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METHOD AND APPARATUS FOR SUPERCRITICAL PRESSURE SYSTEMS
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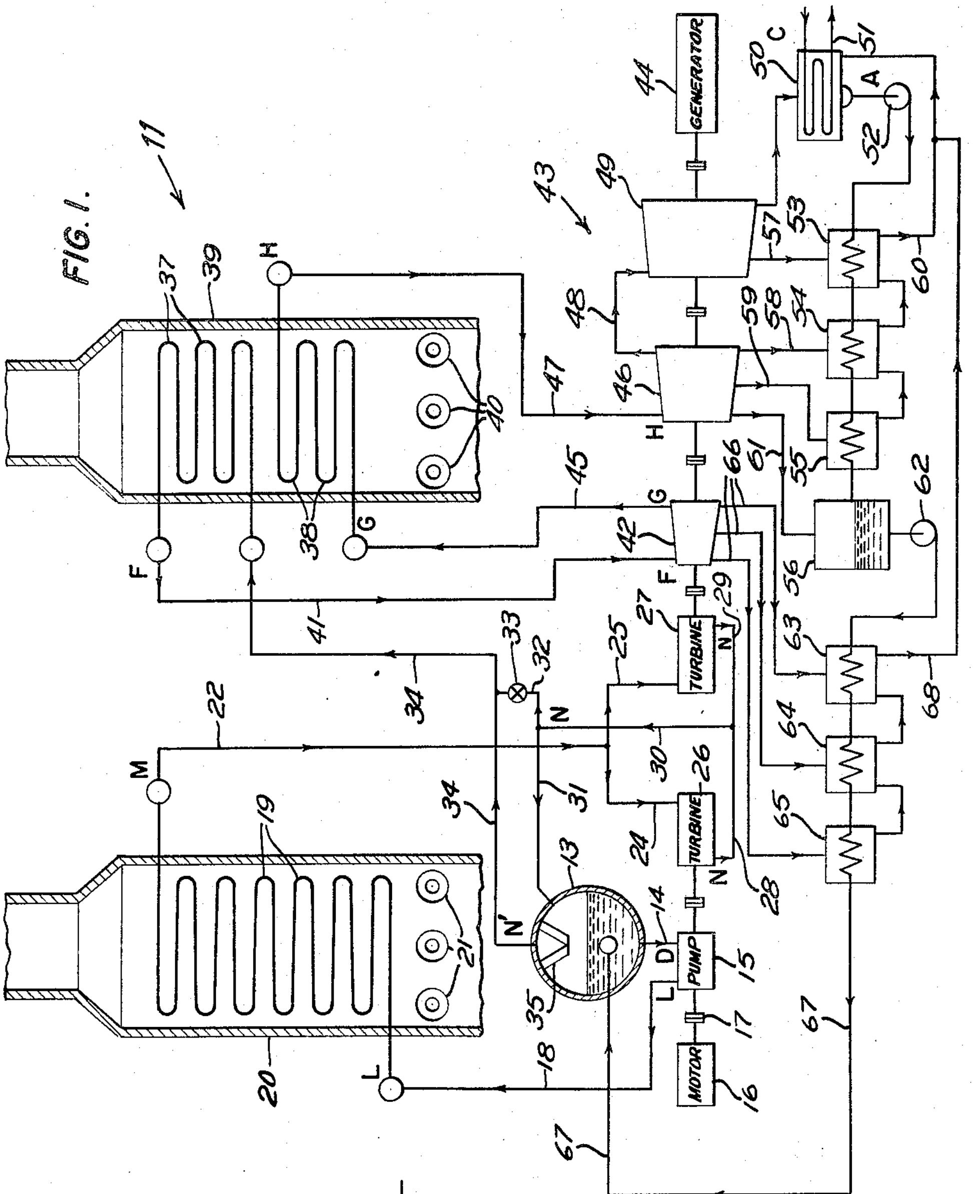


FIG. 1.

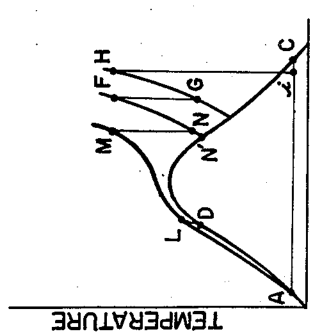


FIG. 2.

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# METHOD AND APPARATUS FOR SUPERCRITICAL PRESSURE SYSTEMS

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10 Claims. (Cl. 60—73)

This invention relates to power generation and more particularly to method and apparatus for supercritical pressure systems.

