United States Patent

Kydd et al.

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[54] **STEAM INJECTION IN GAS TURBINES HAVING FIXED GEOMETRY COMPONENTS**

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[52] **U.S. Cl.** **60/39.05,** 60/39.3, 60/39.55

[51] **Int. Cl.**..**F02g 3/00**

[58] **Field of Search**......60/39.55, 39.3, 39.53, 39.05, 60/39.54, 39.26

[56] **References Cited**

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2,959,005	11/1960	Zara	60/39.55
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[57] **ABSTRACT**

Control means are provided for utilizing maximum tolerable amounts of steam in gas turbines having fixed geometry components under various operating conditions. Optional means include: means for automatically holding a constant cycle pressure ratio under all ambient conditions; temperature sensing control means for automatically adjusting steam injection in both low and high temperature ambients to avoid visible plumes and to avoid acid condensation, respectively; or combined temperature and humidity sensing control means for automatically optimizing steam injection under all conditions of ambient temperature and humidity.

30 Claims, 7 Drawing Figures

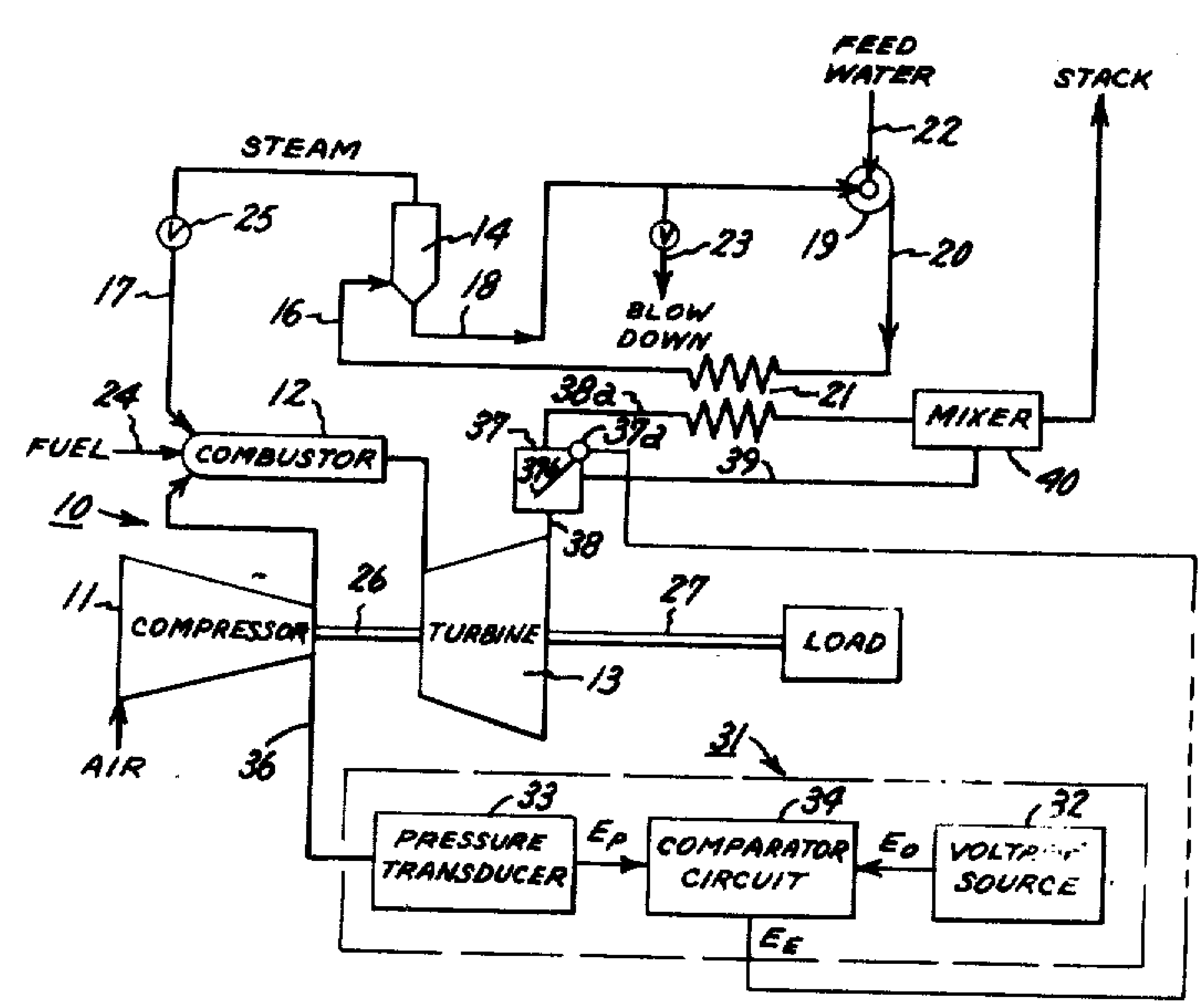

Fig. 1.

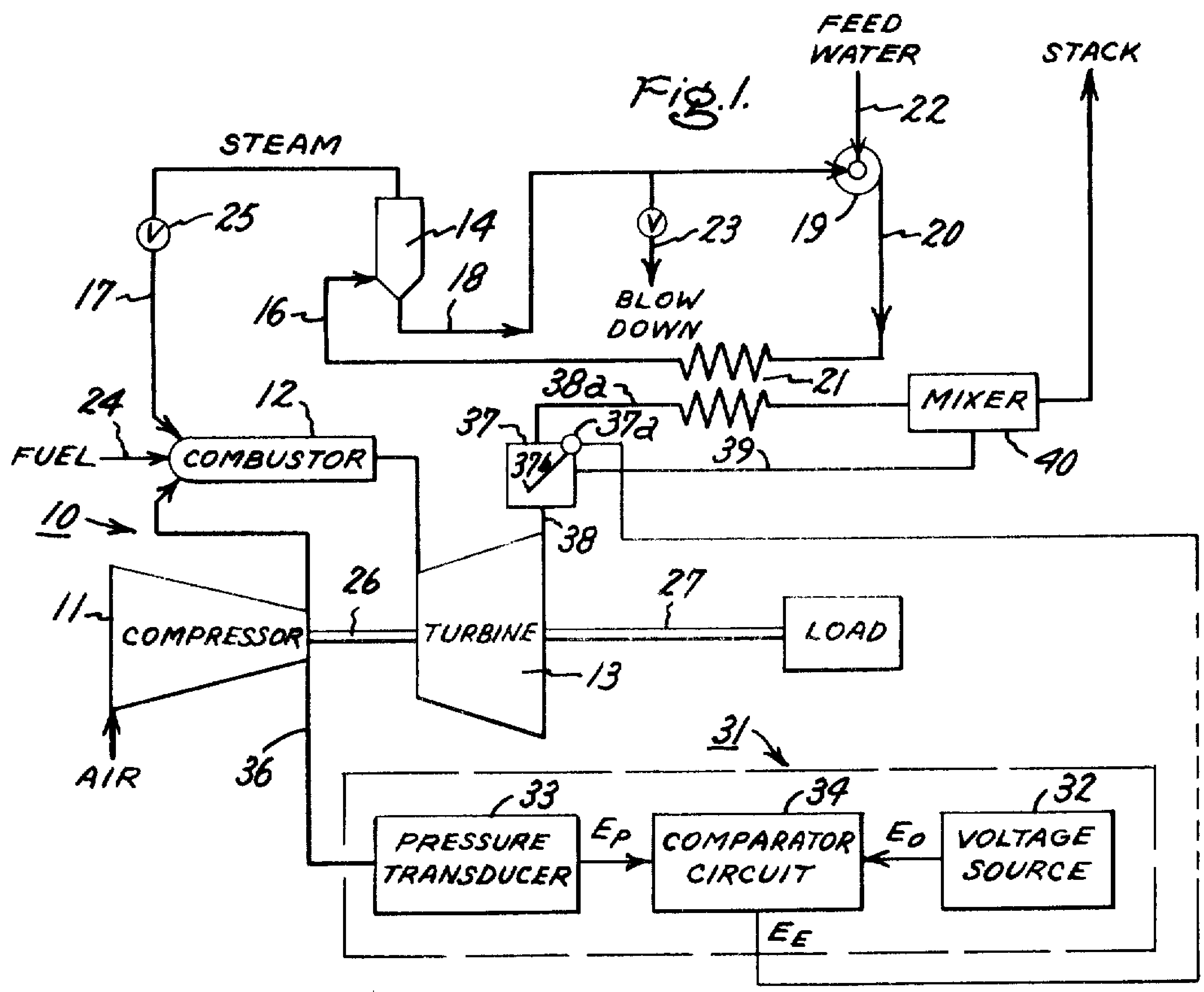

Fig. 2.

