United States Patent [19]

Niggemann

[11] **3,769,789**

[45] **Nov. 6, 1973**

[54] **RANKINE CYCLE ENGINE**

[75] Inventor: **Richard E. Niggemann,** Rockford, Ill.

[73] Assignee: **Sundstrand Corporation,** Rockford, Ill.

[22] Filed: **July 6, 1971**

[21] Appl. No.: **159,804**

[52] **U.S. Cl.** .... **60/36,** 60/107, 122/479 R

[51] **Int. Cl.** **F01k 25/00**

[58] **Field of Search** 60/36, 107; 122/479, 122/250

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Primary Examiner—Martin P. Schwadron
Assistant Examiner—H. Burks, Sr.
Attorney—Axel A. Hofgren et al.

[57] **ABSTRACT**

A power conversion system employing an organic fluid, toluene, including a supercritical heater for vaporizing the organic feed liquid, a turbine for expanding the vapor and providing a mechanical output, a regenerator for receiving superheated vapor from the turbine and preheating a portion of the feed liquid to the main heater, and an economizer built around the main heater for preheating a portion of the feed liquid, cooling the exiting combustion gases in the economizer and directing the preheated liquid to the main heater along with feed liquid from the regenerator.

12 Claims, 2 Drawing Figures

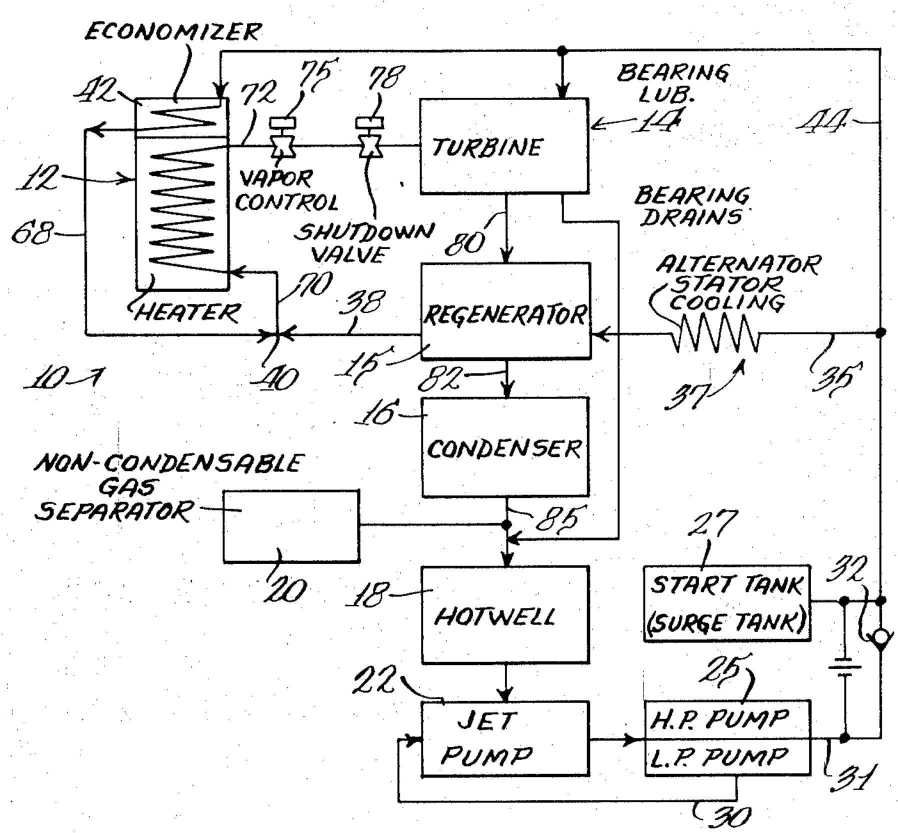


Fig. 1.

