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PATENT SPECIFICATION

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(54) METHOD AND APPARATUS FOR THERMAL POWER GENERATION

(71) We, WESTINGHOUSE ELECTRIC CORPORATION of Westinghouse Building, Gateway Center, Pittsburgh, Pennsylvania, United States of America, a company organised and existing under the laws of the Commonwealth of Pennsylvania, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to an improved reheat cycle utilized with thermal power plants, where the discharge from a first expansion stage is reheated prior to expansion in a subsequent expansion stage.

A reheat thermal cycle has typically been used in many applications where, due to the type and magnitude of the power source, it is desirable to provide multiple expansion stages. Reheat cycles typically are used in conjunction with superheated fluids and in both once-through and recirculating cycles. A recirculating cycle utilizes recirculation of fluid between an evaporator and a drum. A basic reheat cycle superheats the utilization fluid in a superheater, expands it in a first turbine, reheats in a reheater, sometimes referred to as a resuperheater, and expands it in one or more subsequent turbines. A reheat cycle has been considered the most efficient and advantageous for large nuclear power plant application, particularly so for liquid metal cooled fast breeder reactors. Such reactors generally include a primary circuit circulating a liquid metal coolant such as sodium, an intermediate circuit circulating an intermediate fluid, typically similar to the primary liquid, and a utilization circuit or thermal cycle circulating a vaporizable fluid, such as water. Heat energy is transferred from the primary circuit to the intermediate circuit and then to the utilizaiton circuit, vaporizing and superheating the utilization fluid which drives the series of turbines to produce electric power. The evaporator, drum, and superheater may be separate components or combined units.

Use of a reheat cycle for such application, however, presents concerns as the high heat transfer rate of liquid metals causes severe thermal shock to metal structures, including the superheater and reheater, when system temperature changes occur. These temperature changes occur during plant startup and shutdown, as well as during load changes. To mitigate these thermal concerns, several prior art arrangements have been utilized and proposed which, in general, are based upon changing the relative intermediate fluid flow distribution between the superheater and reheater components. These are complicated active control systems which generally include valves and/or pumps operating primarily upon the intermediate fluid circuit, and which must balance flows and sense various parameter changes in all three fluid circuits. The prime control function of such systems is to split and vary the flow of intermediate fluid between the superheater and reheater components. While such control systems reduce the thermal cycling concerns, they do not eliminate it, and further controls such as steam attemperators are typically required. Further, the operational reliability of such control apparatus is a significant concern which can lead to failures and extensive and costly downtime.

It is therefore the principal object of the present invention to provide a reheat cycle arrangement for power generating plants having a primary coolant with a high sheet transfer rate which can accommodate temperature changes in the reheat vapor.

With this object in view, the present invention resides in a thermal power plant arrangement comprising a first circuit circulating a coolant between a heat source and a vapor generator and a utilization circuit circulating vaporizable fluid from said vapor generator as vapor through a first turbine, a reheater, at least a second turbine, and a condenser, the reheat vapor in said reheater being heated by the coolant, characterized in that a preheating means is disposed in the reheat vapor path upstream of the reheater, said preheating means being connected so as to heat said reheat vapor to a predetermined essentially constant value before said reheat vapor enters the coolant heated reheater.

This arrangement reduces thermal transients in the superheater and reheater upon changes in load. In a preferred embodiment, the vapor from the vapor generator is directed through a moisture-separator drum and the reheater is exposed to the vapor in the drum.

The invention will become more readily apparent from the following description of a preferred embodiment thereof shown, by way of example only, in the accompanying drawings in which:

Figure 1 is a flow schematic of a utilization circuit utilizing one embodiment of the instant invention;

Figure 2 is enthalpy-entropy diagram of a partial utilization circuit;

Figure 3 is a flow schematic of utilization circuit utilizing another embodiment of the instant invention;

Figure 4 is a flow schematic of part of a utilization circuit incorporating another embodiment of the instant invention; and

Figure 5 is also a flow schematic of part of a utilization circuit incorporating yet another embodiment of the instant invention.