In applicant's copending application Serial No. 515,729, filed June 15, 1955, now Patent No. 2,802,114, issued August 6, 1957 for Method and Apparatus for the Generation of Power, there is disclosed a system in which a steam power cycle is divided into two parallel pressure stages or cycles, a conventional high pressure cycle and a supercritical pressure cycle. The fluid in the supercritical cycle is raised above the supercritical pressure, and thereafter, is reduced to below critical pressure for use in the conventional high pressure cycle. In the foregoing system, the fluid after being raised to supercritical pressure is heated, thence passed through a liquid turbine where it performs work, and accordingly is reduced in pressure. The fluid from the liquid turbine is discharged as steam, either in wet or superheated state, and is conducted to a vapor and liquid vessel. The steam in the vapor and liquid vessel then is delivered to a superheater, whence the superheated vapor is used to drive a vapor or steam operated turbine in the conventional high pressure cycle.

The present invention has for one of its objects to provide novel method and apparatus to increase the thermal efficiency of supercritical pressure systems at fractional loads on the vapor turbine.

The invention contemplates a supercritical pressure generation system which comprises a supercritical pressure stage and a conventional high pressure stage. A pair of separately fired furnaces are provided, one to house the water heating surface of the supercritical pressure stage and the other for the superheater and reheater elements of the high pressure stage. Liquid turbine means are employed and are operated by the supercritical pressure fluid from the water heating surface, which fluid is discharged from the turbine as superheated steam. During full or normal load on a steam turbine in the high pressure stage, all of the superheated steam from the liquid turbine is conducted to a vapor and liquid vessel where the steam is desuperheated prior to delivery to the superheater in the second furnace. When the steam turbine is operating at fractional loads, a substantial portion of superheated steam from the liquid turbine is conducted to the superheater while the remainder of superheated steam is delivered to the vapor and liquid vessel.

The above and other objects and advantages of the present invention will appear more fully hereinafter from a consideration of the detailed description which follows, taken together with the accompanying drawing in which two figures of the drawing illustrate one embodiment of the invention.

Fig. 1 is a diagrammatic illustration of a supercritical pressure system constituting an embodiment of the present invention; and

Fig. 2 is an entropy-temperature diagram showing the steam power cycle of the present invention.

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Referring now to the drawing, the numeral **11** designates a power generating system, which comprises a vapor and liquid or steam and water vessel **13** which is connected by a conduit **14** to deliver water to a high pressure pump **15**. Pump **15** is drivably connected to a start-up motor **16** by overrunning coupling means **17** and the pump has an outlet which communicates by way of a discharge circuit **18** with tubular elements, such as a water heating surface **19** disposed in a furnace **20**. Burner means **21** are provided in furnace **20** to heat the water in surface **19** and the outlet of the latter is in communication with a line **22**. The water passing through line **22** is subdivided for flow through a pair of conduits **24** and **25** which are connected with the inlets of a pair of liquid or water turbines **26** and **27**, respectively. The outlets of liquid turbines **26** and **27** are connected by conduits **28** and **29**, respectively, with a conduit **30** which joins with a second conduit **31** having an end in communication with the vapor space of vessel **13**. Conduits **30** and **31** also are connected to a bypass conduit **32** which has a valve **33** disposed therein for regulating flow of fluid to a vapor conduit **34** in communication with bypass conduit **32**. A moisture separator or drier **35** is arranged in the upper part of the vapor space and immediately below a vapor offtake which communicates with one end of vapor conduit **34**.

A superheater **37** and a reheater **38** are arranged in a second furnace **39** which is provided with burner means **40**. The inlet of superheater **37** is connected to the other end of vapor conduit **34** and the outlet of the superheater communicates by way of a conduit **41** with a high pressure stage **42** of a vapor or steam operated turbine **43**, connected for operating an electrical generator **44**. High pressure stage **42** is drivably connected to liquid turbine **27** and the exhaust of said stage **42** is conducted to the inlet of reheater **38** by a line **45**. A conduit **47** communicates the outlet of reheater **38** with the inlet of an intermediate pressure stage **46** of turbine **43** and the exhaust of stage **46** passes through a conduit **48** to the inlet of a low pressure stage **49** of turbine **43**. A condenser **50** receives the exhaust of stage **49** where the vapor is totally condensed by cooling coil **51**. Condensate from condenser **50** is delivered by a condensate pump **52** to a plurality of series connected extraction heaters **53**, **54** and **55**, the last mentioned of which communicates with a deaerating direct contact heater **56**. Heater **53** is supplied with steam from low pressure stage **49** by a line **57** while heaters **54** and **55** are supplied with steam from intermediate stage **46** by conduits **58** and **59**, respectively. The steam entering the heaters **53**, **54**, and **55** passes in indirect heat exchange relationship with the condensate flowing therethrough and the condensed steam from the heaters is conducted by a line **60** to the condenser **50**. Direct contact heater **56** receives steam from intermediate stage **46** through a line **61** and the steam entering heater **56** condenses in contact with the condensate from heaters **53**, **54** and **55**. A feed pump **62** has its suction side connected to receive the water in heater **56** for delivery to a plurality of series connected high pressure extraction heaters **63**, **64** and **65**. The water flowing through heaters **63**, **64** and **65** passes in indirect heat exchange relationship with steam delivered from high pressure stage **42** of turbine **43** by conduits **66**, whence the heated water flows into the liquid space of vessel **13** through a feed water conduit **67**. The condensed steam in heaters **63**, **64** and **65** is delivered to condenser **56** via a conduit **68** connected to heater **63** and line **60**.