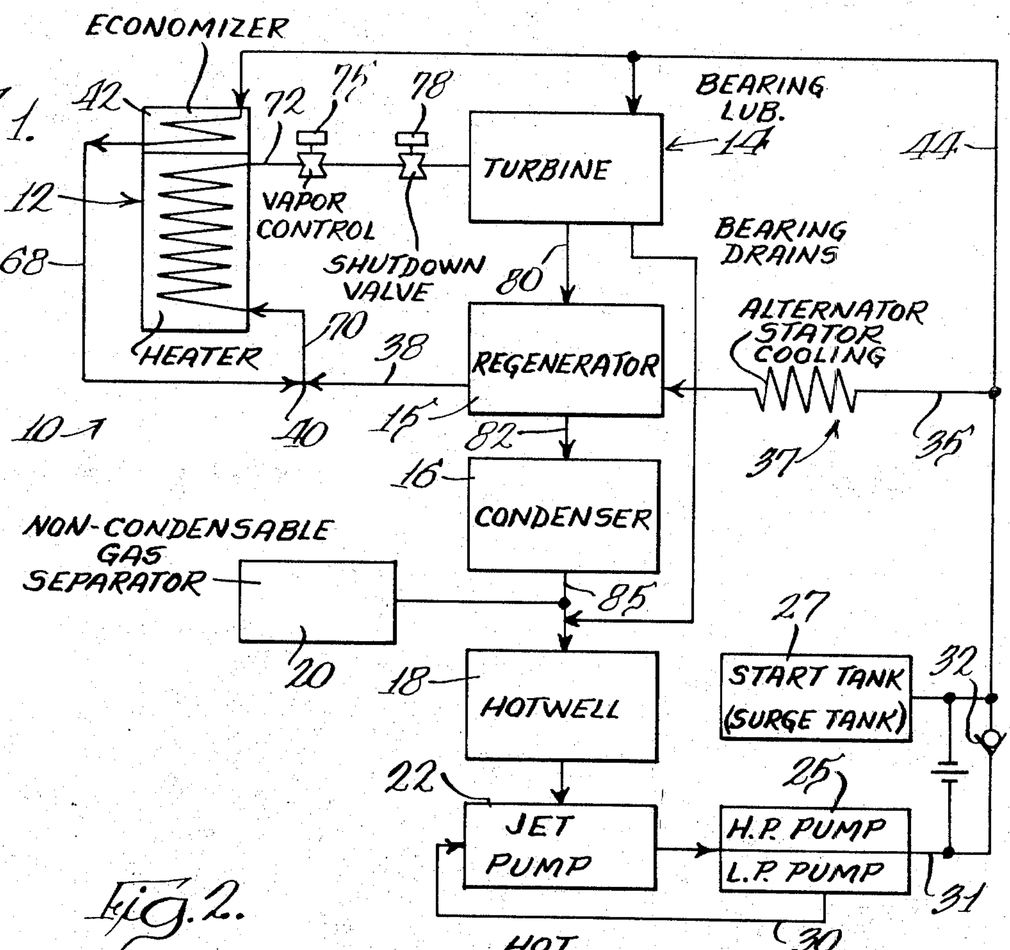
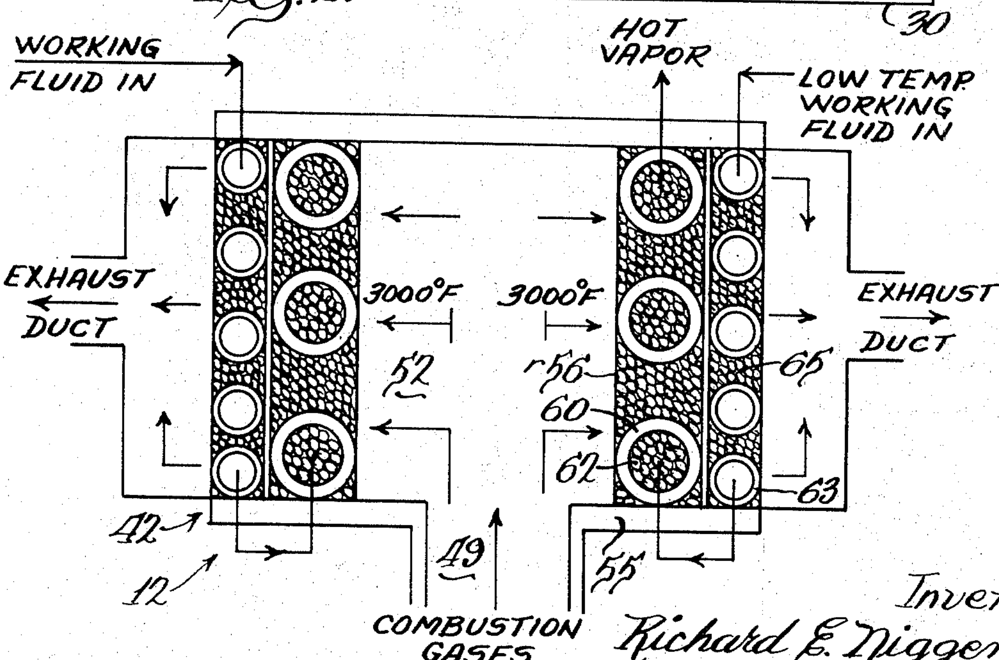


