

June 21, 1955

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FUEL METERING APPARATUS FOR SPEED CONTROL
OF GAS TURBINE ENGINES
Filed Aug. 25, 1950

2,711,073

Fig. 1

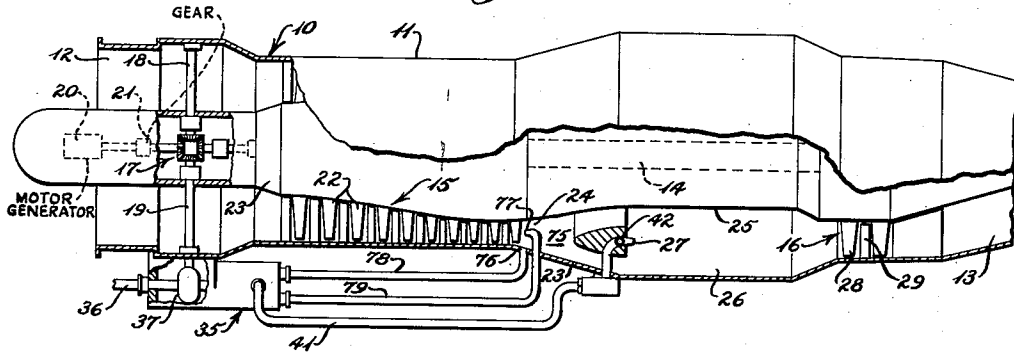
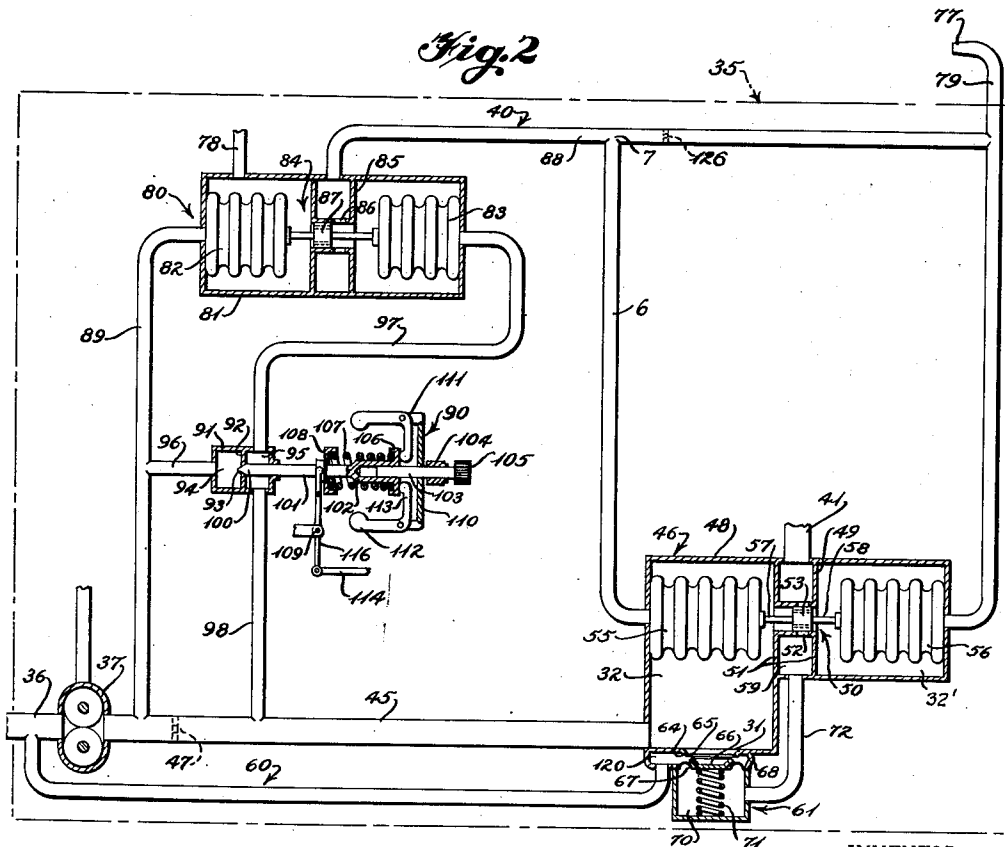