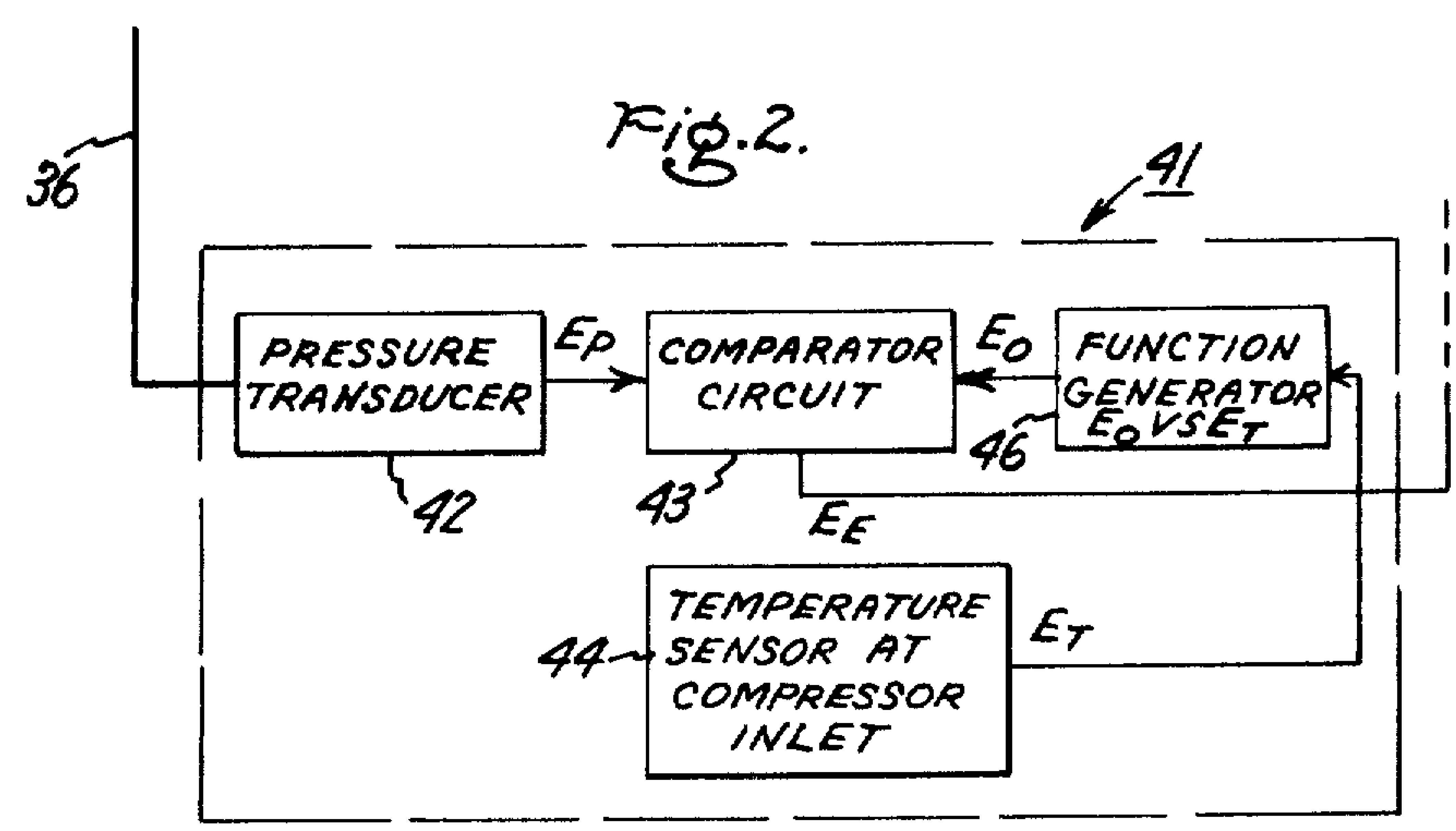

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Fig.3.

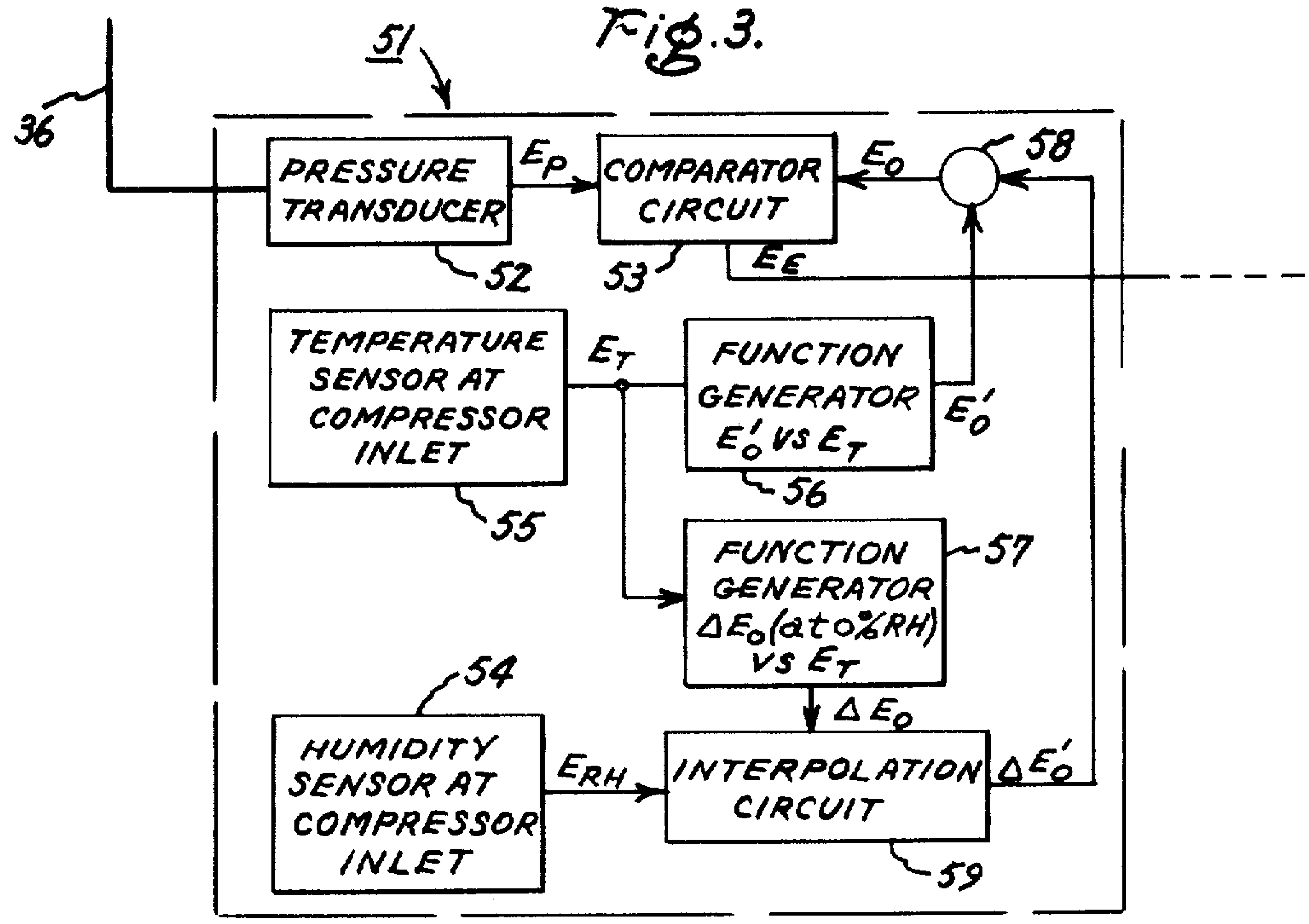

Fig.6.