Fig. 2.



Inventor:
Richard E. Niggemann
By Hofgren, Wegner, Allen, Stellman & McCord
Att'ys

RANKINE CYCLE ENGINE

BACKGROUND OF THE PRESENT INVENTION

Power conversion systems have been provided in the past that employ organic fluids as the working fluid of the system. The use of an organic fluid in the Rankine Cycle has many advantages. Firstly, the positive slope of the saturated vapor line on the temperature entropy diagram results in dry expansion, without turbine erosion, and ability to operate at optimum speeds without wheel stress problems. Moreover, organic fluids provide a wide range of freezing points, thermal stability, system pressure level and cost, that enable one or more fluids to be particularly useful in a given power conversion system.

The present invention has applicability to the generation of mechanical or electric power from thermal power. In some applications there is a low temperature start-up requirement that would render undesirable any fluid that is frozen, slushy, or even highly viscous at the start-up temperature. Because of the high temperature degradation with the resulting noncondensable gas production in organic fluids, it is desirable that the organic fluid have good thermal stability.

Various organic fluids have been tested, and it has been found that many have disadvantages such as poor thermal stability, relatively high freezing points, and relatively low back pressures.

SUMMARY OF THE INVENTION

In accordance with the present invention, a power conversion system is provided employing toluene as the working fluid. Toluene is typical of the organic working fluids in that the vapor superheats upon expansion from a high to a low pressure. This results in a fairly low prime mover isentropic head and a relatively slow turbine tip speed so that a single stage turbine can be employed at its best efficiency safely within the turbine wheel stress limits.

The major components in the system are a supercritical heater-economizer, a single-stage turbine which may drive an alternator, a regenerator, a condenser and a feed pump. Toluene is the working fluid because of its −139° F. freezing point, its good thermal stability, its relatively high system pressure level which leads to compact heat transfer equipment, and its commercial availability.

The supercritical system cycle is selected so that the boiler becomes a liquid heater that precludes hydrodynamic instability, makes very high heat transfer rates possible without excessive wall temperatures, and results in a very small fluid inventory in the heater which minimizes fluid degradation and stored energy. The heater-economizer may be a compact cylindrical unit with the burner surrounded by the heat exchanger. The combustion gases pass over the heat absorbing surfaces of the heater, heating the mixed flows from the regenerator liquid outlet and the economizer liquid outlet to the vapor outlet temperature in the heater.

The combustion gases exit the heater section and are ducted through a surrounding economizer which further cools the gases, thus minimizing stack loss. About 20 percent of the feed liquid is fed to the economizer for preheating the same and reducing the hot gas exit temperature. The economizer feed liquid flow, preheated, is mixed with the other feed liquid (approximately 80 percent) of the system flow at the heater inlet. The 80 percent feed liquid flow passes from the feed pump outlet through the vapor-liquid regenerator. Because of the relatively high back pressure provided in the system through the use of toluene, the regenerator is quite small even though 20 percent of feed liquid bypasses the regenerator, requiring increased heat exchange capacity in place of unavailable liquid. The passing of 20 percent of the feed flow through an economizer allows a significant reduction in flue gas stack loss and a commensurate increase in plant efficiency.

The high pressure hot fluid from the heater outlet passes through a suitable vapor flow control device to a single stage impulse turbine. In an electrical power system, the turbine may be connected to drive either directly or through a gear box alternator and also a system pump. The turbine exhaust is passed through the vapor side of the regenerator where it preheats the feed liquid on its way to the heater. From the exit of the regenerator, the vapor is ducted to a condenser where the waste heat is rejected to the condenser coolant. In some applications, this waste heat can be utilized for heating and/or for driving an adsorption air conditioner.