Fig. 2



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FUEL METERING APPARATUS FOR SPEED CONTROL OF GAS TURBINE ENGINES

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Application August 25, 1950, Serial No. 181,538

16 Claims. (Cl. 60—39.28)

(Granted under Title 35, U. S. Code (1952), sec. 266)

This invention relates to speed control of gas turbine type engines with special reference to control of the fuel-air ratio.

Various control means have heretofore been used for gas turbine type engines with varying degrees of usefulness and success. In general, two basic control methods have been employed. In one of these methods the fuel flow is controlled by the mass air flow through the engine as indicated either by the engine R. P. M. and the pressure rise across the engine compressor or the pressure differential obtained from a venturi in the engine air inlet. In the other method the fuel flow is controlled by the amount of fuel necessary to maintain a predetermined R. P. M., the flow at acceleration being limited by the gas temperature of the discharge of the engine turbine.

Experience has indicated certain pronounced disadvantages in these prior methods. In the first method variation in fuel density affects the engine R. P. M. to distort the indication; a high fuel pressure loss usually is present; mechanism is required to compensate for the effect of temperature change on air flow; and the servo-mechanisms employed are often sensitive to the effects of contaminated fuels. In addition, where a pressure differential is obtained from a venturi in the engine air inlet, variations in air distribution at the air inlet will affect the control adversely. In the second method a separate power source, usually electronic, is required, as well as a separate starting control, and the temperature indicating elements usually have poor endurance characteristics.

The general object of the present invention is to provide a simple and efficient turbine engine speed control which overcomes the disadvantages in controls as hereinabove referred to.

More specifically, the objects of the invention include the provision of engine speed control apparatus in which effects of variation in fuel density are automatically compensated; in which temperature measurement of fluid flow is eliminated; in which pressure loss is markedly reduced; in which servo-mechanisms are not required; and in which injurious effects of contaminated fuels are removed.

Other objects and features of the invention will appear on consideration of the following detailed description of a preferred embodiment of the invention as illustrated in the accompanying drawing in which:

Fig. 1 is an elevational view of a gas turbine engine with sections of the external casing removed to show parts of the air compressor, the turbine, the fuel pump and fluid pressure differential nozzles; and

Fig. 2 is a diagram of the control system as applicable to the engine of Fig. 1.

As applied to gas turbines having a compressor rotor of the centrifugal, axial or mixed flow type, the following relationship, based on well known laws of aerodynamics, is known (see Russ, Daniel G., Pat. No. 2,441,977).

$$W a N = f (\Delta P) m \quad (1)$$

where

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$W a$ is the mass rate of flow (either gas or liquid) per unit time through the rotor,

N indicates rotor revolution per unit time,

f is a function experimentally established which, for practical purposes may be assumed equal to a constant K , and

$(\Delta P) m$ is a fluid pressure differential which is the difference between a special total pressure and a static pressure, both of which are measured in the immediate discharge region of the rotor. The special total pressure is measured by a total pressure tube, the axis of the end portion of which is located coincidental with that fluid velocity vector which is the geometric mean of the tangential fluid velocity component and that fluid velocity component which is both perpendicular to the tangential component and in a plane defined by the resultant velocity vector and the tangential component. For example, in centrifugal compressors the end portion of the total pressure tube is coincidental with that fluid velocity vector which is the geometric mean of the tangential and radial fluid velocity vectors; and likewise, in axial compressors, the tube end is coincidental with that fluid velocity vector which is the geometric mean of the tangential and the axial fluid velocity vectors. The static pressure is measured by a static pressure tube whose mouth is located at a point subject to fluid stream conditions which are the same as those at the mouth of the total pressure tube described above.