Referring now to Figure 1, there is shown a utilization circuit incorporating the instant invention. The conduits 10 and 12 are respectively the main inlet and outlet of fluid from the heat source. For purposes of illustration, the heat source is presumed to be a sodium cooled fast breeder reactor, comprising a primary circuit circulating liquid sodium and an intermediate circuit also circulating liquid sodium in heat exchange relationship with the primary and utilization circuits. It is to be understood, however, that the heat source may be any system, fossil or nuclear, including one or more circuits circulating a fluid in heat exchange relationship with the utilization fluid in the utilization circuit. Similarly, the illustrative utilization fluid is water transformed to steam, although other vaporizable fluids may be utilized. The invention is particularly beneficial when utilized with a liquid metal heat source circuit due to the high heat transfer coefficient of liquid metals which, in the prior art, results in a greater magnitude of thermal cycling than in circuits utilizing other fluids.

The components shown in Figure 1 include a preheater 14, an evaporator 16, a steam drum 18, a superheater 20, a reheater 22, a first turbine 24 and a second turbine 26, typically steam turbines, a condenser 28, a feedwater pump 30, feedwater heaters 32, a recirculation pump 34, and conduits connecting these components in the manner shown. The preheater 14, evaporator 16, drum 18, and superheater 20, although performing distinct functions, may be combined units. The term "steam generation system" 36, when used herein refers to those components through which the source fluid is passed, such as the evaporator 16, superheater 20, and reheater 22.

In a typical recirculating superheat-reheat utilization circuit, and in accordance with the instant invention, the preheater 14 may or may not be incorporated. Typically in the prior art, flow from the heat source is serially through the superheater 20 and reheater 22 (sometimes referred to as a resuperheater) in parallel, through the evaporator 16, through the preheater 14 if utilized, and returned through conduit 12 to heat exchange relationship with the heat source. The main stream of vaporizable fluid, or water/steam flow, is typically passed serially through the preheater 14, evaporator 16, drum 18, supreheater 20, first turbine 24, reheater 22, second turbine 26, condenser 28, and pumped through the feedwater heaters 32 to the preheater 14 or alternatively to the drum 18, completing the circuit. A portion of the water condensed in the drum is recirculated through conduits 40 and 42 by the pump 34. The operation is such that the temperature in the drum 18 and the temperature of steam in conduit 35 (when arranged as in Figure 1) is maintained approximately constant. Flow through conduit 35 is also maintained approximately constant throughout the operating load range, primarily by varying the recirculation flow. A portion of the water condensed in the drum is also typically "blown down" through a nozzle 44, either continuously or intermittently, to maintain chemistry control.

The primary difference between the prior art and the preferred embodiment as shown in Figure 1 is the passage of the discharge from the turbine 24 through conduit 46 and through heat exchange means 45 in the drum 18, in heat exchange relation with the other fluids in the drum 18, desirably the condensed liquid. The heat exchange means 45 may be tubes, at least a portion of which are submerged in the condensed liquid within the drum 18. This places the fluid passed to the reheater 22 through conduit 48 at approximately the same temperature as the fluid passed to the superheater 20 through conduit 50.

Under such conditions, there need be no active controls to vary the relative flows between conduits 52 and 54 passing the heat source fluid, with changes in system power level. This passive system represents a significant advantage over the prior art, which does require complex control elements to vary the flows as necessary with power changes; this typically includes changing the relative flow distribution between the superheater 20 and reheater 22 units, by such controls as multiple valves, sensing devices, and other flow and temperature control means such as pumps and steam attemperators, which not only regulate parameters throughout the utilization circuit, but also through the heat source circuit or circuits. Further, as such control systems inherently have a time delay when varying parameters, significant thermal cycling of the system is involved, particularly in the reheater 22. The instant invention, however, passively alleviates thermal cycling and the necessity for complex active controls.