A device is provided for separating the noncondensable gases that are present in the vapor in the condenser. This device confines the concentrated noncondensable gases in a separate container and prevents noncondensable gas accumulation in the condenser. If these gases were allowed to accumulate in the condenser such that the noncondensable gas partial pressure approached 1 percent of the total condenser pressure, the resulting reduced condensing coefficient would increase condenser pressure and reduce cycle efficiency. From the condenser the condensate drains into a hotwell. A jet pump draws condensate from the hotwell and increases pressure to system inlet pressure. The system pump has two outlets providing high pressure primary flow to the system and also low pressure flow to the jet pump. This minimizes the system pumping power. The main system flow is directed from the impeller pump to the regenerator and to the economizer.

Toluene was selected as the system working fluid for several reasons. It has a −139° F. freezing temperature which makes it desirable for cold starts. The thermal stability of toluene is greater than most organic fluids. Toluene has a high back pressure in an air cooled Rankine cycle power system, i.e., 8 psi at 200° F. The high back pressure in a toluene system permits a small high speed turbine, and a low volume and low weight regenerator, even with 20 percent of the liquid feed bypassed to the economizer. Toluene has thermal stability capabilities at temperatures well in excess of its critical temperature which allows the use of a compact, high heat flux, low fluid inventory supercritical vaporizer, where low inventory subcritical vaporizers (once-through boilers) are subject to hydrodynamic instability. The net result is a minimization of component size which is desirable from a packaging standpoint, and a maximization of plant efficiency due to the incorporation of the economizer utilizing regenerator bypass liquid and also due to the ability to operate at high turbine inlet temperature which is allowed by the basic good thermal stability of toluene and also because of the very low fluid inventory in the heater as a result of the supercritical vaporizer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of a power conversion system according to the present invention; and

FIG. 2 is a schematic illustration of a heater-economizer according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

As viewed in FIG. 1, a power conversion system 10 is seen to include, generally, a heater-economizer 12 which delivers toluene vapor to a turbine 14, with exhaust vapor from the turbine passing through a regenerator 15 decreasing the vapor temperature and increasing the temperature of the feed liquid to the heater-economizer 12. The vapor from the regenerator is condensed in condenser 16 and the condensate passes to hotwell 18 with the noncondensable gases being separated by separator 20. A jet pump 22 withdraws condensate from hotwell 18 and conveys the same to a pump 25 which supplies feed liquid to the system. A start tank 27 is provided for filling the system during start-up.

The jet pump 22 is provided to boost the pressure level of condensate in hotwell 18 up to a pressure which will prevent cavitation of the main system condensate pump 25. Jet pump 22 delivers fluid to main system pump 25 which may be a stepped impeller pump having two outlet diffusers at different radii. The inner diffuser provides fluid through line 30 to drive jet pump 25 and the outer diffuser provides fluid at 710 psi through line 31 to provide main system flow across check valve 32. From line 32, about 80 percent of the organic feed liquid toluene is conveyed through line 35 to cooling tubing 37 associated with the alternator (not shown) for cooling the stator thereof. The feed liquid exits the stator cooling device 37 in a typical system at about 212° F., since it takes up heat generated by machine losses.

Feed liquid at 212° F. is delivered to regenerator 15. The regenerator 15 may be a plate fin heat exchanger arranged in a folded counterflow configuration. Since the vapor is relatively dense and the flow rate is low, the heat exchanger requires a small vapor frontal area and long length in order to increase the heat transfer coefficient and at the same time maintain sufficient heat transfer surface. The fins may be made of wavy nickel metal, while separator sheets, top and bottom plates, side channels and headers are all made of stainless steel, resulting in a unit having a small volume and low weight.

Flow leaving the regenerator 15 on the liquid side through line 38 is at approximately 488° F., in an exemplary installation. Before entering the heater-economizer 12, the flow leaving the liquid side of the regenerator mixes at 40 with the preheated flow from economizer 42.