Giving to f the value K Equation (1) may be written

$$W a = K \frac{(\Delta P) m}{N} \quad (2)$$

The apparatus as hereinafter described incorporates the relationship as set forth in Equation (2) in that the mass of air handled by the compressor per unit of time is an inverse function of the rotational speed of the engine compressor and a direct function of the pressure differential between the static and total pressures at the discharge side of the compressor rotor.

Referring to Fig. 1 the gas turbine engine 10 is provided with an external tubular casing 11 having an open front end 12 of full casing width and a converging but open rear end 13 for the engine exhaust flow. The main shaft 14 is appropriately supported along the casing axis and carries toward the front end the axial compressor 15 and toward the rear end the turbine 16.

A bevel gear box 17 is connected to an extension of the main shaft 14 with connections to wall supports through auxiliary shafts 18 and 19, and to the motor-generator unit 20 through reducing gears 21. The axial flow compressor is formed with progressively reduced rotary blades 22 and expanding diffuser 23 to form the converged annular nozzle space 24. From this space the annular fluid guide shell 25 converges to form the combustion chamber 26 in which air from the compressor 15 and fuel from the spaced annular nozzles 27 combine to form a combustible mixture. The highly heated burnt gases pass through the blades of the rotor 28 and stator 29 of turbine 16 and are expelled at the discharge end 13 of the engine.

The usual control apparatus is assembled as a unit 35 placed under the front end of the engine. The fuel inlet 36 is brought to this point where it is connected to the positive displacement pump 37, and this fuel, after pump compression, is passed through the control system 35, as illustrated diagrammatically in Fig. 2, to the flexible conduit 41 leading to the annular fuel manifold 42 and the fuel nozzles 27.

The control system 40 for developing a balanced relationship of the total-static differential in the discharge side 24 of the compressor with the compressor speed,

as illustrated in Fig. 2, will now be described. Intermediate the fuel pump 37 and outlet conduit 41 is interposed a main pipe section 45 and a valve control unit 46. In the pipe 45 a fixed pressure drop section, indicated by orifice 47, is inserted. The valve control unit 46 is placed in series with the pipe 45 and conduit 41 and includes an elongated casing 48 with a spool 49 therein secured at a side opening adjoining the end of conduit 41. The walls 51 of spool 49 fit snugly in casing 48 to form an annular chamber 59 between the walls and to divide casing 46 into two chambers 32 and 32'; the hollow cylindrical core of the spool is provided with annular ports 52 through which fuel from chamber 32 may pass into the annular chamber 59 and thence to exit conduit 41. A valve 50 is formed at the center of spool 49 including the core with its ports 52 and a slidable axially apertured valve member 53 adapted by axial reciprocation to open and close fuel ports 52, through its axial apertures permitting free communication between chambers 32 and 32'. Flexible bellows 55 and 56 are mounted inside chambers 32 and 32' respectively and in alignment with valve member 53; and this valve member is fixedly connected at its ends directly to each bellows by respective rods 57 and 58, so as to close the valve in normal unstressed position. Thus it is apparent that the movement of valve member 53 is dependent on the differential pressure in bellows 55 and 56.

In order to maintain constant pressure in valve chamber space 59 a by-pass pressure relief pipe 60 is connected between the inlet side of the fuel pump and an opening 31 in valve chamber 32, and a constant pressure relief valve 61 is inserted in this opening 31. The valve 61 may be of any conventional form but is indicated simply as formed of an outwardly extending cone frustum 64 having a port 65 connected in extension of pipe 60. A valve member 66, adapted to engage the port edge of frustum 64, is mounted on the diaphragm wall 67 of chamber 70. A coil spring 71 normally holds the valve member 66 in closed position but yields to permit valve opening when the pressure mounts inside the flow space of casing 48. Pressure variation inside chamber 70 and maintenance of a constant pressure drop between chamber 70 and 32 is obtained by duct 72 connecting the chamber 70 to valve chamber 51.

