# United States Patent [19]

**Borsi et al.**

[11] **3,774,396**

[45] **Nov. 27, 1973**


[54] **METHOD AND APPARATUS FOR CONTROLLING A HEAT EXCHANGER**


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[30] **Foreign Application Priority Data**

Apr. 14, 1971 Germany .................. P 21 18 028.9

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[51] **Int. Cl.** .............................................. **F22b 35/18**

[58] **Field of Search** ...................... 60/105, 106, 107; 122/448, 451; 236/11, 14


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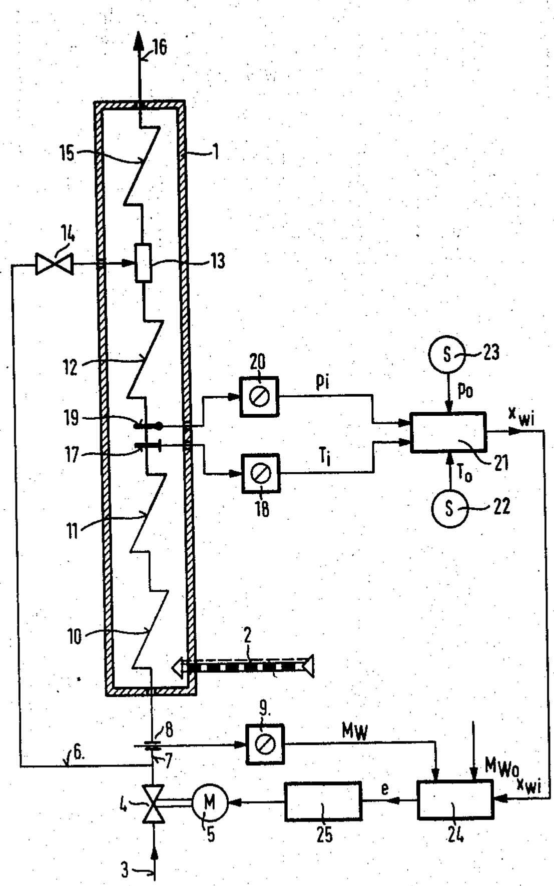
[57] **ABSTRACT**


A method of controlling a heat exchanger such as a force-flow boiler or the like is disclosed. The heat exchanger is supplied with the operating mediums of fuel and feedwater and generates slightly superheated steam. The method includes the steps of continuously determining the specific actual enthalpy of the slightly superheated steam and utilizing this enthalpy to control at least one of the operating mediums.

The apparatus for performing the method of the invention includes sensing devices for sensing the pressure and temperature of the slightly superheated steam. A computation circuit of the apparatus determines the specific actual enthalpy as an electrical quantity to control an adjusting device for controlling at least one of the operating mediums.