The economizer 42 is fed feed liquid through line 44, amounting to about 20 percent of the total system feed liquid. The heater-economizer is shown more clearly in FIG. 2 and is a supercritical once-through unit of compact design. High mass velocity through the heater insures high heat transfer thereby minimizing the hot spots. The vaporizer-economizer 12 includes combustion gas inlets 49 and 50 which receive combustion gases, a central combustion gas chamber 52 at about 3,000° F., for example, an annular heater section 55 and an annular economizer section 42. In the heater section 55, a brazed sphere matrix 56 is provided on the flue gas side to provide a large gas side heat transfer area. Heater tubes 60 are provided packed with a sphere matrix 62 to increase mass velocity and heat transfer coefficient.

The economizer section 42 includes liquid feed tubes 63 surrounded by a brazed sphere matrix 55 through which the flue gases pass.

In operation of a typical system embodying the invention, the feed liquid flowing through tubes 63 reduces the flue gas temperature from about 800° F. exiting from heater section 55 to approximately 400° F., thereby increasing cycle efficiency significantly. The pressure of the liquid exiting economizer 42 is equal to the pressure at the regenerator outlet line 38 to maintain the proper flow split (i.e., about 80 percent–20 percent). This is accomplished by matching the hydraulic impedance of economizer 42 with that of regenerator 15. The temperature of the liquid exiting the economizer in line 68 is approximately 490° F. This flow combines at 40 with the flow from regenerator line 38 and passes through line 70 to the heater tubes 60. Vapor leaving the super-critical heater section 55 exits the heater through line 72 somewhat above 700° F. and over 600 psia.

The high pressure, high temperature vapor in line 72 is controlled by a valve 75 decreasing the turbine inlet pressure somewhat, e.g., to 575 psia. The valve 75 is a speed responsive control for maintaining the speed of turbine 14 constant.

A shut-down valve 78 is provided which responds upon a predetermined temperature in heater-economizer 12 to open, permitting flow initiation to the turbine 14.

The turbine 14 is a single stage, supersonic, axial impulse, partial admission turbine. The organic working fluid toluene superheats upon expansion enabling high pressure ratios to be taken across the single stage of turbine 14 resulting in high cycle efficiencies. The deleterious effect of moisture formation in the turbine nozzles and passages which would otherwise cause blade erosion and lack of flow control is not present. The turbine 14 may, for example, run at 120,000 RPM.

Vapor exiting the turbine 14 at 6.29 psia at 527° F., as indicated by line 80, is directed to the vapor side of regenerator 15. Vapor exits the regenerator 15 through line 82 at 6.09 psia and 243° F. This vapor enters the condenser 16 where the vapor is condensed. The condenser 16 is a fin heat exchanger with the vapor condensing inside tubes and the cooling air flowing across the tubes and between the finned surfaces. A fan (not shown) is provided for directing ambient air across the tubes in condenser 16.

The degradation of toluene results in the generation of noncondensable gases and high boiling compounds. The noncondensable gas separator 20 is provided to prevent a decrease in the condenser heat transfer coefficients and to prevent an increase in the turbine back pressure which would otherwise reduce turbine power and cycle efficiency.

The condensed vapor flows through line 85 into the hotwell 18.

The start-up tank 27 includes a spring loaded valve (not shown) with a locking device for initiating flow from the start tank. During start-up, the burner air and fuel equipment (not shown) would be activated as would an igniter (not shown) delivering hot air to the heater-economizer **12**. Once the flame is proved, and the heater metal reaches a critical temperature, means are provided for releasing the locking device associated with start tank **27** and allowing the spring to force high pressure liquid to fill the high pressure lines **31, 35** and **44**. This also initiates flow to the bearings as indicated in FIG. **1**. While the heater metal and working fluid are coming up to temperature, the loop **30** from pump **25** to pump **22** is being filled by bleeding a small amount of high pressure fluid.

When the heater temperature reaches a certain level, the shut-down valve **78** is opened admitting flow to the turbine. The turbine then accelerates to 120,000 RPM in about 10 to 15 seconds. When the turbine is nearly up to speed, the system pump **25** will put out more pressure than the start tank **27** and the check valve **32** will open supplying system flow. When the turbine is up to speed, the condenser fan (not shown) is activated and batteries associated with the burner are recharged. When the condensate in hotwell **18** reaches a temperature near its normal operating point, the unit is ready to supply full load. This occurs rapidly since the system is relatively light and has a liquid inventory (toluene) of about 3 pounds. Start-up time can be further reduced if the alternator associated with turbine **14** is loaded in a programmed fashion to supply electric energy to heaters wrapped around the hotwell.