Pressure change across orifice 47 in the fluid pipe 45 is utilized to control pressure distribution between the static and total pressure lines. In the space 75 between the compressor discharge and the fuel nozzle ring of the engine the casing is tapped by static pressure line terminal 76 with the end flush with the casing and radial to the engine axis, and by total pressure line terminal 77 with the end entering the fluid chamber and turned parallel to the engine axis and toward the compressor to pick up the air velocity component which is the geometric mean of the axial air velocity and the tangential compressor velocity. The static pressure line is indicated by numeral 78 and the total pressure line by numeral 79.

The static pressure line is directly connected to a valve control unit 80 including elongated casing 81, flexible bellows 82 and 83 supported in the casing at either end thereof, and a valve 84 formed of a spool having end walls and a core together forming an annular cylindrical chamber 85 having an annular port 86 on the inside surface of the chamber, an axially apertured valve member 87 movable slidably to cover and uncover the port, with support rods between the valve member 87 and bellows 82 and 83 for supporting the valve member fixedly between the bellows. A pipe 88 connects the chamber 85 to the total pressure line 79. Bellows 82 is directly connected by pipe 89 to the main fuel line 45 between the pump 37 and orifice 47. Bellows 83 is connected also to the main fuel line 45, but below the orifice and through a speed controlled valve unit 90.

The speed controlled valve unit 90 is a regulator formed of a specific valve unit and centrifugal speed

controlling apparatus for controlling the port opening of the speed valve. The valve unit consists of a casing 91 having a dividing partition 92 in which is formed centrally thereof a conically shaped valve port 93. The partition divides the casing into two chambers 94 and 95, the chamber 94 being connected by conduit 96 to pipe 89, and chamber 95 by pipe 97 to bellows 83 of valve unit 84. Chamber 95 is also connected to main fuel line 45 between orifice 47 and the valve unit 46 by pipe 98, pipes 97 and 98 forming together the connection between the fuel line and bellows 83 of valve unit 80.

It now appears that the pressure on the inlet side of orifice 47 in the main fuel line, effective in bellows 82 of valve unit 80 depends on the extent of leakage through port 93 of the partition of casing 91. To control this leakage, and, particularly, to control it as a function of compressor speed, use is made of a needle valve 100 mounted on stem 101. This valve is adapted to seat in partition aperture 93 to close the same, but is mounted for axial movement to open position by means of socket slide connection 102 at the base end of the stem. The socket slidably coacts with a protruding stub shaft stem 103 fixedly mounted on support 104 as to axial movement but free to rotate by means of power applied to power device 105, from the turbine engine shaft.

The socket slide 102 at its outer end is formed with a radial stop 106 for coil spring 107. The other end of the coil spring is adapted to engage a stop 108 surrounding valve stem 101 movably mounted on pivot pin 109 by means of shank 116 for adjustment of the tension of the coil spring. Also the support stem 103 adjacent its base is provided with lateral arms 110 having angled sections 111 on which fly-weights 112 are pivoted. Arms 113, fixed to the ball weight arms 110, are provided with rounded terminals for bearing against the base surface of spring stop 106 so that pressure is applied to the spring end varying directly with the speed of rotation of the engine shaft. An operating member 114 is connected to the shank 116 of spring support member 108 and means, as, for example, a friction device, provided to hold this member in any desired position, so that the effect of speed variation of the engine may be transmitted to the spring with variations in elastic resistance.

With further reference to valve unit 46 it is noted that bellows 55 is connected by pipe 6 to pipe 88 at point 7 between the static and total pressure lines 78 and 79 and on the static or low pressure side of orifice 126, and hence takes a pressure dependent both upon the position of valve 84 in valve unit 80 and upon the pressure differential between the static and total pressure lines. Also bellows 56 of valve unit 46 is connected directly to the total pressure line 79, and, consequently, the position of the valve 53 in valve unit 46 is directly dependent on the pressure differential between the static and total pressure lines and the area of opening in valve 84.

Again it is noted that the opening of valve 84 is dependent both on the pressure drop in the fuel line 45 across orifice 47 and on the leakage value of aperture 93 as controlled directly by the speed of rotation of the engine shaft, assuming a set position of spring support 108 by means of control means 114.