**22 Claims, 8 Drawing Figures**



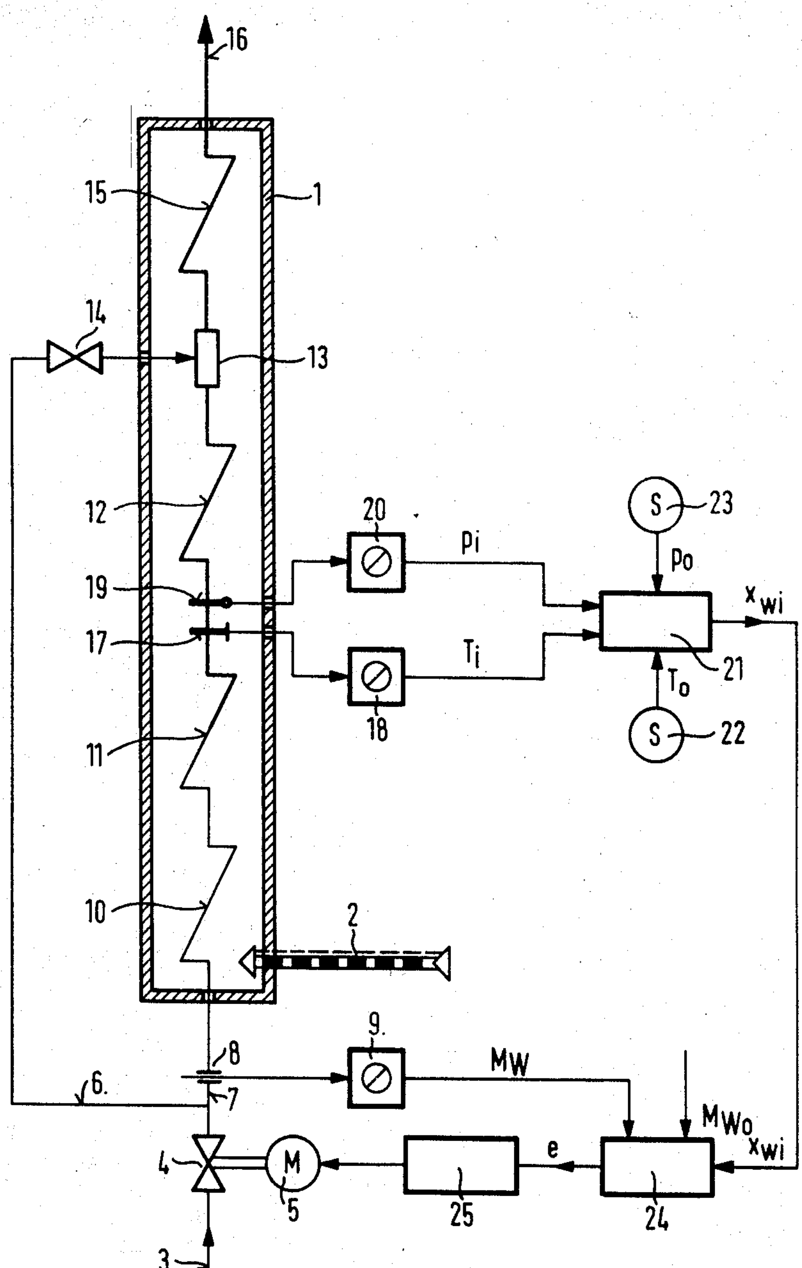

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Fig. 1

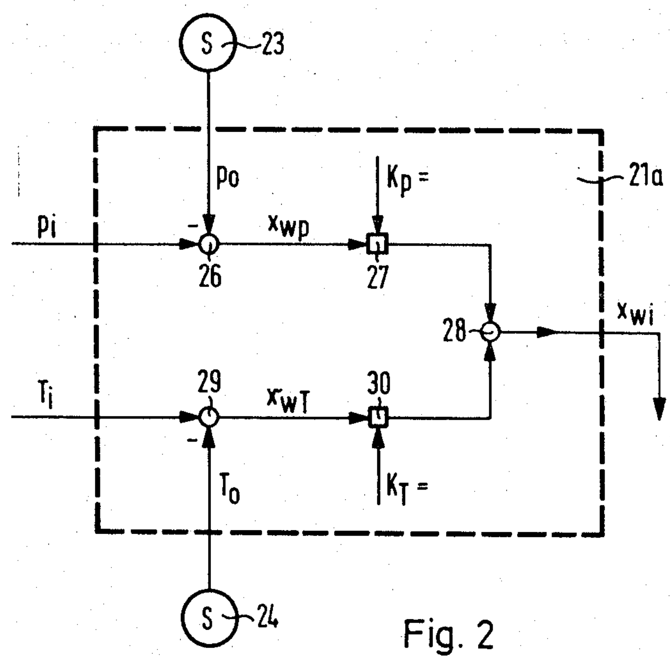
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Fig. 2

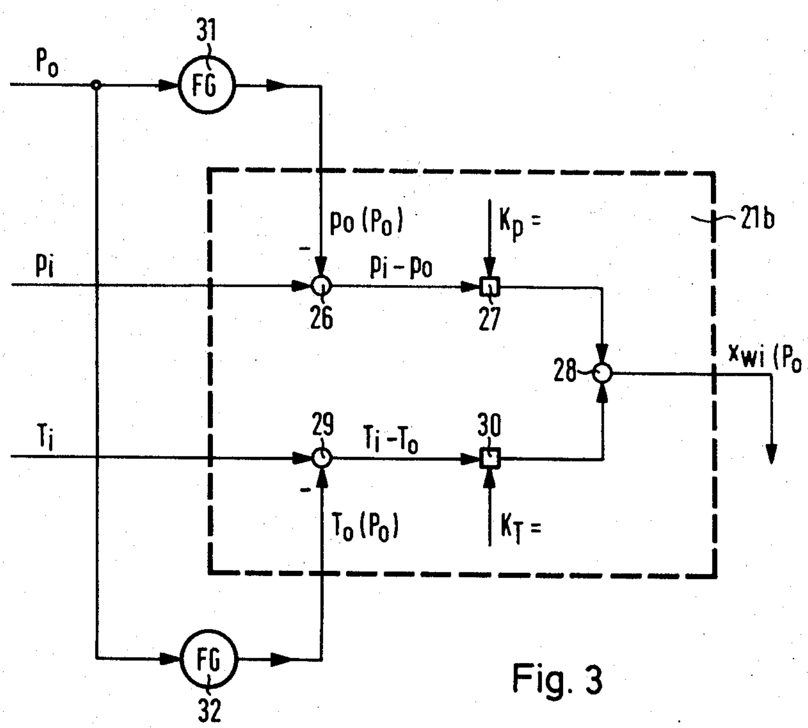
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Fig. 3