During normal operation or full load on the steam turbine **43**, burner means **21** and **40** are fired at rates such as to provide for equal absorption of heat in furnaces **20** and **39** by the heat absorbing elements therein. Under this condition of operation, pump 15 is operated by liquid turbine 26 to raise the pressure of the water in water heating surface 19 to an economical excess above the critical value, as for example 5000 pounds per square inch. The supercritical pressure water from surface 19 then flows through line 22 and conduits 24 and 25 to liquid turbines 26 and 27. The firing rate of burner means 21 in furnace 20 is maintained at a level which provides a temperature value of the water in surface 19 which effects the discharge of fluid from liquid turbines 26 and 27 in the state of superheated steam, and, at a pressure substantially equal to the pressure in vapor and liquid vessel 13. The exhausted superheated steam then is conveyed via conduits 28, 29, 30 and 31 to the vapor space of vessel 13; valve 33 in bypass conduit 32 being closed under this condition of operation, whereby the steam does not flow through the bypass conduit. The steam entering vessel 13 loses its residual superheat and generates more steam after preheating the water in the vessel to saturation. Saturated steam is conducted from vessel 13 by vapor conduit 34 to the superheater 37 where the steam is heated to the desired superheated temperature. The superheated steam then flows through high pressure stage 42 of vapor operated turbine 43 and is discharged thereafter to reheater 38. From reheater 38, the steam flows through intermediate and low pressure stages 46 and 49, respectively, whence the steam is discharged to condenser 50.

Under fractional loads, or less than full load operation, valve 33 in bypass conduit 32 is opened an amount to allow a part, only, of the superheated steam from liquid turbines 26 and 27 to flow through line 31 into vessel 13, while the greater portion of the steam flows through bypass conduit 32. The quantity of steam entering vessel 13 is sufficient to heat all of the feedwater entering the vessel to saturation and provides saturated steam. The balance of the steam with its residual superheat flows from bypass conduit 32 into line 34 and in admixture with the saturated steam from vessel 13, whence the mixed vapors flow to superheater 37. By reason of the foregoing, the heat required in furnace 39 is greatly reduced and, as a result, the firing rate of burner means 40 in furnace 39 is reduced while the firing rate of burner means 21 is kept high. Under this condition of operation, the steam flowing through vapor line 34 is at a higher temperature than that flowing therethrough under full load operation of the system and includes saturated steam from vessel 13 and the superheated steam from bypass conduit 32. It is to be understood that it is not necessary to the utilization of the present invention that liquid turbine 27 impress the net energy of the supercritical pressure stage on the shaft of vapor turbine 43, because the liquid turbine may be employed elsewhere in the high pressure part of the system, as for example, to drive a second electrical generator or to operate a compressor. Furthermore, the present invention is operable with liquid turbine 27 alone since a variable speed motor may be substituted for liquid turbine 26 to drive pump 15.

The steam power cycle of the present invention is represented on the entropy-temperature chart of Fig. 2 where water is taken from condenser 50 at point *i* on the chart and is brought to point A where the condensate is raised to a high pressure and heated along line AD to its saturation temperature point D. The saturated liquid at point D is then raised to a pressure above the critical value by pump 15 along line DL and then heated in water heating surface 19 along line LM to a point M. Under full load operation of the steam turbine 43 the above critical fluid is expanded in liquid turbines 26 and 27 to a point N′ then brought to point N in vessel 13, whence it is heated in superheater 37 along the line NF to point F. The superheated vapor is expanded in high pressure stage 42 of steam turbine 43 along the line FG to point G whence the exhaust of such stage 42 is reheated at constant pressure in reheater 38 along line GH to point H. The reheated steam from point H then is expanded in intermediate and low pressure stages 46 and 49 of turbine 43 to condenser pressure along line H*i* to point *i* and the cycle is repeated after condensation to point A.