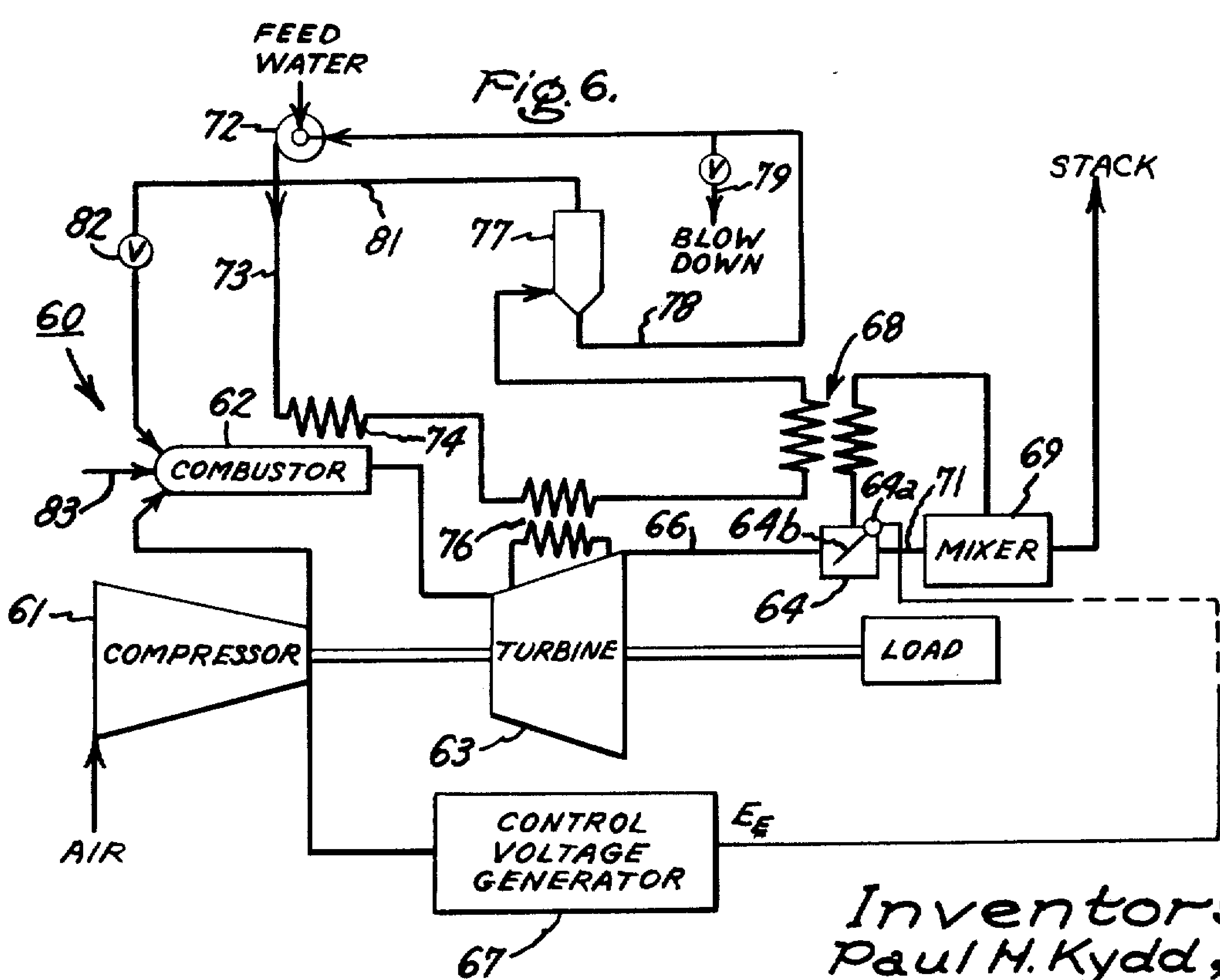

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Fig. 5.

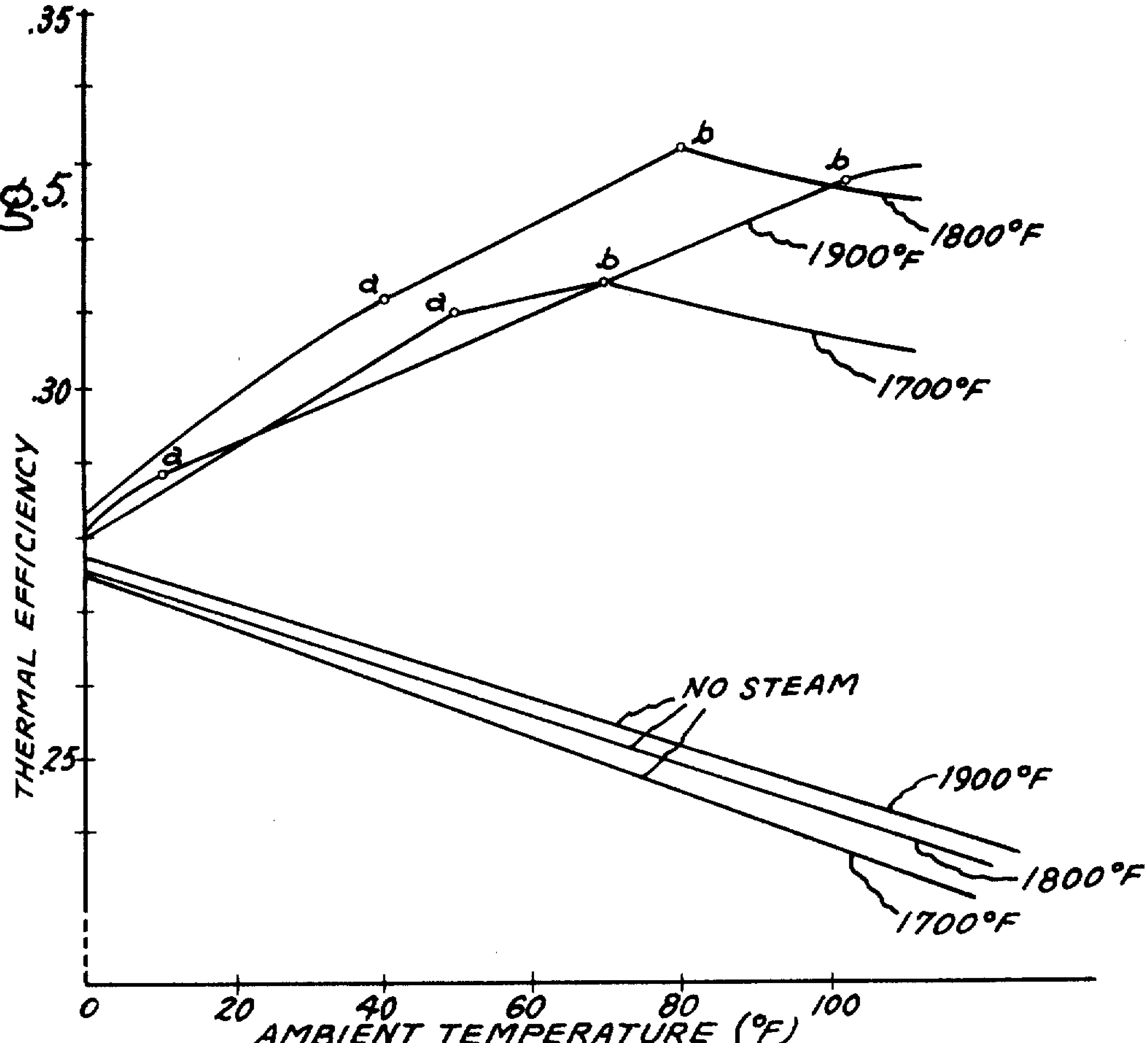

Fig. 4.