A description of the operation and use of the apparatus follows. Fuel from a fuel tank enters pump 37 through pipe 36 and is discharged from the pump through orifice 47 in pipe 45 to the chamber 32 of casing 48. From this chamber the fuel enters chamber 59 and outlet pipe 41 through control valve 53 and passes on to the engine fuel discharge nozzles. Constant pressure valve 61 discharges excess fuel from chamber 120 back to the inlet of pump 37; and since the pump is of the constant displacement type and since, moreover, except for the minute quantity moving through orifice 93, the entire pump output passes through orifice 47, the pressure drop across orifice 47 is a function of the R. P. M. of pump 37. Assuming for purpose of description that the orifice

93 is closed, the pressure differential across fixed orifice 47 is transferred to the bellows 82 and 83 by pipes 89, 97 and 98. Since the pressure difference between bellows 82 and 83 is a function of pump (or engine compressor) R. P. M., both the amount of displacement of valve 87 and the area of opening at orifice 86 are known functions of engine compressor R. P. M. The area of orifice opening 86 determines the amount of "bleed" of the air pressure between the total pressure in pipe 79 and the static pressure in pipe 78 by way of pipe 40, from total pressure pipe 79, through orifice opening 86 to static pressure pipe 78. Therefore, the pressure differential which exists between bellows 55 and 56 of valve unit 46 is a function of the pressure differential which exists between points in the total and static pressure pipes 79 and 78 and the area of valve opening at 86.

The area of the port 86 which valve 87 covers on movement is so contoured that it results in a pressure differential between bellows 55 and 56 which is equal to the pressure differential between pipes 78 and 79 divided by the speed of the engine compressor. From Equation (2) it then follows that the pressure differential between bellows 55 and 56 is directly proportional to the mass air flow through the engine compressor; and since the movement of valve 53 is proportional to the pressure differential of bellows 55 and 56 the port openings of the valve may be so shaped that the area of the valve opening is directly proportional to or a function of the mass air flow through the engine compressor. Since the fuel pressure differential across orifice 47 is constant, the flow through valve 50 is directly proportional to or a function of the mass air flow through the engine compressor and combustion chambers. In this manner the fuel-air ratio is maintained at a predetermined value in the engine combustion chamber as long as needle 100 closes orifice 93, as originally assumed.

If, now, the valve needle 100 is placed at extreme open position it will be apparent that a leakage line is established for fuel about the orifice 47 and including pipe 89, chamber 94, orifice 93, chamber 95 and pipe 98. Since the pressure drop across orifice 47 is reduced by the leakage path the pressure differential between bellows 82 and 83 of valve unit 80 is also reduced thereby increasing the opening of valve 87. Since the pressure differential between bellows 82 and 83 is a measure of pump speed which acts through valve 84 to regulate the pressure differential between bellows 55 and 56 of unit 46, and to establish the area of opening at valve 50 directly proportional to

$$\frac{(\Delta P)m}{N}$$

and since the pressure differential between bellows 82 and 83 is less with orifice 93 wide open than when it is closed, the apparent value of the ratio

$$\frac{(\Delta P)m}{N}$$

will be higher. The area of the opening of valve 50 is proportional to the apparent ratio

$$\frac{(\Delta P)m}{N}$$

and is therefore larger; and likewise the final flow through valve 50 to the engine is greater when orifice 93 is completely open than when it is closed. The "error" in speed indication resulting with orifice 93 wide open is a constant percentage of the value which would result when orifice 93 is closed, and therefore, the increase in fuel flow over that obtained with orifice 93 closed is proportional to the mass air flow through the engine compressor.

From the above description it may be seen that by moving the needle 100 to modify the area of orifice 93 the fuel-air ratio may be adjusted from some predetermined minimum value. By establishing the minimum fuel-air

ratio at a value which will always maintain stable combustion and the maximum ratio at a value which will maintain the temperature at the exit of the combustion chamber within the design limits, the fuel flow to the engine will always be maintained within the desired operating range.

