plane of the array; and [0009] (c) the controller is arranged to receive one or more signals indicative of one or more of [0010] (i) starting of the gas turbine engine; [0011] (ii) flame-out of the combustion apparatus; and [0012] (ii) a manoeuvring of the aircraft associated with a risk of flame-out of the [0013] combustion apparatus or preparation for such manoeuvring; and in response thereto to control the fuel system to commence supply of fuel from the fuel store to the secondary fuel-injectors of the combustion apparatus. The fuel store may comprise a first fuel tank containing a first fuel and a second fuel tank containing a second fuel, the fuel system being arranged to provide the first fuel to the primary fuel-injectors and the second fuel to the secondary fuel-injectors. Each primary fuel-injector may be arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent secondary fuel-injector, each such component having the same sense with respect to the array. Each primary fuel-injector may be arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent secondary fuel-injector.
[0014] Each secondary fuel-injector may be arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent primary fuel-injector, each such component having the same sense with respect to the array. Each secondary fuel-injector may be arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent primary fuel-injector.
[0015] A second aspect of the invention provides an engine system comprising [0016] (i) a gas turbine engine including combustion apparatus having an annular array of alternating primary and

secondary fuel-injectors each having a respective fuel-emitting face; and [0017] (ii) a fuel system comprising a first fuel tank containing a first fuel and a second tank containing a second fuel, and a controller; wherein [0018] (a) the fuel system is arranged to provide the first fuel from the first fuel tank to the primary fuel-injectors and the second fuel from the second fuel tank to the secondary fuel-injectors; [0019] (b) each primary and secondary fuel-injector is arranged to emit fuel in a direction having a component normal to the plane of the array; and [0020] (c) the controller is arranged to control respective proportions of a total fuel flow rate or a total chemical energy flow rate to the combustion apparatus which are provided to the primary fuel-injectors and the secondary fuel-injectors. Each primary fuel-injector may be arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent secondary fuel-injector, each such component having the same sense with respect to the array. Each primary fuel-injector may be arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent secondary fuel-injector. Each secondary fuel-injector may be arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent primary fuel-injector, each such component having the same sense with respect to the array. Each secondary fuel-injector may be arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent primary fuel-injector.
[0021] A third aspect of the invention provides an aircraft comprising an engine system according to the second aspect.
[0022] A fourth aspect of the invention provides a method of operating combustion apparatus which comprises an annular array of alternating primary and secondary fuel-injectors, each primary and secondary fuel-injector being arranged to emit fuel in a direction having a component normal to the plane of the array and the combustion apparatus being comprised in a gas turbine engine of an aircraft, the method comprising the steps of [0023] (i) providing fuel to the primary fuel-injectors; [0024] (ii) detecting one or more of [0025] (a) starting of the gas turbine engine; [0026] (b) flame-out of the combustion apparatus; and [0027] (c) manoeuvring of the aircraft associated with a risk of flame-out of the combustion apparatus, or preparation for such manoeuvring; and [0028] (iii) in response to such detection, commencing supply of fuel from the fuel store to the secondary fuel-injectors of the combustion apparatus.
[0029] A fifth aspect of the invention provides a method of operating combustion apparatus which comprises an annular array of alternating primary and secondary fuel-injectors, each primary and secondary fuel-injector being arranged to emit fuel in a direction having a component normal to the plane of the array and the combustion apparatus being comprised in a gas turbine engine of an aircraft, the method comprising the steps of [0030] (i) providing first and second fuels to the primary and secondary fuel-injectors respectively; and [0031] (ii) controlling respective proportions of the total fuel flow rate, or total chemical energy flow rate, provided to the combustion apparatus which are provided to the primary and secondary fuel-injectors.
[0032] Step (ii) may be carried out to maximise the range of the aircraft or to mitigate climate forcing produced by products of fuel combustion and/or contrails of the aircraft.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0033] Embodiments of the invention are described below by way of example only and with reference to the accompanying drawings in which:
[0034] FIG. **1** shows combustion apparatus; [0035] FIG. **2** shows an engine system of the invention comprising a turbofan engine having the combustion apparatus of FIG. **1**; and [0036] FIG. **3** shows

an aircraft of the invention comprising the engine system of FIG. **2**.