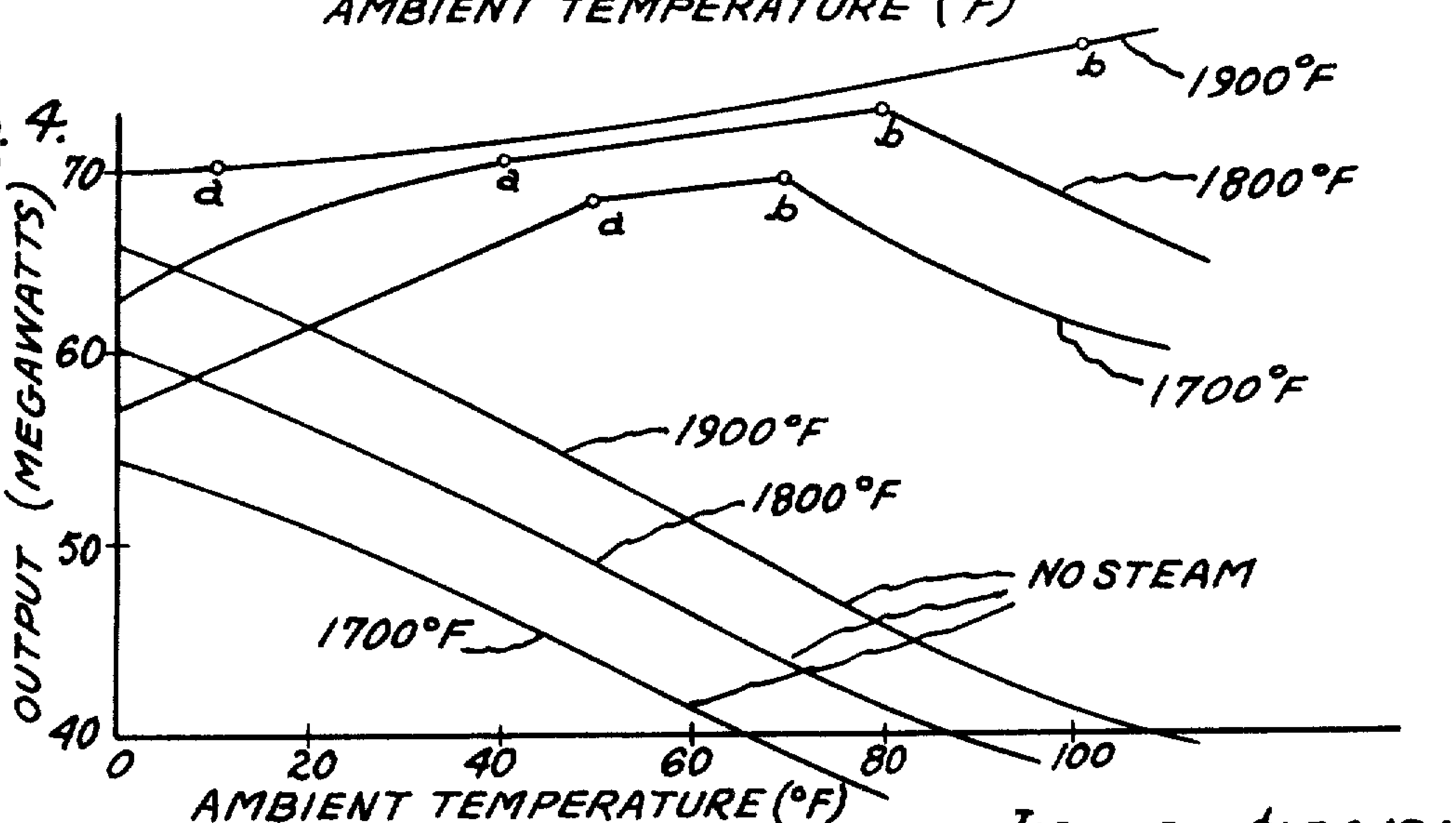

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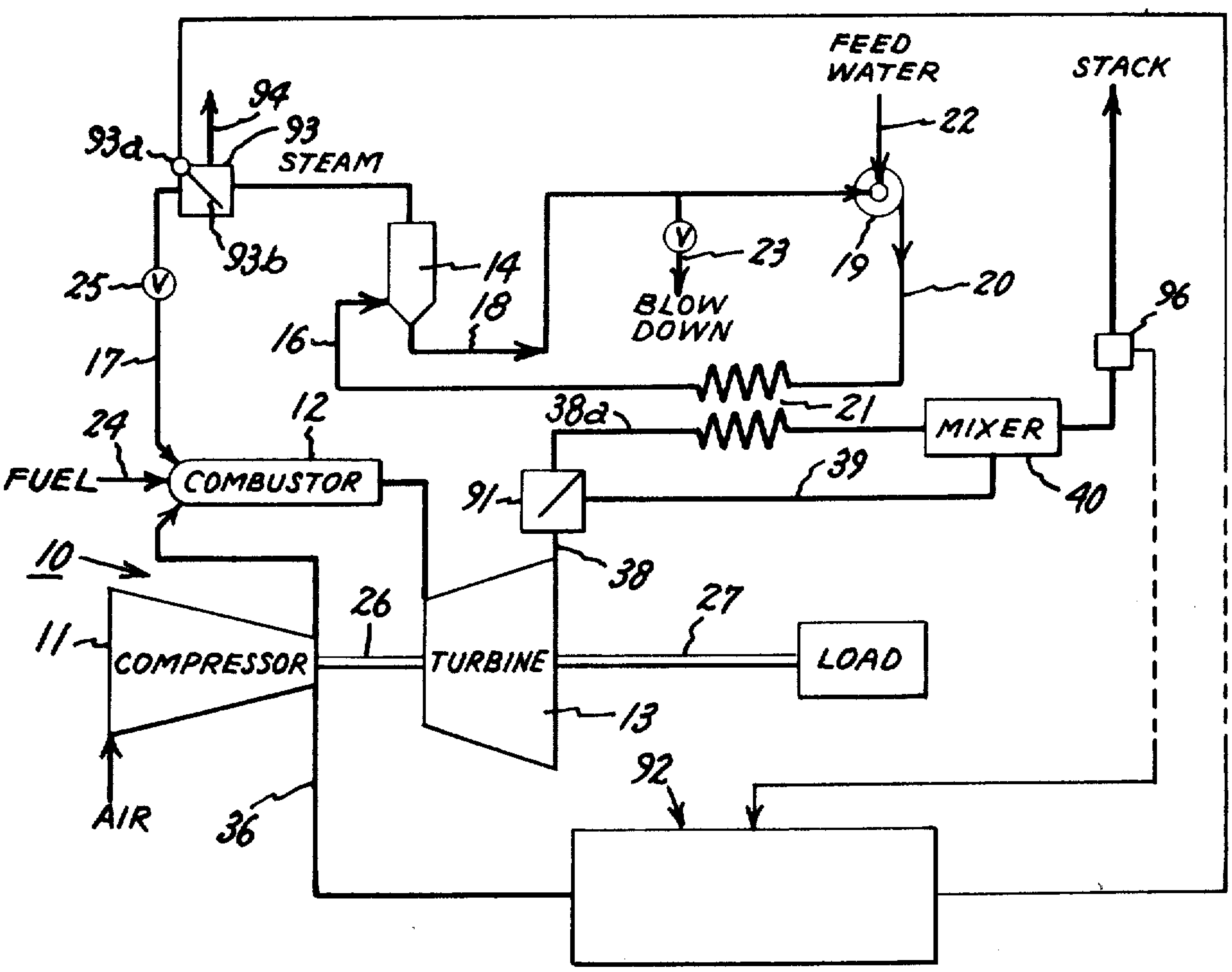
Fig. 7.



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STEAM INJECTION IN GAS TURBINES HAVING FIXED GEOMETRY COMPONENTS

BACKGROUND OF THE INVENTION

The injection of steam into the combustion chamber of a gas turbine is broadly old as is shown in U.S. Pat. No. 2,678,531—Miller and U.S. Pat. No. 3,353,360—Gorzegno. The operation of gas turbines in the steam injection mode provides greater output, because of the increased mass flow through the turbine and because of the higher specific heat of the turbine working fluid. A higher cycle efficiency also results, because this mass flow is obtained without the expenditure of additional compressor power, and the steam for the steam injection can be generated utilizing heat losses or exhaust heat which otherwise is not effectively utilized.

SUMMARY OF THE INVENTION

Control means are provided for utilizing the maximum amounts of steam that can be tolerated in the operation of gas turbines having fixed geometry components under various operating conditions. Optional means are provided as follows: means for automatically holding a constant cycle pressure ratio (compressor discharge pressure/ambient pressure) under all ambient conditions; temperature sensing control means for automatically adjusting steam injection in both low and high temperature ambients to avoid visible plumes and to avoid acid condensation, respectively; or combined temperature and humidity sensing control means for automatically optimizing steam injection under all conditions of ambient temperature and humidity.

BRIEF DESCRIPTION OF THE DRAWING

The exact nature of this invention as well as objects and advantages thereof will be readily apparent from consideration of the following specification relating to the annexed drawing in which:

FIG. 1 is a schematic representation of one embodiment of means according to this invention for automatically controlling the extent of steam injection employed in a fixed geometry continuous flow gas turbine;

FIG. 2 shows a second embodiment of the control voltage generator shown in FIG. 1 including ambient temperature as a control parameter;

FIG. 3 is another modification of the control voltage generator shown in FIG. 1 including both ambient temperature and ambient humidity as control parameters;

FIGS. 4 and 5 considered together constitute a gas turbine performance map setting forth output and thermal efficiency as a function of ambient temperature at a series of turbine inlet temperatures;

FIG. 6 is a schematic representation of an automatically controlled steam injection system according to this invention wherein in addition to the steam injection means of FIG. 1 steam is also generated from the heat in the coolant stream of a liquid cooled turbine and from the liner of the combustor and

FIG. 7 is a schematic representation of a system in which steam is generated at a substantially fixed rate and a control voltage generator according to this invention is used to adjust the admission of steam to the combustor.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Although steam injection, per se, of gas turbines has been previously employed, no consideration appears to have been given to the elimination of problems encountered in the use of steam injection. These problems include the emission of visible exhaust plumes at low ambient temperatures and the occurrence of sulfuric acid condensation in the system under high ambient/low stack temperature conditions. The emission of visible plumes and/or exhausts containing droplets of acid are unacceptable in view of the increasing concern for the quality of the environment. Further, the corrosion caused in the gas turbine exhaust system by sulfuric acid generation must be avoided. Control over the steam injection rate insuring an ecologically acceptable stack exhaust is highly desirable for environmental pollution considerations, of course, however, it has also been found that this control capability can still further improve the operation of gas turbines using steam injection.