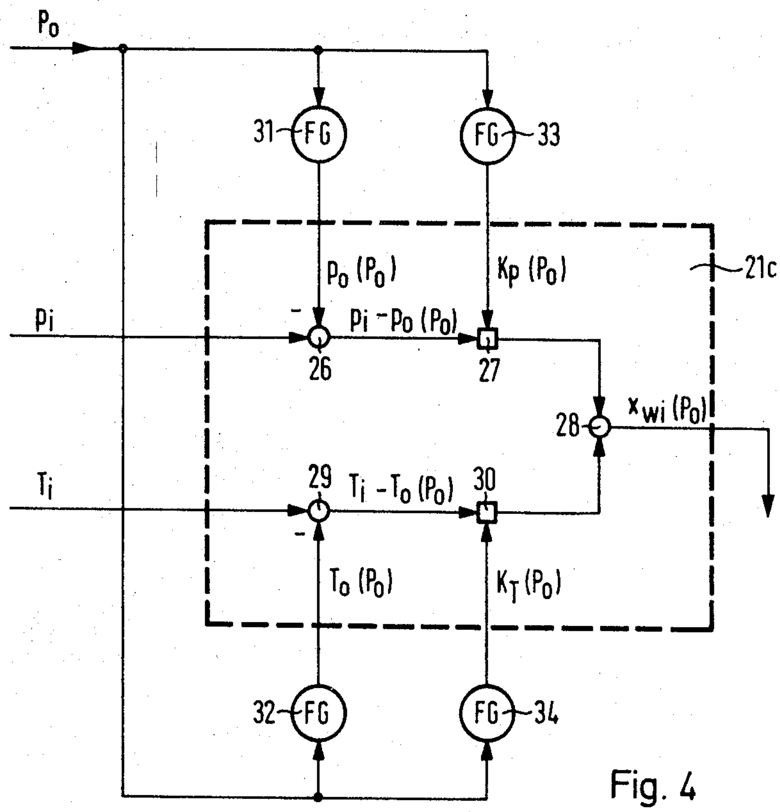
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Fig. 4

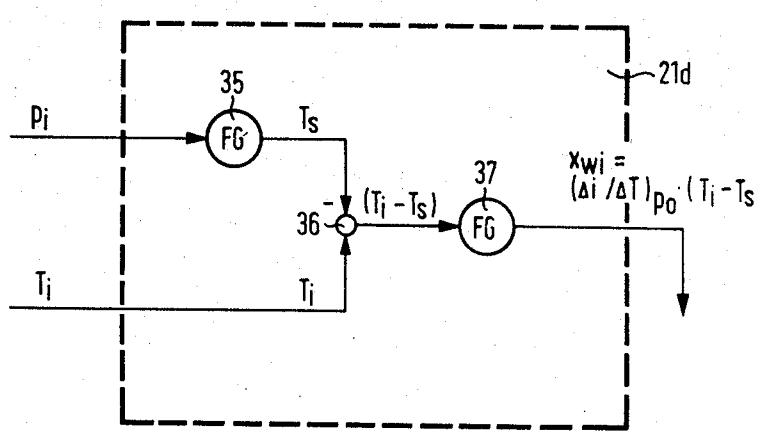
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Fig. 5