In tracing the steam power cycle of the present arrangement under fractional loads on the steam turbine the points of difference between full load and fractional load are at N and N′ on the chart. As indicated above, under full load operation all of the exhaust from the liquid turbines 26 and 27 was brought to a condition indicated at point N on the chart prior to flowing to the superheater 37 but at fractional load most of the superheated vapor from turbines 26 and 27 is brought to point N′, then heated at a constant pressure to point F where the same cycle is followed.

It will now be apparent that the present invention provides a novel system for obtaining maximum thermal efficiency in a supercritical pressure system operating at fractional loads. By conducting a substantial portion of the superheated steam from the liquid turbine directly to the superheater under fractional loads rather than to the vapor and liquid vessel where it would be desuperheated, greater thermal efficiency results in that the firing rate may be maintained high in the most efficient part of the generating system, that is, the supercritical pressure part.

Although one embodiment of the present invention has been illustrated and described in detail, it is to be understood that the invention is not limited thereto. Various changes can be made in the steps of the method and in the design and arrangement of the parts without departing from the spirit and scope of the invention as the same will now be understood by those skilled in the art.

What is claimed is:

1. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the steps comprising, compressing and heating a liquid to raise the pressure and temperature thereof to values above the critical point, decreasing the pressure of said liquid, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of said superheated vapor, conducting a greater portion of the superheated vapor to a heating element for heating the vapor, flowing the heated vapor to a vapor turbine to operate the latter, and condensing vapor discharged from the vapor turbine to a liquid.

2. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the steps comprising, compressing and heating a liquid to raise the pressure and temperature thereof to values above the critical point, decreasing the pressure of said liquid, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of said vapor in contact with the liquid before compression to heat the liquid, conducting a greater portion of superheated vapor to a heating element for heating the vapor, flowing the heated vapor to a vapor turbine to operate the latter, and condensing vapor discharged from the vapor turbine to a liquid.

3. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the steps comprising, compressing and heating a liquid to raise the pressure and temperature thereof to values above the critical point, decreasing the pressure of said liquid, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of said vapor in contact with the liquid before compression to heat the liquid and effecting thereby a saturated vapor, mixing the saturated vapor and the remainder of the superheated vapor, conducting the vapor mixture to a heating element for heating the mixture, flowing the heated vapor mixture to a vapor operated

turbine to operate the latter, and condensing vapor discharged from the vapor turbine to a liquid.

4. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the system comprising a furnace which includes a liquid heating means and a second furnace containing reheater elements, the firing rates in the furnaces being such that the elements absorb equal quantities of heat under full load operation of the vapor turbine, the steps comprising, compressing liquid to raise the pressure to a value above the critical point, firing the first furnace at a rate sufficient to heat and maintain the compressed liquid at above the critical point, decreasing the pressure of the liquid from the first furnace, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of said superheated vapor, conducting the remainder of the superheated vapor to the reheater elements in the second furnace to heat the vapor, reducing the firing rate in the second furnace while maintaining the firing rate in the first furnace at a high level, flowing the vapor from the reheater elements to the vapor turbine to operate the latter, and condensing vapor discharged from the vapor turbine to a liquid.

5. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the system comprising a furnace which includes a liquid heating element and a second furnace containing reheater elements, the firing rates in the furnace being such that the elements absorb equal quantities of heat under full load operation of the vapor turbine, the steps comprising, compressing liquid to raise the pressure to a value above the critical point, firing the first furnace at a rate sufficient to heat and maintain the compressed liquid at above the critical point, decreasing the pressure of the liquid from the first furnace, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of the vapor in contact with the liquid before compression to heat the liquid to a saturated state, conducting the remainder of the superheated vapor to the reheater elements in the second furnace to heat the vapor, reducing the firing rate in the second furnace while maintaining the firing rate in the first furnace at a high level, flowing the vapor from the reheater elements to the vapor turbine to operate the latter, and condensing vapor discharged from the vapor turbine to a liquid.

6. The method of operating a supercritical pressure power generating system to obtain maximum thermal efficiency under fractional loads on a vapor operated turbine, the system comprising a furnace which includes a liquid heating element and a second furnace containing reheater elements, the firing rates in the furnaces being such that the elements absorb equal quantities of heat under full load operation of the vapor turbine, the steps comprising, compressing liquid to raise the pressure to a value above the critical point, firing the first furnace at a rate sufficient to heat and maintain the compressed liquid at above the critical point, decreasing the pressure of the liquid from the first furnace, by causing it to do work, to below critical pressure and to a superheated vapor state, desuperheating a portion of the vapor in contact with the liquid before compression to heat the liquid to a saturated state and effecting thereby a saturated vapor, mixing the saturated vapor and the remainder of the superheated vapor, conducting the vapor mixture to the reheater elements in the second furnace to heat the vapor mixture, reducing the firing rate in the second furnace while maintaining the firing rate in the first furnace at a high level, flowing the vapor mixture from the reheater elements to the vapor turbine to operate the latter, and condensing the vapor discharged from the vapor turbine to a liquid.