Investigations during the development of the instant invention have shown that steam injection reduces the emission of nitric oxide by diluting the combustion air and by reducing the maximum flame temperature. Reduction of flame temperature is important, because the bulk of the nitric oxide is produced at temperatures in excess of about 3,400°F.

In the steam injection process high-pressure steam can be used to atomize heavy fuel oil and eliminate the cost and the power consumption of the atomizing air booster compressor. Atomization energy for improved combustion is virtually unlimited with the use of heat recovery steam as the atomizing medium. Additional advantages also accrue in that by using high-pressure steam as the atomizing medium the problem of formation of deposits in the turbine and in the heat recovery boiler is reduced. Further, by concentrating the steam flow in the primary zone of the combustor the nitric oxide emission can be even more effectively reduced.

It has also been shown during the aforementioned investigations that even though visible plume-free operation of gas turbines should be possible at ambient temperatures above about 75°F when using very substantial steam flows, the problem of the condensation of sulfuric acid in the stack (whereupon this objectionable corrosive condensate is present in the stack exhaust) still remains. Further, the generation of visible plumes at ambient temperatures below 75°F is still a problem. Both of these troublesome conditions can be eliminated by the practice of at least one of the several options presented in the instant invention.

FIG. 1 schematically represents a gas turbine **10** having fixed geometry components; compressor **11**, combustor **12** and turbine **13**. Gas turbine **10** has been provided with steam injection means and controls therefor in accordance with the instant invention.

The steam injection means comprises a steam separator **14** [which may for example be of the drum variety], conduit **16** carrying a hot water/steam mixture to steam separator **14**, conduit **17**, which conducts steam from steam separator **14** to the combustor **12**, conduit **18** which removes liquid water to the feedwater pump **19**, conduit **20** which conducts water to boiler **21**, inlet water conduit **22** for water makeup and valved blowldown line **23**. A flash tank and pressure reducing valve combination as is shown in the aforementioned Gorzegno patent (incorporated by reference) may be substituted for steam separator **14**.

During operation in the steam injection mode compressor **11** takes in atmospheric air and forces it under substantial superatmospheric pressure into combustor **12**. Fuel is supplied to combustor **12** through fuel inlet **24** and steam is injected into combustor **12** via line **17**. Either high-pressure air or the steam (or suitable mixtures thereof) may be employed to atomize the fuel in combustor **12**. Combustion of the fuel in combustor **12** produces hot gases, which pass through turbine **13**, where expansion of the hot gases occurs with the generation of mechanical energy part of which drives compressor **12** via shaft **26** and part of which is available to drive a load via shaft **27**.

Control voltage generator **31** consists of the preset voltage source **32**, pressure transducer **33** and comparator circuit **34**. These components are electrically connected as shown. When operating, voltage source **32** continuously applies a fixed biasing voltage E_O to comparator circuit **34** and pressure transducer **33** continuously applies voltage E_P to comparator circuit **34**, E_P being a voltage that is proportional to the compressor discharge pressure applied to pressure transducer **33** via conduit **36**. Comparator circuit **34** is adjusted so that for a voltage E_P reflecting a compressor discharge pressure equal to the selected operating value of cycle pressure ratio selected as described hereinabove, the bias voltage E_O is just compensated.

In the event of a change in the compressor discharge pressure, voltage E_P will not be equal to bias voltage E_O and the voltage error is the control voltage (E_E) that is thereby generated (and amplified, if required) is supplied to by-pass unit **37** (with motorized actuator **37***a*), e.g., a damper actuator (as manufactured by the General Electric Company, Instrument Department, Lynn, Mass.), so as to change the position of baffle **37***b* and thereby modify the amount of exhaust gas passing through boiler **21** to reduce and then eliminate the error. Thus, if voltage E_P is temporarily greater than bias voltage E_O, a negative control voltage E_E is generated resetting bypass actuator **37***a* to decrease the amount of exhaust gas from turbine **13** passing through line **38**, bypass unit **37**, line **38***a* and boiler **21**. This change results in a decrease in the amount of steam generated in boiler **21** and separated in steam separator **14** thereby decreasing the steam input to combustor **12**. If the reverse situation occurs (E_P is less than E_O), a positive control voltage E_E results and bypass actuator **37***a* is readjusted so as to increase the exhaust flow through boiler **21** and decrease the amount of exhaust passing through the exhaust conduit **39** and mixer **40** to the stack. The changes in steam flow so accomplished will reduce and eliminate control voltage E_E changing the pressure ratio across compressor **12** by changing the amount of mass flow occurring at fixed temperature through the fixed geometry turbine. If desired, some of the injected steam is introduced into the head end of the combustor and the balance of the input is introduced therein downstream of the head.

Valve **25** in steam line **17** is controlled in the conventional manner (as by sensing the rotational speed of shaft **27**) to compensate for large increases or decreases in gas turbine load. Valve **25** may be a throttling/shut-off type valve or a bypass valve.

There are at least two types of situations in which the automatic elimination of visible exhaust plume and exhaust system corrosion must be accomplished at some turbine inlet temperature lower than the temperature at which steam injection which maintains constant pressure ratio will do so automatically. In such situations the control voltage generator device **31** will not provide sufficiently sophisticated control. Either of the control voltage generators shown in FIGS. **2** and **3** may then be employed to effect control such that the maximum amount of steam is generated (and injected) as required for maximum output and thermal efficiency over the preselected range of ambient temperatures. Examples of the aforementioned types of situations are as follows:

a. when it is desired to operate the machine at a turbine inlet temperature below the maximum turbine inlet temperature thereof (although such operation is within its capability) in order to achieve reduced power output but yet operate in this regime at maximum steam flow and efficiency and

b. when the compressor/turbine combination is such that the turbine cannot tolerate as high an inlet temperature as is necessary for the maintenance by steam injection of the maximum pressure ratio over the full preselected range of ambient temperatures.

The device of FIG. **2** supplies a voltage to automatically control steam generation as a function of ambient temperature while the device shown in FIG. **3** supplies a voltage to automatically control steam generation as a function of both the ambient temperature and ambient relative humidity (RH). All components shown in connection with all the control means disclosed herein are commercially available items.

The device **41** shown in FIG. **2** is interchangeable with control voltage generator **31** shown in FIG. **1**. Pressure transducer **42** is hydraulically connected via line **36** to the compressor discharge. Voltage E_P having a value proportional to the compressor discharge pressure is supplied to comparator circuit **43** as described hereinabove. Temperature sensor **44** (e.g., a thermocouple or temperature transmitter such as GE/MAC type 550 manufactured by the General Electric Company, Instrument Department, Lynn, Mass.) is located at or near the compressor inlet emitting a voltage E_T reflecting the ambient temperature conditions. Temperature sensor **44** is electrically connected to function generator **46** (e.g., GE/MAC type 566 function generator manufactured by the General Electric Company, Instrument Department, Lynn, Mass.) as shown so as to apply voltage E_T thereto. In function generator **46** (set for a 100 percent relative humidity condition), a bias voltage E_O is generated as a function of voltage E_T and, as a result, reflects the effect of any ambient temperature in the preselected range at 100 percent RH. Voltages E_O and E_P are applied to comparator circuit **43** in the manner described hereinabove for comparator circuit **34**. The value of the voltage error (control voltage E_E), if any, determines the setting of motorized bypass unit **37** in the same manner as described hereinabove.

Thus, should the ambient temperature decrease below the point at which a constant pressure ratio can be maintained by steam injection without visible plume, there will be automatic compensation of the rate of steam injection, because the electrical control signal E_E will automatically relate to the selected compressor discharge pressure compensated for low ambients. Thus, control voltage E_E (via bypass actuator **37a**) will adjust the rate of steam injection to combustor **12** as required to avoid visible plumes in the exhaust. Similarly, should the ambient temperature increase above the point at which a constant pressure ratio can be maintained by steam injection without forming acid condensate in the exhaust, control voltage E_E will automatically properly adjust the rate of steam injection to combustor **12** to eliminate the acid condition. This mode of operation will allow satisfactory performance at all ambient relative humidities, but must sacrifice the opportunity to add more steam at ambient humidities lower than 100 percent RH.