Dependent upon the type, size and number of components in the utilization circuit, the ratio of flows through conduits 52 and 54 and through conduits 48 and 50 will be fixed. This may be done by properly sizing the inside diameter of the conduits consistent with system requirements, and if necessary, fine tuning the flow during construction and testing by placing orifices or other passive flow control devices in the conduits. The flow is therefore desirably adjusted such that, throughout the operating load range, the ratio of sodium flow through conduit 52 to sodium flow through conduit 54 is approximately constant. The same is true for steam flow through conduit 50 and conduit 48.

To illustrate the advantages functioning of a system under such conditions consider, for example, a load change from one hundred percent power to fifty percent power. Whatever adjustments are necessary to reduce flows and other parameters throughout the utilization and heat source circuits, the ratios of flows through the superheater 20 and reheater 22 are automatically maintained. Similarly, as the fluid from the heat source enters the utilization circuit from a common path, as shown by the conduit 10, and the utilization fluid to the superheater 20 and reheater 22 is from a common temperature source, the drum 18, the temperatures are automatically matched. Also, operation of a recirculating system utilizing a drum is such that the drum 18 temperature remains relatively constant throughout the operating load range. As the basic control mechanism during a load change is to vary the flow rate of fluid through the heat source and hence through the heat source side of the utilization circuit components, thermal cycling of the reheater 22 is alleviated. In the prior art, when the turbines 24, 26 go to part load, the pressure and temperature of the cold reheat steam (in conduit 46) drops, which changes the relative loads between the superheater 20 and the reheater 22, and therefore, the temperature profile, resulting in undesirable thermal cycling. This is alleviated in the instant invention by automatically heating the cold reheat steam to an approximately constant temperature before entering the reheater 22.

This concept can be further exemplified by Figure 2, which shows a portion of a super-heat-reheat steam cycle represented on an enthalpy(h)-entropy(s), or Mollier diagram. The solid line represents the cycle at full load; the dotted line represents the cycle at half load. Point 1 illustrates the inlet of the evaporator 16. The feedwater is brought to saturation through the evaporator 16 and drum 18, and is then superheated in the superheater 20, represented by point 2 to point 3. It then expands in the turbine 24, point 3 to point A, and is reheated between points A and C, prior to subsequent expansion. In prior art systems, all of the reheating (points A to C) is performed by the reheater. In accordance with the instant invention, passage through the drum 18 performs the reheating from point A to point B, and the reheater 22 performs the further reheating, points B to C.

Three major advantages can be seen from the diagram. The first is the alleviation of thermal cycling of the reheater with load changes. With a load decrease, a prior art reheater receives cold reheat steam at a reduced temperature, the difference between A and A′. Similarly, on load increases, the inlet temperature rises from A′ to A. With the instant invention, however, a reheater receives steam which already has been heated in the drum, whatever the load, and therefore receives steam at approximately the same temperature, B or B′. At any operating load, the reheater raises the temperature of the steam to an approximately constant value, C or C′. To state the conditions in another manner, the reheater in the prior art must raise the steam temperature from A to C at full load, and from A′ to C′, a greater magnitude, at part load. The reheater of the instant invention must raise the temperature from B to C at full load, and from B′ to C′ at part load, an approximately same temperature differential. This leads to the second advantage, a smaller reheater. The reheater need only provide sufficient surface area to reheat the steam between points B and C or B′ and C′, while a prior art unit must be larger to reheat the steam between a point below point A′, and C′. From a cost standpoint, the reduction in reheater size may offset the cost of the added heat exchange means within the drum. The third advantage results from the first two. Alleviating the thermal cycling concern and reducing the preheater surface area significantly reduces any likelihood of reheater failure. With a liquid metal circulating heat source, ensuring integrity of the preheater is of prime concern, as the exothermic reaction upon mixing of a liquid metal, such as sodium, and water, could significantly damage the system. Although there will be some thermal cycling of the heat exchange means within the drum, the heat transfer is between water and steam, and not, for example, sodium and steam.