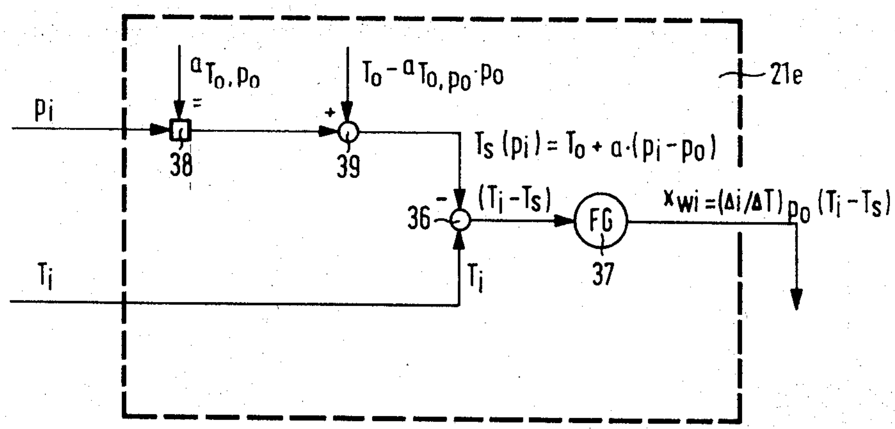


Fig. 6

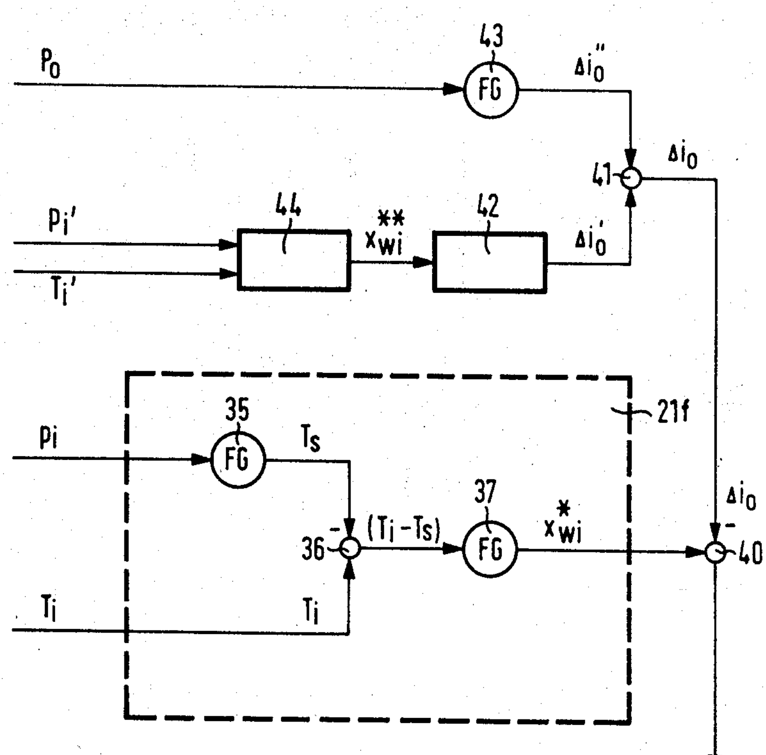


Fig. 7

$x_{wi} = x^*_{wi} - \Delta i_0$

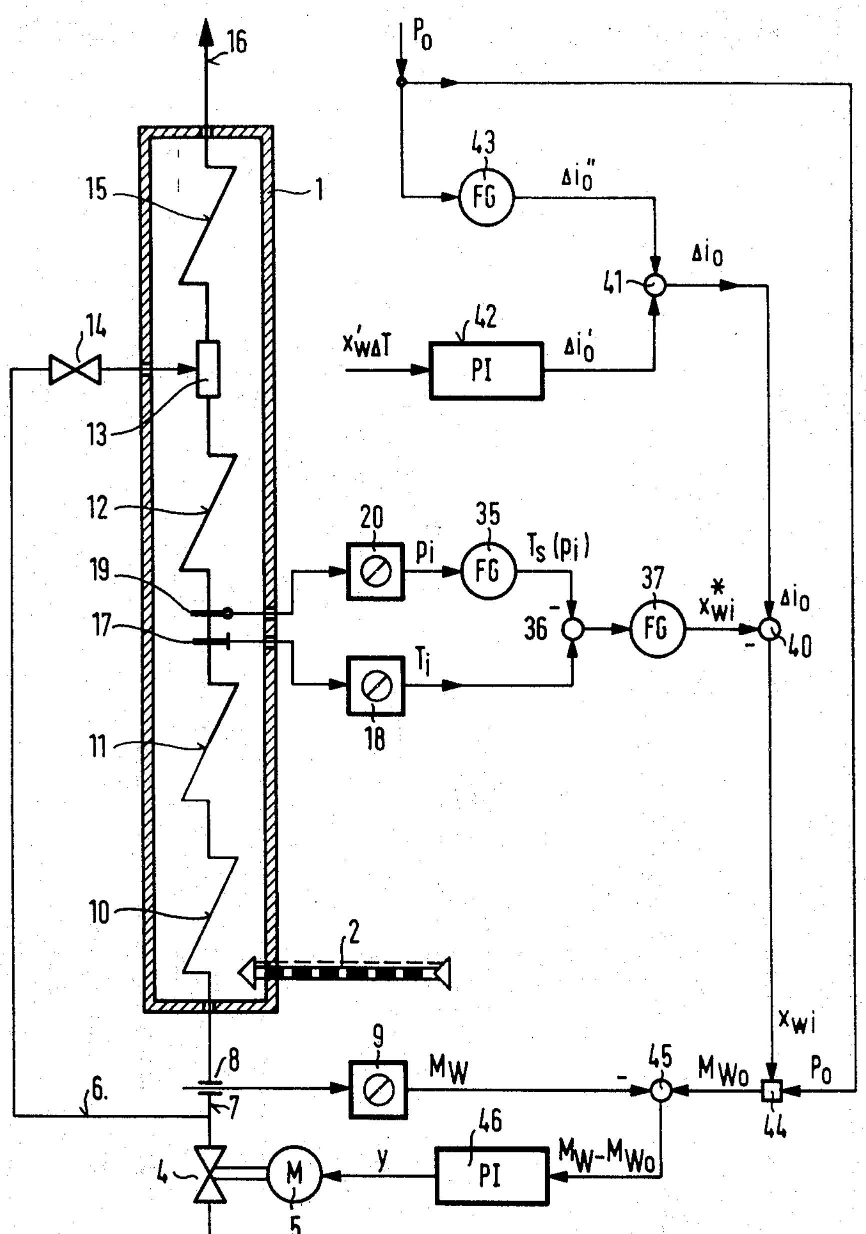
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Fig. 8

# METHOD AND APPARATUS FOR CONTROLLING A HEAT EXCHANGER

## BACKGROUND OF THE INVENTION

The invention relates to a method and apparatus for controlling a steam-generating heat exchanger such as a forced-flow boiler or the like. More particularly, the invention relates to a method and apparatus for controlling at least one of the operating mediums such as feedwater and fuel, supplied to the heat exchanger.

In a forced-flow boiler such as a Benson boiler, it is known to have a number of primary control loops for controlling, for example, the feedwater throughput, the output pressure of the steam delivered, the temperature of the steam generated and the pressure in the combustion chamber. It has now been found advisable for the control of forced-flow boilers to provide, additionally, a control loop which serves for the rapid detection and compensation of heating disturbances.

A supplementary control loop of this type is known, in which the actual temperature $T_i$ of the steam in the boiler is measured at a point where the steam is in a slightly superheated state. The term "slightly superheated state" refers here and in the following to steam at temperature T in the range of 370°C ± 40°C, at a pressure $p$ in the range of 180 atm ± 100 atm and having a specific enthalpy $i$ in the range of 640 kcal/kg ± 60kcal/kg.

In the known supplementary control loop, the measurement point for the actual temperature $T_i$ is at the output of the evaporator. Measurements have shown that at this location the most advantageous positioning transfer function is obtained. Normally, the most advantageous disturbance transfer function also is obtained at this location. Specifically, a heating disturbance that is caused by a change in the energy output of the energy carrier is noted most quickly at the output of the evaporator, the energy carrier being, for example, oil, gas or coal. The actual temperature $T_i$ determined here is compared with a predetermined reference temperature $T_o$, and the temperature difference $(\Delta T + T_i - T_o)$ obtained, is used as the correction quantity for a subordinated control circuit, for example, for controlling the feedwater throughput. Because of this known measure, a certain degree of control of the slightly superheated steam has been previously possible in a once-through forced-flow boiler when heating disturbances occur.

It has now been found that a supplementary control loop configured in the foregoing manner has several shortcomings.