The control voltage generator **51** includes pressure transducer **52**, the electrical output (voltage E_P) of which passes to comparator circuit **53** as described hereinabove and the electrical signal E_P is compared therein to biasing signal E_O, which latter voltage factors into the automatic control function the parameters of ambient temperature and ambient humidity. Both a temperature sensor and a humidity sensor (e.g., of the surface ion exchange type as manufactured by the Amlab Company of Essex, Conn., used in a bridge circuit with thermistor compensation for temperature effects) are located at or near the compressor inlet and these sensors respectively emit electrical signals E_T and E_{RH}. The humidity sensor **54** is adjusted so that at 100 percent RH the output voltage E_{RH} is zero and at zero relative humidity E_{RH} is one unit. Temperature sensor **55** is electrically connected to each of function generators **56** and **57**. Function generator **56** emits voltage E_O' as some function of E_T (and therefore as a function of the ambient temperature) at 100 percent RH. Function generator **56** is electrically connected to summing junction **58**,which in turn is electrically connected to comparator circuit **53**.

The electrical signal E_T impressed on function generator **57** generates the voltage designated as ΔE_O. This electrical signal (voltage ΔE_O) reflects any requisite correction voltage for the actual ambient temperature at a relative humidity of zero or, in effect is indicative of the rate of steam injection that should be employed under these conditions. Voltage ΔE_O is then further modified (as described hereinbelow) in interpolation circuit **59** (e.g., voltage multiplier, type 564S manufactured by General Electric Company, Instrument Department, Lynn, Mass.) to reflect the actual ambient humidity sensed by humidity sensor **54**. Voltage E_{RH} emitted by humidity sensor **54** reflects the actual ambient humidity and is indicative of the fraction of voltage ΔE_O that can form part of the bias voltage to be applied to comparator circuit **53**.

As shown, both voltage E_{RH} and voltage ΔE_O are introduced to interpolation circuit **59**. The interpolation circuit **59** electrically multiplies voltage ΔE_O by voltage E_{RH} and the product thereof (voltage $\Delta E_O'$) reflects the incremental rate of steam injection that can be tolerated at the ambient temperature and ambient relative humidity over the rate of steam injection permissible for the ambient temperature/100 percent RH condition. Interpolation circuit **59** is electrically connected to summing junction **58** to which the electrical signals E_O' (representing rate of steam injection for the ambient temperature at 100 percent RH) and $\Delta E_O'$ (representing the increment of added rate of steam injection for ambient humidity) are introduced. In summing junction **58**, E_O' and $\Delta E_O'$ are added to produce the net biasing voltage E_O impressed upon comparator circuit **53**. Any resulting error signal E_E from comparator circuit **53** controls the setting of actuator **37a** in the same manner described hereinabove thereby providing automatically optimized operation at all ambient temperatures (in the preselected range) and all ambient relative humidities.

Although the control devices illustrated herein are electrical in nature, this invention is intended to encompass hydraulic, pneumatic and mechanical analogs of these electrical devices. In each instance, it is required to produce a signal quantitatively related to the pressure ratio and interrelate a bias signal therewith. The bias signal may have a constant value or may be variable either as a function of ambient temperature or as a function of both ambient temperature and ambient humidity.

Any one of the three optional control voltage generators described hereinabove may be utilized for controlling the steam injection into any given gas turbine. The choice of which one is to be used will be determined by the characteristics of the gas turbine in question, the range of ambient temperature and relative humidity over which the machine must operate and whether the power output and efficiency are to be optimized with regard to relative humidity.

The characteristics of the gas turbine which are important are the compressor map (pressure ratio versus air flow at various speeds), which defines the stall or pulsation limit as a function of speed, and the first stage turbine nozzle area. The turbine nozzle area must be large enough that the compressor does not stall at maximum turbine inlet temperature and minimum ambient air temperature under which conditions the air flow and pressure ratio of the compressor are high due to the high inlet air density. Consequently at higher ambient temperatures additional mass flow can be accepted by the turbine without stalling the compressor.

The first step in selecting a control voltage generator from the options disclosed herein for a given gas turbine is to choose a turbine inlet temperature and steam flow which provides the desired balance between power output and efficiency at the design point. High turbine inlet temperatures provide maximum output (FIG. 4). Lower turbine inlet temperatures and higher steam flow produce a higher thermal efficiency (FIG. 5) down to the point at which the exhaust temperature is too low to generate the required amount of steam or at which the decline in available energy due to reduced turbine inlet temperature is no longer offset by the increase in available energy from the permissible increase in steam addition. The above-noted combination of turbine inlet temperature and steam flow will be chosen to increase the pressure ratio to the maximum that the compressor can deliver with an adequate stall margin.

The next step in selecting the control system is to investigate the performance of the gas turbine over the intended range of ambient temperature. The objective is to maintain optimum performance over as wide a range of ambient conditions as are to be encountered. This is most easily accomplished by holding turbine inlet temperature constant via the conventional exhaust temperature measurement and fuel control system and holding pressure ratio constant at its maximum value by controlling the rate of steam injection. It may be that for the given gas turbine components and turbine inlet temperature constant pressure ratio operation can be achieved over the entire range of expected ambient temperature. In this case control voltage generator **31** will suffice.

If at low ambient temperatures and 100 percent RH it is found either that the exhaust moisture content is such that a visible plume forms, or that at high ambient temperatures and 100 percent RH,acid condensation occurs due to excessive steam flow and correspondingly low stack temperature, it will be necessary to restrict the steam flow into the combustor at low temperatures, at high temperatures or both. This restriction of steam flow, which will reduce the pressure ratio and the performance of the gas turbine at extreme ambient conditions can be accomplished with control voltage generator **41**.

If it is desired to take advantage of the fact that low ambient relative humidity will reduce the tendency to generate an exhaust plume or stack condensation, one can extend the region of maximum steam flow and performance under low relative humidity conditions by using control voltage generator **51**.

In all cases it is desired to achieve the maximum steam flow permitted by the boundaries imposed by exhaust plume formation, compressor stall, and acid condensation, at the chosen turbine inlet temperature. Higher turbine inlet temperatures widen the range of ambient temperature over which operation at constant maximum pressure ratio is possible. The operating boundaries for a representative gas turbine at different turbine inlet temperatures are shown in FIGS. **4** and **5**. Thus, for operation at each of the turbine inlet temperatures shown, the compressor stall boundary lies between letters *a* and *b;* the exhaust plume boundary lies to the low ambient temperature side of letter *a* and the acid condensation boundary lies to the high ambient temperature side of letter *b*. For operation between letters *a* and *b* the pressure ratio is constant. This map further illustrates the substantial change in thermal efficiency and output between operation in the steam injection mode and operation without steam injection.

The generation of the data required to prepare a turbine performance map such as FIGS. **4** and **5** (considered together) requires a considerable amount of cut-and-try calculating and is, therefore, most effectively accomplished by the use of a computer, e.g., time-sharing. The development of a suitable computer program would employ steps as follows:

a. tentative selection of a range of turbine inlet temperatures providing a desired balance between thermal efficiency and power output for the gas turbine,

b. selection from the compressor map of a range of operating pressure ratios for the gas turbine along the 100 percent speed curve; the highest pressure ratio being that pressure ratio which the compressor can deliver without stalling and the lowest pressure ratio being the pressure ratio for the non-steam injected condition at lowest ambient temperature,

c. selection of an operating range of ambient temperatures,

d. calculation of the range of operating turbine inlet temperatures to be employed using known relationships of gas properties (at different temperatures and steam content) and turbine efficiency (as a function of pressure ratio, turbine inlet temperature, steam content and fuel content),

e. selection of a range for the amount of steam to be injected (i.e., rates of steam injection) into the gas,

f. calculation of a map of the efficiency of the turbine alone as a function of the parameters in the three selected ranges (pressure ratio, turbine inlet temperature and steam injection),

g. selection of some value of turbine inlet temperature from the calculated temperature range,

h. selection of an ambient temperature and a relative humidity of either zero or 100 percent,

i. calculation of the compressor efficiency for the selected ambient conditions to determine the maximum pressure ratio available from the compressor,

j. calculation of the amount of steam and fuel flow required to create this maximum pressure ratio at the selected turbine inlet temperature,

k. determination of the efficiency of the turbine itself from the turbine performance map for the selected turbine inlet temperature, maximum pressure ratio and gas properties,

l. calculation of the turbine exhaust temperature (accounting for the effects of cooling and diluting of the gas flow),

m. calculation of the stack temperature considering any heat removal from the exhaust gas and, knowing the stack temperature, determining whether stack corrosion (acid condensation) will occur, and

n. determination of whether visible plume will be generated under the selected operating conditions at the selected ambient temperature and relative humidity by calculating the relative humidity of successive dilutions of stack effluent with the ambient air.

If it be determined that either an acid condition or visible plume would occur, the amount of steam being injected is too great. In such case, the procedure will have to be repeated using a smaller steam flow and considering the changes (lower pressure ratio) that accompany the reduced steam injection.