DETAILED DESCRIPTION

[0037] FIG. **1** shows combustion apparatus **100** having an alternating annular array of **15** like primary fuel-injectors **102** and **15** like secondary fuel-injectors **103** arranged within and towards one end of a cylindrical outer casing **130**. The cylindrical outer casing **130** has a central longitudinal axis **196** defining an axial direction with unit vector z (out of the plane of FIG. **1**). The axis **196** also defines radial and azimuthal directions having unit vectors r **197**, ϕ **198**. Each primary fuel-injector **102** has a fuel-emitting face **104**. Each secondary fuel-injector **103** has a fuel-emitting face **105**. The fuel-emitting face **104** of each primary fuel injector comprises a set of primary fuel-emitting apertures (not shown). The fuel-emitting face **105** of each secondary fuel-injector **103** comprises a set of secondary fuel-emitting apertures (not shown).

[0038] In operation of the combustion apparatus **100** fuel is emitted from each of the primary fuel-injectors **102** in a direction having a component in the z direction, i.e. normal to the plane **199** of the annular array of fuel-injectors. The direction in which fuel is emitted from any given primary fuel-injector may additionally have a component in the ϕ (or −ϕ) and/or −r directions. For example, **194** indicates a component in the ϕ direction, the component being in the plane **199** of the annular array and directed towards the fuel-emitting face of an adjacent secondary fuel-injector. In a variant of the combustion apparatus **100**, a given primary fuel-injector **102** may emit fuel in first and second directions having components in the ϕ and −ϕ directions respectively.

[0039] Each of the secondary fuel-injectors **103** may emit fuel in a direction having a component in the z direction. The direction in which fuel is emitted from a given secondary fuel-injector may additionally have a component in the ϕ (or −ϕ) and/or −r directions. For example, fuel may be emitted from a given secondary fuel-injector in a direction having a component in the plane **199** of the array of fuel-injectors directed towards the fuel-emitting face of an adjacent primary fuel-injector. In a variant of the combustion apparatus **100**, a given secondary fuel-injector **102** may emit fuel in first and second directions having components in the ϕ and −ϕ directions respectively.

[0040] Referring to FIGS. **2** and **3**, an aircraft **400** of the invention comprises an engine system **300** of the invention, the engine system **300** comprising first and second like turbofan engines **101**, **201**. The first turbofan engine **101** has combustion apparatus **100**, like to the apparatus **100** of FIG. **1**, and includes a set **102** of primary fuel-injectors and a set **103** of secondary fuel-injectors. Similarly, the second turbofan engine **201** has combustion apparatus **200**, like to the apparatus **100** of FIG. **1**, and includes a set **202** of primary fuel-injectors and a set **203** of secondary fuel injectors. The engine system **300** further comprises a fuel store having first and second fuel tanks **370**A, **370**B arranged to provide fuel to the sets **102**, **202** of primary fuel-injectors and the set **103**, **203** of secondary fuel-injectors respectively. If the fuel stored within the fuel tanks **370**A, **370**B is the same type of fuel, then the individual tanks **370**A, **370**B may be replaced by a fuel store having only a single fuel tank. The fuel tanks **370**A, **370**B are comprised in a fuel system **376** which further includes a controller **374** and a balance-of-fuel-system **372** which includes fuel pumps and other equipment necessary to deliver fuel from the fuel tanks **370**A, **370**B to the combustion apparatus **100**, **200**.

[0041] The controller **374** is arranged to receive a signal corresponding to a thrust demanded of the engine system **300** and to control the total fuel flow (or total chemical energy flow) provided to the combustion apparatus **100**, **200** such that the demanded thrust is provided to the aircraft **400**. During normal operation of the aircraft **400**, for example during cruising at altitude, fuel is provided only to the primary fuel-injectors **102**, **202**.