First, from an inspection of the enthalpy-temperature diagram ($i$-T diagram) for water, it has been found that a temperature change ΔT of the slightly superheated steam at the output of the evaporator caused, for example, by a heating disturbance is not proportional to the heating disturbance. The change of the output quantity of the control loop, which is proportional to this temperature change ΔT, leads to a proportional change of the working quantity, for example, to a proportional change $\Delta M_W$ of the feedwater throughput, but not to a proportional correction of the heating disturbance. This nonlinearity exists also if the pres-sure $p$ of the superheated steam is kept constant because the specific heat $C_p$ of slightly superheated steam is temperature-dependent for constant pressure. The following two examples will illustrate this:

### Example 1

Assume that the slightly superheated steam is in a first state $a$ defined by the temperature $T_a = 370$°C and the pressure $p_a = 200$ atm. From the i-T diagram, the steam has an enthalpy of $i_a = 610$ kcal/kg. An increase of the enthalpy $\Delta i_a = 30$ kcal/kg (for example, because of a heating disturbance) results in a temperature change $\Delta T_a = 10$°C for a fixed pressure $p_a$. A calculation shows that this temperature change $\Delta T_a$ can be compensated by a relative change $\Delta M_W/M_W$ of the feedwater throughput $M_W$ of 8 percent.

### Example 2

Assume that the steam now is in a second state $b$ defined by the temperature $T_b = 400$°C and the pressure $p_b = 200$ atm. The pressure has therefore not been changed relative to the first state $a$ $(p_a = p_b)$. An enthalpy of $i_b = 680$ kcal/kg is read from the i-T diagram. If this value is likewise increased by $\Delta i_b = 30$ kcal/kg, a temperature change $\Delta T_b = 27$°C results. In order to fully compensate for this temperature change $\Delta T_b$, a relative change $\Delta M_W/M_W$ of the feedwater throughput of also 8 percent is required because $\Delta i_a = \Delta i_b$.

These two examples show that even if the pressure is kept constant $(p_a = p_b = \text{const})$ in the case of an enthalpy change, a given relative change $\Delta M_W/M_W$ (for example 8 percent) of the feedwater throughput $M_W$ results in a different temperature change ΔT depending upon the state $a$ or $b$ of the slightly superheated steam. This relative change $\Delta M_W/M_W$ is brought about by a changed adjustment of the positioning valve. Furthermore, it follows from the i-T diagram that the temperature change ΔT depends in a nonlinear manner on the output quantity of the known supplementary control loop. From this, it follows that the gain of the controlled system is a function of the state of the steam, so that linear control, for example, via the control of the feedwater flow, is not possible.

A further disadvantage of the control method customarily used up to now is that changes in the state of the slightly superheated steam, which are not caused by heating disturbances, are also picked up as being such a heating disturbance and are erroneously compensated for by a change of the adjustment of the positioning member, for example, for the feedwater throughput. A temperature change ΔT in the slightly superheated steam in a heat exchanger can be caused not only by a heating disturbance; it can also be caused by a pressure change $\Delta p$ that is produced by a change in the steam consumption. Another example will serve to illustrate this.

### Example 3

The slightly superheated steam is assumed to be in the state $c$ defined by the temperature $T_c = 370$°C, pressure $p_c = 180$ atm, and specific enthalpy $i_c = 650$ kcal/kg. A pressure change of $\Delta p = 15$ atm, which may be caused, for example, by a change in steam withdrawal, leads with no change in the heating, that is, with constant enthalpy $i_c$, to a temperature change $\Delta T_c = 10$°C which, although not caused by a heating disturbance, automatically results in an unnecessary control action in the known control loop.

Pressure changes of this kind occur very frequently, especially when the steam generator is operated at varying pressure, that is, if the pressure $p_i$ changes with a change in load, or if its storage capacity is heavily drawn upon or more specifically, if the steam output delivered is predetermined over a large pressure range, for example, by a superordinated control of the electric power output of a connected turbogenerator.

## SUMMARY OF THE INVENTION

It is an object of the invention to provide an improved method of control for a heat exchanger such as a once-through, forced-flow boiler or the like. Subsidiary to this object it is an object of the invention to provide such a method for detecting and compensating for an operational disturbance such as a heating disturbance.