If neither acid condensation nor visible plume occur, the aforementioned steps are repeated using a different set of ambient conditions. When a sufficiently large number of sets of ambient conditions have been considered (e.g., at temperature increments of about 20°F) one curve of gas turbine thermal efficiency and output will be generated for the single selected turbine inlet temperature as described hereinabove. Thereafter, the procedure is repeated until a map of gas turbine thermal efficiency and output referred to hereinabove (FIGS. **4** and **5**) has been prepared for different turbine inlet temperatures (at increments of about 100°F). This map provides the option of selecting at will a turbine inlet temperature for optimizing the combination of gas turbine thermal efficiency and gas turbine output (consistent with machine capabilities). Having determined this map, the method described hereinabove for the determination of the several options may be carried out.

If the gas turbine is one that may be operated at less than 100 percent speed a tachometer with a signal output proportional to speed may be introduced to sense the compressor speed and adjust the sensing of the pressure ratio (described hereinbelow) to reflect changes in speed. With known gas turbine construction, the selected ambient temperature range may be as narrow as about 60°F or as wide as at least 110°F depending upon the selected turbine inlet temperature. The higher the turbine inlet temperature, the greater the available ambient temperature range. By way of example, in a General Electric MS7000 gas turbine at peak reserve turbine inlet temperature the operating ambient temperature range available, which is free of visible plume or acid condensation in the exhaust, is 110°F (from 0° to 110°F) at 14.17 psia inlet.

The unexpected aspect of this invention is that having made the aforementioned determinations, the rate (e.g., pounds of steam/hour) of injection of steam remains the only control parameter that is required to simultaneously achieve:

a. the maximum power and efficiency of which the machine is capable in the selected operating range of ambient temperature,

b. freedom from visible plume and

c. freedom from the formation of acid condensation.

This invention, thus, provides optional means that enable control of the steam injection rate. These devices vary in their capabilities for accommodating the extent of ambient temperature range, when the pressure ratio is not held constant. In the simplest arrangement (control signal generator device **31**) the selected pressure ratio must be held constant and the turbine is operated at the constant selected turbine inlet temperature.

Increased efficiency can be obtained by utilizing superheated steam with a penalty of a slightly higher rate of production of nitric oxide. Still further increases in specific output and efficiency can be achieved by increasing the turbine inlet temperature. This is made possible by utilizing internal cooling. Arrangements for liquid cooling are described in U.S. Pat. Nos. 3,446,481—Kydd and 3,446,482—Kydd. Internal cooling, of course, results in heat losses from the gas stream. However, by using this lost heat to generate steam for injection into the gas turbine in addition to that generated from the turbine exhaust, approximately 70 percent of the performance decrease due to the heat losses can be recovered.

The liquid-cooled turbine parts actually function as a boiler in the cooling sequence. The liquid coolant may either be circulated in a fully closed circuit or, in the case of water as the coolant, in an open circuit from which the steam that is generated may be withdrawn and replaced with make-up water. The former arrangement has the advantage of minimizing contaminant content. Such is the arrangement shown in FIG. **6**.

Gas turbine **60** comprises compressor **61**, combustor **62** and liquid-cooled turbine **63**. In addition to the steam injection means and control means therefor shown in FIGS. **1–3** the liquid coolant for turbine **63** and liquid coolant for combustor **62** are used as sources of steam generation. The rate of steam generation from these added sources is fixed by the amount of cooling required and is substantially constant. Although the rate of steam generation (and steam injection) is not subject to the control means for the exhaust-generated steam, this does not pose a problem, because the turbine inlet temperature for a liquid-cooled turbine may be set sufficiently high to adequately accommodate the maximum rate of steam generation from the liquid coolant for turbine **63** and from the cooling of the liner of combustor **62** without visible plume or acid condensate formation.

As in the arrangement shown in FIG. **1**, the flow bypass **64** receives exhaust gas from turbine **63** via line **66**. Motorized actuator **64**a receives control voltage E_E from control voltage generator **67** electrically connected thereto and fixes the position of damper **64**b in response to voltage E_E. The position of damper **64**b determines what proportion of the exhaust gas passes through bypass unit **64** to boiler **68** via line **66**a and what proportion of the exhaust gas passes through bypass unit **64** to mixer **69** via line **71**. Control voltage generator **67** may be any of the options **31**, **41** or **51** described hereinabove.

Thus, water circulated by pump **72** through line **73** passes through combustor liner **74**, heat exchanger **76** and boiler **68**. Steam generation may occur in heat exchanger **76** and liner **74** and will always occur in boiler **68** depending on the setting of damper **64***b*. The steam/water mixture proceeds to steam separator **77** wherein liquid and steam are separated, the liquid passing via line **78** to feed pump **72**. Valved blow-down line **79** connected to conduit **78** is used to remove contaminating material.

Steam from steam separator **77** passes to combustor **62** via line **81**. Valve **82** in steam line **81** is controlled in the conventional manner to compensate for large increases or decreases in gas turbine load. Fuel is supplied to combustor **62** via pipe **83** and compressed air flows to combustor **62** from compressor **61** to burn the fuel and generate hot gases, which pass to liquid-cooled turbine **63**.

In alternate construction (not shown) instead of employing a fully closed circuit for the turbine liquid coolant and passing the water flow in line **73** through heat exchanger **74**, the turbine cooling circuit would be made part of the steam injection circuit.

If desired, the exhaust of the turbine may be used in part or in whole to generate steam at a substantially constant rate in which case the adjusting means would be disposed between the steam generating means and the combustor with which it is in flow communication. The control voltage generator options of this invention would then be used to control the admission of steam to the combustor, the steam not injected into combustor **62** being diverted to other uses, such as process steam or space heating. Such an arrangement is shown in FIG. **7** in which elements the same as those in FIG. **1** have like numerals. Flow splitter **91** with an adjustable baffle is connected between exhaust lines **38** and **38***a*. The baffle is positioned so that the amount of exhaust gas passing through boiler **21** is sufficient to generate steam at the maximum useable rate. Control voltage generator **92** would be a modified version of options **31**, **41**, **51** described hereinabove and controls the admission of steam to combustor **12** by adjusting the setting of bypass unit **93** in which baffle **93*b*** is positioned by motor actuator **93*a***. Unused steam is conducted to an alternate use via pipe **94**. If too much steam is being generated for the combined demands of steam injection and the alternate use, the baffle in flow splitter **91** is reset.

The proper setting of flow splitter **91** will, therefore, depend on the requirements for injection steam and for the alternate use and the amount of steam generated in excess of that required for steam injection will affect the stack gas temperature. If the stack gas temperature is reduced to too low a level, the amount of steam that may be injected at low and at high ambient temperatures without the formation of visible plume or acid condensate will be reduced. A control signal derived from stack gas temperature sensor **96** should, therefore, be used to generate an additional signal to control voltage generator **92** contributing to bias voltage E_0 in the same manner as humidity sensor **54** and interpolation circuit **59** contribute to signal E_0 in control voltage generator **51**.

As an alternate to this modification, the stack gas temperature can be raised and additional steam can be generated by the use of a supplemental burner (not shown), that would be located between flow splitter **91** and boiler **21**.

Conditions may be encountered in which it is preferred to use a source of steam, which employs some heat energy source for the conversion of water to steam other than the turbine exhaust or coolant streams. In such instances the source of steam may be placed in flow communication with the combustor with a control voltage generator of this invention being used either to adjust the rate at which heat energy is provided for the steam generating function (as in FIGS. **1** and **6**) or to adjust the admission of steam to the combustor (as in FIG. **7**).

By utilizing the arrangements of the instant invention for automatically controlling steam injection, very significant improvements in performance resulting from optimized steam injection may be achieved in varying degrees in conventional gas turbines having fixed geometry components depending upon which option is selected.

The control devices of this invention may be incorporated either into existing machines or into new machines as described herein.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. In a gas turbine power plant wherein the turbine is mechanically connected to and drives a compressor; said compressor supplies compressed air to a combustor in flow communication therewith; steam injecting means including steam generating means is in flow communication with said combustor and generates and supplies steam thereto; means in flow communication with said combustor supplies fuel thereto for combustion thereof with air in said combustor for the generation of hot gases, and said combustor supplies the hot gases generated therein to said turbine being in flow communication therewith, the combination with said steam generating means of means to automatically control the generation of steam for admission to said combustor, said control means comprising:

a. means in flow communication with said compressor for generating a control signal and
b. means connected to said control signal generating means and responsive to said control signal for adjusting the rate of heat energy input to said steam generating means.

2. The combination of claim **1** wherein said steam generating means is in flow communication with the exhaust system of said turbine and said adjusting means determines the flow of exhaust gas thereto.

3. The combination of claim **1** wherein said steam generating means comprises a first steam generator in flow communication with the exhaust system of said turbine and a second steam generator in series with said first steam generator, said first steam generator alone having the exhaust gas input thereto adjustable by said adjusting means.