[0042] The controller **374** is further arranged to receive one or more signals from one or more sensors (not shown) of the aircraft **400** indicative of one or more of [0043] (i) flame-out of either or both turbofan engines **101**, **201**; [0044] (ii) manoeuvring of the aircraft **400** associated with a risk of flame-out of the combustion apparatus **100**, **200**, or preparation for such manoeuvring; and [0045] (iii) starting of one or both of the turbofan engines **101**, **201**;

[0046] and in response provide a control signal to the balance-of fuel-system **372** such that fuel is provided to one or both sets **103**, **203** of secondary fuel-injectors, as necessary, in addition to fuel being provided to the primary sets **102**, **202** of fuel-injectors, in order to provide lighting or re-lighting of one or both engines **101**, **201**, or to prevent flame-out in one or both engines **101**, **201**.
[0047] Due to operation of one or both sets **103**, **203** of secondary fuel-injectors, the speed and reliability of lighting and re-lighting of one or both combustion apparatus **100**, **200** is increased compared to combustion apparatus of the prior art, and the resistance of the combustion apparatus **100**, **200** to flame-out is improved compared to combustion apparatus of the prior art, especially in a case where hydrogen fuel is supplied to one or both turbofan engines **101**, **201**. Lighting, re-lighting and flame-out resistance are particularly improved where fuel is emitted from each of the primary fuel-injectors in a direction having a component in the plane **199** of the annular array of fuel-injectors in the $\pm\phi$ direction directed towards the fuel-emitting face of an adjacent secondary fuel-injector, in addition to a component in the z direction. Similarly, lighting, re-lighting and flame-out resistance are particularly improved where fuel is emitted from each of the secondary fuel-injectors in a direction having a component in the plane **199** of the annular array of fuel-injectors in the $\pm\phi$ direction directed towards the fuel-emitting face of an adjacent primary fuel-injector, in addition to a component in the z direction.
[0048] Lighting, re-lighting and flame-out resistance are particularly improved with respect to combustion apparatus of the prior art when using hydrogen fuel, since in combustion apparatus of the prior art hydrogen has negligible bulk swirl and there is little or no transport of fuel between adjacent azimuthal sections of a combustor of the prior art.
[0049] Once lighting or re-lighting of one or both combustion apparatus **100**, **200** has been achieved, or once a manoeuvre of the aircraft **400** associated with a risk of flame-out has been completed, the controller **374** is arranged to provide a control signal to the balance-of-fuel-system **372** so that the fuel supply to the secondary fuel-injectors **103**, **203** of one or both combustion apparatus **100**, **200** is terminated.
[0050] According to another example, the aircraft **400** is a so-called “dual-fuel” aircraft and the fuel tanks **370**A, **370**B each store a respective type of fuel. A first fuel is stored in the first fuel tank **370**A and provided to the sets **102**, **202** of primary fuel-injectors of both combustion apparatus **100**, **200**. A second fuel is stored in the second fuel tank **370**B and provided to the sets **103**, **203** of secondary fuel-injectors of both combustion apparatus **100**, **200**. In general, during operation of the aircraft **400**, fuel is provided to both the primary **102**, **202** and secondary **103**, **203** fuel-injectors of the combustion apparatus **100**, **200** from the first **370**A and second **370**B fuel tanks respectively.
[0051] According to operational and flight requirements for maximising aircraft range, or meeting other flight mission objectives, the controller **374** is arranged to control the proportion x of the total fuel flow (or total chemical energy flow) to the combustion apparatus **100**, **200** which is provided to the sets **102**, **202** of primary fuel-injectors in the range $0 \leq x \leq 1$, with arbitrary precision, and the corresponding proportion $1-x$ which is provided to the sets **103**, **203** of secondary fuel-injectors.
SUMMARY OF REFERENCE NUMERALS USED IN THE ACCOMPANYING DRAWINGS
[0052] **100**, **200** combustion apparatus [0053] **101**, **201** turbofan engines [0054] **102**, **202** primary fuel-injector(s) [0055] **103**, **203** secondary fuel-injector(s) [0056] **104** fuel-emitting face of primary fuel-injector [0057] **105** fuel-emitting face of secondary fuel-injector [0058] **130** combustor casing [0059] **194** component of direction of fuel emission from primary fuel-injector [0060] **196** central longitudinal axis of combustor casing; unit vector in z direction [0061] **197**, **198** unit vectors in r, $\phi$ directions [0062] **199** plane of annular arrays of primary and secondary fuel-injectors [0063] **300** engine system [0064] **370**A, **370**B first and second fuel tanks [0065] **372** balance-of-fuel-system [0066] **374** controller [0067] **376** fuel system [0068] **400** aircraft