After system shut-down, a battery driven motor (not shown) is activated to reset the spring on start tank **27** to its prestart position. A crank may also be provided to compress the start tank spring.

While the system has been shown and described in connection with the provision of power to a turbine for driving an alternator in an electrical power supply system, it should be understood that utility of the invention is not limited to electrical systems, and it may be utilized to drive a turbine to supply power to an automotive vehicle transmission, for example.

I claim:

1. A power conversion system employing the Rankine cycle, comprising: a source of organic fluid feed liquid, a combustion gas heater for heating the feed liquid to a high pressure-high temperature state, a turbine connected to receive the hot fluid from the heater, a regenerator connected to receive exhaust vapor from the turbine, said regenerator being constructed to pass at least a portion of said feed liquid in out-of-contact heat exchange relation with vapor from said turbine, and an economizer forming a part of the combustion gas heater for passing at least another portion of the feed liquid in out-of-contact heat exchange relation to the combustion gases from the heater to reduce the gas exit temperature.

2. A power conversion system as defined in claim **1**, wherein the organic fluid is toluene.

3. A power conversion system as defined in claim **1**, including means for directing a minor portion of the feed liquid to the economizer, and means for combining the preheated feed liquid from the economizer and the preheated feed liquid from the regenerator and directing the combined liquid to the combustion gas heater.

4. A power conversion system employing the Rankine cycle, comprising; a source of organic feed liquid including a first feed liquid, a combustion gas heater for the feed liquid to raise the temperature and pressure thereof, a turbine constructed to receive vapor from the heater to drive the turbine in expansion, means for receiving and condensing the vapor from the turbine, and an economizer associated with and forming a part of the combustion gas heater for receiving at least another portion of the feed liquid in out-of-contact heat exchange relation with the hot combustion gases exiting the heater, and means for adding feed liquid from the economizer with said first feed liquid and directing the combined feed liquid to the combustion gas heater.

5. A power conversion system as defined in claim **4**, including a regenerator for preheating at least a portion of the feed liquid, said regenerator receiving superheated vapor from the turbine and passing the same in out-of-contact heat exchange relation with the feed liquid in the regenerator.

6. A power conversion system as defined in claim **4**, wherein said heater is a once through super-critical heater having a first main set of heater tubes generally annular in configuration, means directing the combustion gases outwardly across the main heater tubes.

7. A power conversion system as defined in claim **6**, wherein said economizer includes a set of tubes surrounding the heater tubes, said combustion gases being directed over said preheater tubes.

8. A power conversion system as defined in claim **4**, including a conduit means between the combustion gas heater and the turbine for conveying hot vapor to the turbine, and a vapor flow control valve in said conduit means for controlling the speed of the turbine.

9. A power conversion system as defined in claim **4**, including conduit means between the combustion gas heater and the turbine for conveying vapor from the heater to the turbine, and a start-up valve in said conduit means for passing vapor to the turbine when the heater reaches a predetermined temperature level.

10. A power conversion system as defined in claim **6**, wherein the organic fluid is toluene.

11. A power conversion system as defined in claim **1**, including means for directing a major portion of the feed liquid to the regenerator.

12. An organic Rankine cycle power conversion system, comprising, a hotwell for organic feed liquid, a pump for pumping fluid from the hotwell, a regenerator for preheating feed liquid, conduit means for directing a major portion of the feed liquid to the regenerator, a combustion gas heater, means for conveying feed liquid from the regenerator to the heater, an economizer forming part of the combustion gas heater including means for passing at least a portion of the feed liquid in out-of-contact heat exchange relation with exiting combustion gases to reduce the temperature of the gases, means to convey preheated liquid from the economizer to the heater, a turbine, means for conveying vapor from the heater to the turbine, means for conveying vapor from the turbine to the regenerator, a condenser, means for conveying vapor from the regenerator to the condenser, and means for conveying condensate from the condenser to the hotwell.

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