Figure 3 represents another embodiment of the instant invention, which also passively functions to alleviate reheater 22 thermal cycling upon load changes. As shown, flow of fluid from the heat source is unchanged. However, the flow path of the utilization fluid is modified such that the cold reheat steam from the first expansion 24 is passed through a separate heat preheater 53, shown as a tube and shell heat exchanger, prior to passage through the reheater 22. The main stream of utilization fluid therefore passes serially through the preheater 14, the evaporator 16, conduit 35 to the drum 18, then through a first flow path 54 in the preheater 53, through conduit 50′ to superheater 20, through the first expansion 24, through a second flow path 56 of the preheater 53, through conduit 48′ to the reheater 22, through the second expansion 26 and condenser 28, and pumped through the feedwater heaters 32, drum 18, and returned to the preheater 14. The particular flow path, as shown, passing from the feedwater heaters 32 through the drum 18 has been utilized in the prior art, and is not dependent upon the means utilized to heat the utilization fluid between the first expansion 24 and the reheater 22.

The performance and function of this embodiment is similar to that discussed above, and represents an alternate method for alleviating complex controls and thermal cycling of the reheater 22. Although the heat preheater 53 will be subject to some thermal cycling, it is a smaller and less costly component than the reheater 22. Further, it passes only the utilization fluid through both flow paths, not a liquid metal which typically has a higher specific heat than a utilization fluid, such as water. It should be noted that as the drum 18 raises the quality of the fluid exiting the evaporator 16, and not the temperature, another suitable flow path (not shown) would be serially from the evaporator 16, through the heat exchange means 53 and then the drum 18, and then to the superheater 20.

It should further be noted that the invention is compatible with typical modifications of the utilization circuit. These include such items as additional expansion stages, bleeding utilization fluid from the expansions to preheat to the evaporator 16, and utilizing blowdown fluid to preheat the feed, among many others. Other alternatives are also applicable to the above teachings. One, for example, which does provide the thermal cycling advantage but which, however, requires some active control, is shown in Figure 4. This embodiment utilizes direct mixing of some fluid from the superheater 20 with the cold reheat fluid from the first turbine 24, eliminating the need for the previously illustrated preheaters 45 and 53 in the form of heat exchangers. Although this requires an active steam control system, typically including a valve 58, active control of the heat source fluid is still eliminated. An advantageous means of mixing would be through a jet pump or steam ejector 60, by which the pressure of the fluid entering the reheater 22 could be increased as well as the temperature. This provides the added benefit of recovering part of the line pressure losses.

Another modification consistent with the instant teaching, similar to the embodiment shown in Figure 3, is shown in Figure 5. Here the source of heat for the cold reheat steam in the preheater 53 is the hot liquid from the drum 18. A portion of the liquid is passed from the drum 18 through an outlet nozzle 60 to the preheater 53, heating the reheat fluid prior to its entering the reheater 22. The liquid from the drum 18 may be pumped by pump 62 to the preheater 53. The fluid exiting the preheater 53 may then be returned to the drum for recirculation to the evaporator 16, or directed to the feedwater heaters.

WHAT WE CLAIM IS:—

1. A thermal power plant arrangement comprising a first circuit circulating a coolant between a heat source and a vapor generator and a utilization circuit circulating vaporizable fluid from said vapor generator as vapor through a first turbine, a reheater, at least a second turbine, and a condenser, the reheat vapor in said reheater being heated by the coolant, characterized in that a preheating means is disposed in the reheat vapor path upstream of the reheater, said preheating means being connected so as to heat said reheat vapor to a predetermined essentially constant value before said reheat vapor enters the coolant heated reheater.

2. An arrangement as claimed in claim 1, characterized in that said preheating means is connected so as to receive heating vapor from said vapor generator.

3. An arrangement as claimed in claim 2, wherein said circuit includes a superheater disposed, with regard to the vapor flow, downstream of said evaporator and a moisture-separator drum between said vapor generator and said superheater, characterized in that said preheating means is disposed within said drum and exposed to the moist vapor of essentially constant temperature in said drum so as to provide a vapor of essentially constant temperature to the coolant heated reheater.

4. An arrangement as claimed in claim 3, characterized in that said first circuit has a conduit arrangement so connected that said coolant passes in parallel through said superheater and said reheater and then collectively through said evaporator, and the main stream of said vaporizable fluid passes serially through said evaporator, said drum, said superheater, said first turbine, said preheating means, said reheaters, and said second turbine, said main

stream then being mixed with vaporizable fluid from said drum and returned to said evaporator.