## Claims

**1**. An aircraft comprising an engine system which includes: (i) a gas turbine engine including combustion apparatus having an annular array of alternating primary and secondary fuel-injectors each having a respective fuel-emitting face; and (ii) a fuel system comprising a fuel store and a controller; wherein (a) the fuel system is arranged to provide fuel from the fuel store to the primary and secondary fuel-injectors; (b) each primary and secondary fuel-injector is arranged to emit fuel in a direction having a component normal to the plane of the array; and (c) the controller is arranged to receive one or more signals indicative of one or more of (i) starting of the gas turbine engine; (ii) flame-out of the combustion apparatus; and (ii) a manoeuvring of the aircraft associated with a risk of flame-out of the combustion apparatus or preparation for such manoeuvring; and in response thereto to control the fuel system to commence supply of fuel from the fuel store to the secondary fuel-injectors of the combustion apparatus.
**2**. An aircraft according to claim 1 wherein the fuel store comprises a first fuel tank containing a first fuel and a second fuel tank containing a second fuel and wherein the fuel system is arranged to provide the first fuel to the primary fuel-injectors and the second fuel to the secondary fuel-injectors.
**3**. An aircraft according to claim 1 wherein each primary fuel-injector is arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent secondary fuel-injector, each such component having the same sense with respect to the array.
**4**. An aircraft according to claim 3 wherein each primary fuel-injector is arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent secondary fuel-injector.
**5**. An aircraft according to claim 1 wherein each secondary fuel-injector is arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent primary fuel-injector, each such component having the same sense with respect to the array.
**6**. An aircraft according to claim 5 wherein each secondary fuel-injector is arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent primary fuel-injector.
**7**. An engine system comprising (i) a gas turbine engine including combustion apparatus having an annular array of alternating primary and secondary fuel-injectors each having a respective fuel-emitting face; and (ii) a fuel system comprising a first fuel tank containing a first fuel and a second tank containing a second fuel, and a controller; wherein (a) the fuel system is arranged to provide the first fuel from the first fuel tank to the primary fuel-injectors and the second fuel from the second fuel tank to the secondary fuel-injectors; (b) each primary and secondary fuel-injector is arranged to emit fuel in a direction having a component normal to the plane of the array; and (c) the controller is arranged to control respective proportions of a total fuel flow rate or a total chemical energy flow rate to the combustion apparatus which are provided to the primary fuel-injectors and the secondary fuel-injectors.
**8**. An engine system according to claim 7 wherein each primary fuel-injector is arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent secondary fuel-injector, each such component having the same sense with respect to the array.
**9**. An engine system according to claim 8 wherein each primary fuel-injector is arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent secondary fuel-injector.
**10**. An engine system according to claim 7 wherein each secondary fuel-injector is arranged to emit fuel in a direction having a component in the plane of the array directed towards the fuel-emitting face of an adjacent primary fuel-injector, each such component having the same sense with respect

to the array.

**11**. An engine system according to claim 10 wherein each secondary fuel-injector is arranged to emit fuel in first and second directions each having a respective component in the plane of the array directed towards the fuel-emitting face of a respective adjacent primary fuel-injector.

**12**. A method of operating combustion apparatus which comprises an annular array of alternating primary and secondary fuel-injectors, each primary and secondary fuel-injector being arranged to emit fuel in a direction having a component normal to the plane of the array and the combustion apparatus being comprised in a gas turbine engine of an aircraft, the method comprising the steps of (i) providing fuel to the primary fuel-injectors; (ii) detecting one or more of (a) starting of the gas turbine engine; (b) flame-out of the combustion apparatus; and (c) manoeuvring of the aircraft associated with a risk of flame-out of the combustion apparatus, or preparation for such manoeuvring; and (iii) in response to such detection, commencing supply of fuel from the fuel store to the secondary fuel-injectors of the combustion apparatus.

**13**. A method of operating combustion apparatus which comprises an annular array of alternating primary and secondary fuel-injectors, each primary and secondary fuel-injector being arranged to emit fuel in a direction having a component normal to the plane of the array and the combustion apparatus being comprised in a gas turbine engine of an aircraft, the method comprising the steps of (i) providing first and second fuels to the primary and secondary fuel-injectors respectively; (ii) controlling respective proportions of the total fuel flow rate, or total chemical energy flow rate, provided to the combustion apparatus which are provided to the primary and secondary fuel-injectors.

**14**. A method according to claim 13 where in step (ii) is carried out to maximise the range of the aircraft or to mitigate climate forcing produced by products of fuel combustion and/or contrails of the aircraft.