7. A power generation system comprising a supercritical pressure stage and a subcritical pressure stage, a vapor and liquid vessel containing a liquid, means in said supercritical pressure stage connected to said vapor and liquid vessel for receiving and raising the pressure of the liquid to above its critical value, heating means connected to said last-mentioned means for receiving and heating said above critical liquid to raise the tempearture thereof above the critical point, liquid turbine means connected to said heating means for receiving and being operable by said above critical pressure liquid, said turbine means effecting the reduction of the pressure of said above critical liquid and exhausting the latter as a superheated vapor, a superheater, conduit means communicating the exhaust of the liquid turbine means with the vapor and liquid vessel and with the superheater to provide parallel flow of superheated vapor from the turbine exhaust means to the vapor and liquid vessel and the superheater, control means connected in said conduit means for proportioning the quantity of superheated vapor to the vapor and liquid vessel and to the superheater, and a vapor-operated turbine connected for receiving and being operable by the vapor from the superheater.

8. A power generation system comprising a supercritical pressure stage and a subcritical pressure stage, a vapor and liquid vessel containing a liquid, means in said supercritical pressure stage connected to said vapor and liquid vessel for receiving and raising the pressure of the liquid to above its critical value, heating means connected to said last-mentioned means for receiving and heating said above critical liquid to raise the temperature thereof above the critical point, liquid turbine means connected to said heating means for receiving and being operable by said above critical pressure liquid, said turbine means effecting the reduction of the pressure of said above critical liquid and exhausting the latter as a superheated vapor, a superheater, conduit means connecting the exhaust of the liquid turbine means with the vapor and liquid vessel and the superheater to provide parallel flow of superheated vapor from the turbine exhaust means to the vapor and liquid vessel and the superheater, valve means disposed in said conduit means for proportioning the amount of superheated vapor to the vessel and to the superheater, and a vapor-operated turbine connected for receiving and being operable by the vapor from the superheater.

9. A power generation system comprising a supercritical pressure stage and a subcritical pressure stage, a vapor and liquid vessel containing a liquid, means in said supercritical pressure stage connected to said vapor and liquid vessel for receiving and raising the pressure of the liquid to above its critical value, heating means connected to said last-mentioned means for receiving and heating said above critical liquid to raise the temperature thereof above the critical point, liquid turbine means connected to said heating means for receiving and being operable by said above critical pressure liquid, said turbine means effecting the reduction of the pressure of said above critical liquid and exhausting the latter as a superheated vapor, a superheater, a first conduit communicating the exhaust of the liquid turbine means with the vapor and liquid vessel, a second conduit connected to receive vapor from the vapor and liquid vessel for passage to the superheater, a bypass conduit in communication with said first conduit and with the superheater for diverting superheated vapor in said first conduit to said superheater, valve means for said bypass conduit for regulating the flow of superheated vapor therethrough, and a vapor turbine for receiving and being operable by the vapor from the superheater.

10. A power generation system comprising a supercritical pressure stage and a subcritical pressure stage, a vapor and liquid vessel containing a liquid, a pump in said supercritical pressure stage and connected to receive liquid from said vessel for raising the pressure of the

liquid above critical pressure, heating means connected to said pump for heating said above critical pressure liquid to raise the temperature of the liquid above the critical point, a liquid turbine connected for driving the pump and connected to said heating means for receiving and being operable by the above critical liquid from the heating means, a vapor-operated turbine, a second liquid turbine also connected to said heating means for receiving and being operable by the above-critical liquid, and connected for impressing the net energy of the supercritical pressure stage upon the vapor turbine to supplement the energy necessary to operate it, said first and said second liquid turbines effecting the reduction of the pressure of the above liquid turbines to exhaust it as a superheated vapor, a superheater, conduit means communicating the exhaust of the first and the second liquid turbines with the vapor and liquid vessel and the superheater for conducting in parallel flow the exhausted superheated vapor to the vapor and liquid vessel and to said superheater, control means connected in said conduit means for proportioning the amount of the exhausted superheated vapor to the vessel and to the superheater, and means for delivering the vapor from the superheater to the vapor turbine to operate the latter.

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