5. An arrangement as claimed in claim 1, and including a superheater disposed downstream of the steam generator, characterized in that said preheating means consists of a vapor ejector mixing the reheat vapor with a controlled amount of superheated vapor from the superheater so as to provide a vapor of essentially constant temperature to the coolant heated reheater.

6. A thermal power plant arrangement substantially as hereinbefore described with reference to, and as shown in, the accompanying drawings.

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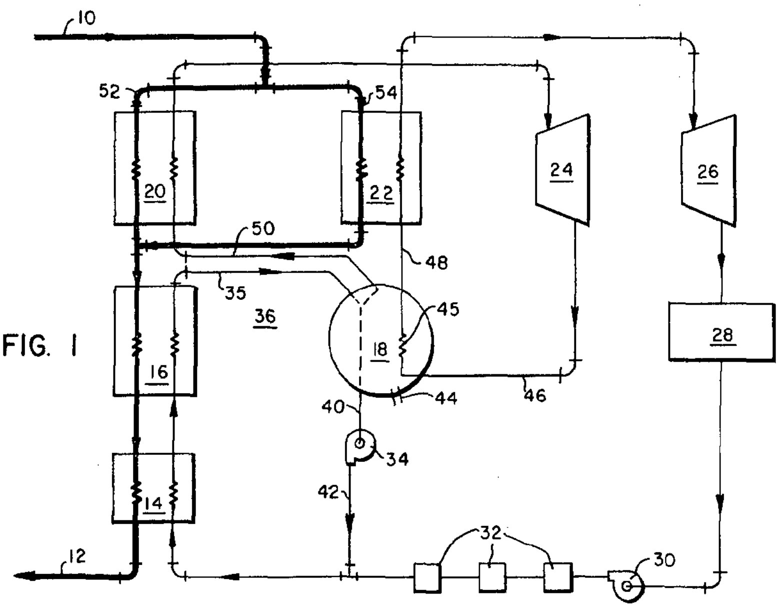
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FIG. 1