In using the apparatus as described, to maintain constant operation within the operating range as above mentioned, it may be assumed that the engine is operating at a steady state and it is desired to increase the engine speed. Control lever 114 is first moved to the left. This action instantly increases the compression on spring 107 which, in turn, moves needle valve 100 to its extreme right position, thus opening orifice 93 completely. This increases the fuel-air ratio of the engine to its maximum value, as previously explained, resulting in an increase in the R. P. M. of the engine. As the engine speed increases the centrifugal force on the flyweights 112 increases moving needle stem 101 to the left and reducing the fuel-air ratio until it reaches the value required to maintain the engine at the new speed setting. Reverse movement to the right of lever 114 produces a new setting at lower speed.

By the above means there is obtained an effective and positive control of fuel flow in gas turbine type engines which is free of servo-mechanisms; which avoids temperature devices; and which is unaffected by variations in fuel density or fuel contamination.

The showing is diagrammatic including well known units such as bellows and fly-weights which may be replaced by equivalent devices. While the specific illustrative application of the invention has been described in connection with gas turbines involving an air-fuel ratio it is apparent that other media and prime movers may be employed in utilization of the control mechanism. Other modifications may obviously be resorted to without departing from the spirit and scope of the invention as hereinafter defined.

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

In the claims:

1. In a gas turbine having a tubular casing, a combustion chamber therein, a fuel supply device adjacent said chamber, and an air compressor adjacent but spaced from said fuel supply apparatus for forcing air to said combustion chamber by said fuel apparatus, control apparatus for regulating the air-fuel ratio of said turbine comprising a main fuel line connected to said fuel supply apparatus, a pressure drop section in said main fuel line, means for forcing fuel through said section at constant pressure, a main fuel valve unit connected to said main fuel line on the outlet side of said pressure drop section, pressure means for actuating said main fuel valve, two conduit lines registering respectively the static and total air pressures of the compressor discharge region inside the engine casing, said lines having connection to said pressure means for imparting thereto the static-total pressure differential as a force directly variable with compressor speed, a pressure drop conduit section connecting said static-total pressure lines and bridging said pressure means in parallel therewith, and a regulator unit interposed in said static line for impressing a force on said main fuel valve pressure means inversely variable with compressor speed, whereby a predetermined fuel-air ratio is maintained.

2. The apparatus of claim 1 including means for adjusting the regulator unit at will to select different air-fuel ratios whereby the compressor speed values may be varied.

3. The apparatus of claim 1 with the means for forcing fuel through the pressure drop section of the main fuel line including a force pump, a feed back conduit in parallel with said main fuel line pressure drop section, and a constant pressure control device connected to said

main fuel section and feed back conduit on the low pressure side of said main fuel section.

4. The apparatus as defined in claim 1 with the pressure means for activating the main fuel valve including two flexible bellows chamber units each being positioned in alignment with the line of main valve movement and joined to said main valve at the adjacent inner bellows face and each having the outer bellows face fixedly supported, one of said bellows having tube connection to the static pressure line and the other of said bellows having tube connection to the total pressure line whereby a force amounting to the differential between the static and total forces is made effective on said main valve.

5. The apparatus as defined in claim 1 with the regulator unit including a valve for modifying the pressure in the pressure drop conduit between the static and total pressure lines, pressure means connected to said valve, and speed controlled means connected to said pressure means for modifying the force applied to said regulator pressure means inversely as the compressor speed.

6. The apparatus of claim 5 with the main fuel valve being normally closed and movable progressively to open position with increase in compressor speed and with said regulator valve being normally open and progressively movable with increase in compressor speed to closed position.

7. The apparatus as defined in claim 5 in which the regulator pressure drop valve is slidably mounted relative to a valve port; the regulator pressure means is formed of two tubular bellows having movable ends fixed to opposite sides of the pressure drop valve and fixed ends supported adjacent the valves and a duct from each bellows, respectively, to the inlet and outlet sides of the pressure drop section of the main fuel line; and the speed controlled means includes a leakage tube between the bellows ducts and across the main fuel line pressure drop section, a valve in said tube and speed controlled means for moving said valve toward closed position with increase in speed.