4. The combination of claim **1** wherein the means for generating a control signal comprises:

a. electrical signal comparing means having first and second inputs and having an output, said output being electrically connected to said adjusting means,
b. means electrically connected to said first input of said comparing means and in flow communication with the compressor discharge for sensing the compressor discharge pressure and generating a pressure-response signal quantitatively related thereto and
c. means electrically connected to said second input of said comparing means for applying a bias signal thereto, said comparing means supplying a control signal to said adjusting means via said output when the relationship between said bias signal and said pressure-response signal deviates from some predetermined value.

5. The combination of claim **4** wherein said means for applying a bias signal is a fixed voltage source.

6. The combination of claim **4** wherein said means for applying a bias signal includes a voltage generator and a temperature sensor having an electrical signal output quantitatively related to the temperature sensed, said temperature sensor being located adjacent the inlet to said compressor and being electrically connected to said voltage generator, said voltage generator being electrically connected to said second input and the bias signal generated thereby being quantitatively related to the signal from said temperature sensor.

7. The combination of claim **4** wherein the means for applying a bias signal includes a temperature sensor having an electrical signal output quantitatively related to the temperature sensed; first and second voltage generators electrically connected at their respective inputs to said temperature sensor; a humidity sensor having an electrical signal output quantitatively related to the relative humidity sensed; a voltage multiplier having separate inputs electrically connected to the outputs of said second voltage generator and said humidity sensor, respectively; and the outputs of said first voltage generator and said voltage multiplier being electrically connected to a summing junction, the bias signal output of said summing junction being electrically connected to said comparing means and said temperature sensor and said humidity sensor being located adjacent the inlet to said compressor.

8. The combination of claim 4 wherein the means for sensing and generating a pressure-response signal is a pressure transducer.

9. The combination of claim 1 wherein said adjusting means is a flow bypass having powered actuating means, said flow bypass being in flow communication with said steam generating means.

10. The combination of claim 2 wherein said adjusting means is a flow bypass having powered actuating means, said flow bypass being in flow communication with the outlet of said turbine, with said steam generating means and with mixing means located downstream in the turbine exhaust system.

11. In a gas turbine power plant wherein the turbine is mechanically connected to and drives a compressor; said compressor supplies compressed air to a combustor in flow communication therewith; steam injecting means including steam generating means is in flow communication with said combustor and generates and supplies steam thereto; means in flow communication with said combustor supplies fuel thereto for combustion thereof with air in said combustor for the generation of hot gases, and said combustor supplies the hot gases generated therein to said turbine being in flow communication therewith, the combination with said steam generating means of means to automatically control steam flow to said combustor, said control means comprising:

a. means in flow communication with said compressor for generating a control signal and

b. means for adjusting the admission of steam to said combustor, said adjusting means being in flow communication with both said steam injecting means and said combustor and being automatically responsive to said control signal.

12. The combination of claim 11 wherein said steam generating means is in flow communication with the exhaust system of said turbine.

13. The combination of claim 11 wherein the means for generating a control signal comprises:

a. electrical signal comparing means having first and second inputs and having an output, said output being electrically connected to said adjusting means,

b. means electrically connected to said first input of said comparing means and in flow communication with the compressor discharge for sensing the compressor discharge pressure and generating a pressure-response signal quantitatively related thereto and

c. means electrically connected to said second input of said comparing means for applying a bias signal thereto, said comparing means supplying a control signal to said adjusting means via said output when the relationship between said bias signal and said pressure-response signal deviates from some predetermined value.

14. The combination of claim 13 wherein said means for applying a bias signal is a fixed voltage source.

15. The combination of claim 13 wherein said means for applying a control bias signal includes a voltage generator and a temperature sensor having an electrical signal output quantitatively related to the temperature sensed, said temperature sensor being located adjacent the inlet to said compressor and being electrically connected to said voltage generator, said voltage generator being electrically connected to said second input and the bias signal generated thereby being quantitatively related to the signal from said temperature sensor.

16. The combination of claim 13 wherein the means for applying a bias signal includes a temperature sensor having an electrical signal output quantitatively related to the temperature sensed; first and second voltage generators electrically connected at their respective inputs to said temperature sensor; a humidity sensor having an electrical signal output quantitatively related to the relative humidity sensed, a voltage multiplier having separate inputs electrically connected to the outputs of said second voltage generator and said humidity sensor, respectively; and the outputs of said first voltage generator and said voltage multiplier being electrically connected to a summing junction, the output of said summing junction being electrically connected to said comparing means and said temperature sensor and said humidity sensor being located adjacent the inlet to said compressor.

17. The combination of claim 13 wherein the means for sensing and generating a pressure-response signal is a pressure transducer.

18. The combination of claim 11 wherein said adjusting means is a flow by-pass having powered actuating means.

19. In a gas turbine power plant wherein a liquid-cooled turbine is mechanically connected to and drives a compressor; said compressor supplies compressed air to a combustor in flow communication therewith; steam injecting means including steam generating means is in flow communication with said combustor and supplies steam thereto; means in flow communication with said combustor supplies fuel thereto for combustion thereof with air in said combustor for the generation of hot gases and said combustor supplies the hot gases generated therein to said turbine being in flow communication therewith, the combination with said steam injecting means of:

a. first steam generating means in flow communication with the exhaust system of said turbine,

b. second steam generating means in series with said first steam generating means; said second steam generating means being in heat exchange relationship with the cooling circuit of said turbine,

c. means in flow communication with said compressor for generating a control signal and

d. means connected to said control signal generating means and responsive to said control signal for adjusting the flow of exhaust gas to said first steam generating means.

20. The combination of claim 19 wherein the means for generating a control signal comprises:

a. electrical signal comparing means having first and second inputs and having an output, said output being electrically connected to said adjusting means,

b. means electrically connected to said first input of said comparing means and in flow communication with the compressor discharge for sensing the compressor discharge pressure and generating a pressure-response signal quantitatively related thereto and

c. means electrically connected to said second input of said comparing means for applying a bias signal thereto, said comparing means supplying a control signal to said adjusting means via said output when the relationship between said bias signal and said pressure-response signal deviates from some predetermined value.

21. The combination of claim **20** wherein said means for applying a bias signal is a fixed voltage source.

22. The combination of claim **20** wherein said means for applying a bias signal includes a voltage generator and a temperature sensor having an electrical signal output quantitatively related to the temperature sensed, said temperature sensor being located adjacent the inlet to said compressor and being electrically connected to said voltage generator, said voltage generator being electrically connected to said second input and the bias signal generated thereby being quantitatively related to the signal from said temperature sensor.

23. The combination of claim **20** wherein the means for applying a bias signal includes a temperature sensor having an electrical signal output quantitatively related to the temperature sensed; first and second voltage generators electrically connected at their respective inputs to said temperature sensor; a humidity sensor having an electrical signal output quantitatively related to the relative humidity sensed; a voltage multiplier having separate inputs electrically connected to the outputs of said second voltage generator and said humidity sensor, respectively; and the outputs of said first voltage generator and said voltage multiplier being electrically connected to a summing junction, the bias signal output of said summing junction being electrically connected to said comparing means and said temperature sensor and said humidity sensor being located adjacent the inlet to said compressor.

24. The combination of claim **20** wherein the means for sensing and generating a pressure-response signal is a pressure transducer.

25. The combination of claim **19** wherein said adjusting means is a flow bypass having powered actuating means, said flow bypass being in flow communication with said steam generating means.

26. The combination of claim **19** wherein said adjusting means is a flow bypass having powered actuating means, said flow bypass being in flow communication with the outlet of said turbine, with said steam generating means and with mixing means located downstream in the turbine exhaust system.

27. In the operation of a gas turbine power plant in the steam injection mode wherein the following steps are performed: generating steam from liquid water; compressing atmospheric air to superatmospheric pressure; passing the compressed air to a combustion zone, where fuel is introduced and continuous combustion occurs; passing the generated steam to said combustion zone, and passing hot gases continuously from said combustion zone through an expansion zone where mechanical energy is abstracted in substantially greater amount than the mechanical energy absorbed in the compression step, the combination with said series of step of:

a. automatically controlling the flow of steam to said combustion zone by means of a control signal, said control signal resulting from the interrelation of a bias signal and a signal quantitatively comparable to the compressor pressure ratio.

28. The steps of operation of a gas turbine power plant as recited in claim **27** wherein the bias signal is a constant voltage signal.

29. The steps of operation of a gas turbine power plant as recited in claim **27** wherein the bias signal is quantitatively related to the ambient temperature.

30. The steps of operation of a gas turbine power plant as recited in claim **27** wherein the bias signal is quantitatively related both to the ambient temperature and to the ambient humidity.

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