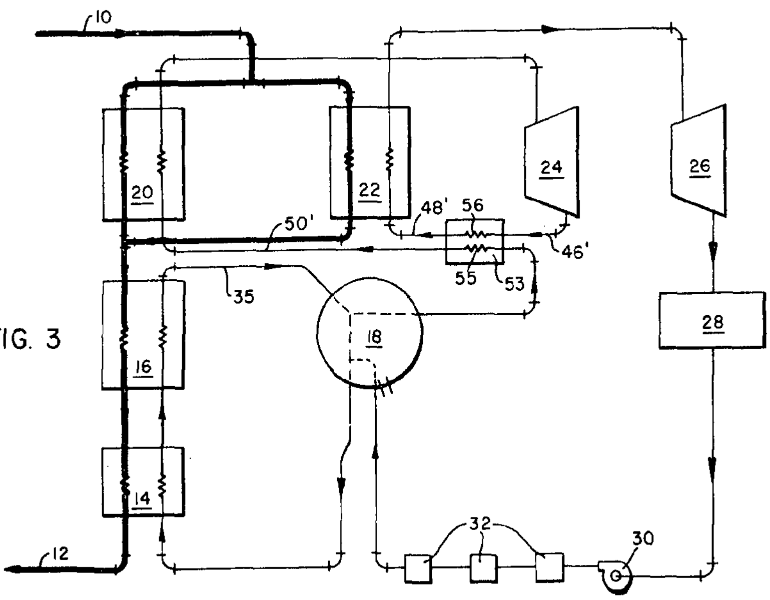
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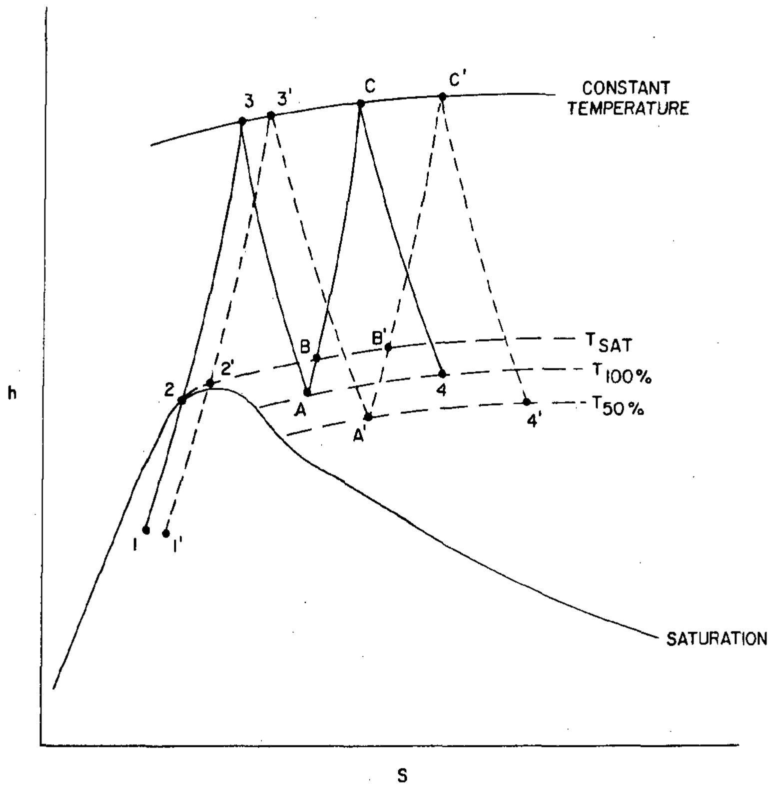
FIG. 3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SATURATION
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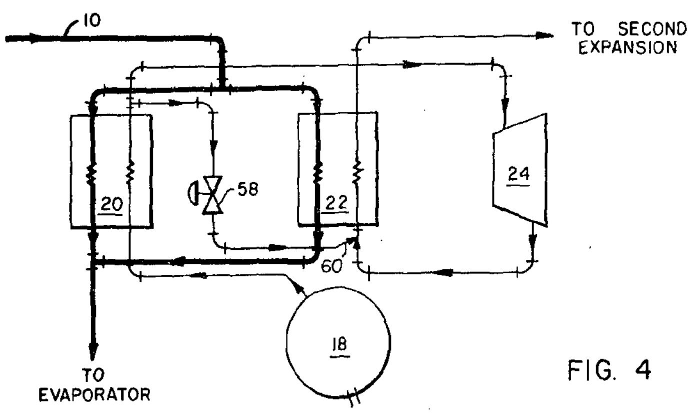
FIG. 2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TO SECOND EXPANSION
58
20
22
24
60
18
TO EVAPORATOR

FIG. 4

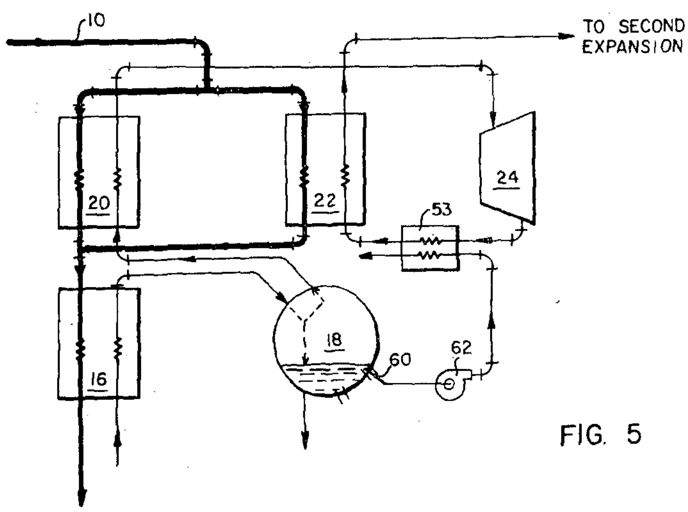
10
TO SECOND EXPANSION
20
22
24
53
16
18
60
62

FIG. 5