8. In a fluid flow system including parallel flow lines for gas and liquid, control apparatus for regulating the flow of gas in accordance with the pressure drop at a selected section in the liquid line, which comprises a main liquid line, a force pump in said line, a pressure drop section in said liquid line, means for maintaining the pressure drop in said section constant, a gas line, a valve in said gas line, pressure means for actuating said valve, separate ducts connecting respectively the inlet and outlet sides of the fuel conduit pressure drop section to said valve pressure means whereby the duct pressure differential is made effective on said pressure means, a leakage tube connecting said ducts in parallel with said fuel conduit pressure drop section, a valve in said tube, and speed controlled means for actuating said valve in accordance with speed variation in said pump.

9. The apparatus of claim 8 in which the speed controlled means moves the tube valve toward closed position in accordance with increase in speed of the fuel pump.

10. The apparatus of claim 8 with additional means for adjusting the range of speed variation in said speed controlled means.

11. The apparatus of claim 8 in which the tube valve comprises a slidably mounted valve member adapted to close tube ports at one end and provided at the opposite end with a spring stop, and the speed controlled means comprises a stub shaft having a stem engageable and aligned with said valve member, means for supporting said shaft rotatably, means for rotating said shaft at a speed in direct ratio to speed of said fuel pump, weight

devices pivotably mounted on said shaft having contact arms engageable with said valve spring stop tending to move said valve member to closed position with increase in speed of said shaft, an adjustable spring stop, and a spring intermediate said valve stop and adjustable stop normally tending to move said valve to open position.

12. A fuel-air regulation system for gas turbines, comprising a tubular casing having front and rear ends, a shaft in said casing, an air compressor mounted on said shaft toward the front end of said casing, a combustion chamber to the rear of said compressor, a fuel ring having rearwardly directed nozzles, said ring being placed at the front end of the combustion chamber, an air chamber between the fuel ring and the rear end of the compressor, a first tube projecting radially into said air chamber through the casing and having a tip turned so as to register total pressure, a second tube having an end lying radially in the air chamber wall and adapted to register static pressure of the air chamber, a fuel line connected to said fuel ring, means in said fuel line for supplying fuel at constant pressure to said nozzles, a valve in said fuel line and means for controlling the valve directly in accordance with the differential between said air chamber static and total pressures and inversely as the shaft speed, said means including mechanism for establishing predetermined maximum and minimum limits to the fuel-air ratio of said fuel supply.

13. The apparatus of claim 12 with additional means for adjusting the shaft speed.

14. The apparatus of claim 12 with the air chamber first tube having a tip turned in alignment with the air velocity resultant which is the geometric mean of the component velocities of the air compressor.

15. In a gas turbine having a rotor, fuel supply apparatus for regulating the fuel supply to said turbine, said apparatus comprising a device responsive to the total pressure in the immediate discharge region of said rotor, a device responsive to the static pressure in the immediate discharge region of said rotor, a fuel line connected to said turbine, valvular means for controlling the flow of fuel in said fuel line, and means responsive directly to the pressure difference of said devices and inversely to said rotor speed for regulating the flow of fuel in said fuel line to produce a desired fuel-air ratio in said fuel supply, said means including mechanism for establishing predetermined maximum and minimum limits to the fuel-air ratio of said fuel supply.

16. In a gas turbine having a rotor, fuel supply apparatus for regulating the fuel supply to said turbine, said apparatus comprising a device responsive to the total pressure in the immediate discharge region of said rotor, a device responsive to the static pressure in the immediate discharge region of said rotor, a device responsive to the rotor speed, a fuel line connected to said turbine, valvular means for controlling the flow of fuel in said fuel line, and means responsive to the pressure difference of said total and static pressures as indicated by said pressure responsive devices and to the rotor speed as indicated by said speed responsive device for establishing a predetermined fuel-air ratio and limits for variation of said ratio in said fuel supply.

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