It is another object of the invention to provide a control method for a heat exchanger for controlling at least one of the operating mediums of fuel and feedwater supplied to the heat exchanger in response to a heating disturbance.

It is still another object of the invention to provide an apparatus for carrying out the above method objects.

According to the invention, the foregoing method objects are realized by continuously determining the specific actual enthalpy ($i_i$) of the slightly superheated steam in the heat exchanger and using this quantity as an auxiliary control quantity.

A preferred embodiment of the invention includes continuously measuring the pressure ($p_i$) and temperature ($T_i$) of the slightly superheated steam at a location of the heat exchanger. The measured actual values of pressure ($P_i$) and temperature ($T_i$) are supplied to a computation circuit for determining the control deviation ($x_{wi}$) of the specific actual enthalpy ($i_i$) from the reference value of the enthalpy ($i_o$), and the control deviation ($x_{wi}$) of the specific enthalpy is used as a correction quantity for the input quantity of an adjusting means. The adjusting means can include a controller to which the input quantity is supplied. The adjusting means further can include positioning equipment connected to the controller. The positioning equipment can, for example, in turn include a valve for adjusting the supply of feedwater to the heat exchanger as well as a positioning device connected to the valve for adjusting the position of the valve. It is also possible to provide a similar arrangement for adjusting the supply of fuel to the heat exchanger.

If the positioning actions of a positioning device are derived in the manner indicated from the control deviation $x_{wi}$ of the specific enthalpy, the relative loop gain is constant at any operating point $T_o$, which is considered as a special advantage. If, for instance, a feedwater positioning valve is used as the positioning member, the quantity $(\Delta i/(\Delta M_W/M_{Wo}))$ is constant for any temperature $T_o$. Expressed otherwise, an enthalpy change $\Delta i$ is directly proportional to the change $\Delta M_W/\Delta M_{Wo}$ of the feedwater flow. In contrast to the known control method, in which only the actual temperature $T_i$ of the slightly superheated steam is measured, there occurs therefore no nonlinearity in the gain of the temperature control loop (operating point and drive dependence).

In a further embodiment of the method according to the invention, the control deviation $x_{wi}$ of the specific enthalpy is determined from the measured actual values $p_i$ and $T_i$ and from predetermined reference values for the pressure $p_o$ and for the temperature $T_o$.

The specific enthalpy $i$ is the determining factor for the equilibrium between the heat supply and the feedwater flow and is an unambiguous function of the temperature T and the pressure $p$:

$$i = i\ (p,\ T) \tag{1}$$

This function is nonlinear and can be stated explicitly in the range of slight superheating considered only by complex empirical approximation equations, for example, by Koch's state or condition equation. The derivation of the control deviation $x_{wi}$, however, can be obtained generally on the basis of the following considerations:

The total differential of the function (1) is formed:

$$di = (\delta i/\delta p)_{T_0}\, dp + (\delta i/\delta T)_{p_0}\, dT \tag{2}$$

For the deviation $(i - i_o)$ from the desired reference state, which is to be defined by the quantities $i_o$, $T_o$ and $p_o$, the following approximation is obtained:

$$i - i_o \approx (\delta i/\delta p)_{T_0} \cdot (p - p_o) + (\delta i/\delta T)_{p_0} \cdot (T - T_o) \tag{3}$$

With the definitions customary in control engineering: $x_{wi} = i_i - i_o$ representing the control deviation of the specific enthalpy, $x_{wp} = p_i - p_o$ the control deviation of the pressure, and $x_{wT} = T_i - T_o$ the control deviation of the temperature, the following equation is obtained:

$$x_{wi} = (\delta i/\delta p)_{T_0} - x_{wp} + (\delta i/\delta T)_{p_0} \cdot x_{wT} \tag{4}$$

The quantities $i$, $p$ and $T$ denoted with the subscript $i$ are the actual values. For small changes about a fixed operating point ($i_o$, $p_o$, $T_o$), the partial differential quotients contained in equation (4) can be considered as constants. If one thus sets $K_p = (\delta i/\delta p)_{T_0}$ and $K_T = (\delta i/\delta T)_{p_0}$, the defining equation for the control deviation of the specific enthalpy is obtained as:

$$x_{wi} = K_p\, x_{wp} + K_T x_{wT} \tag{5}$$

Accordingly, a further embodiment of the method for control on a heat exchanger according to the invention is therefore given by providing that the control deviation $X_{wi}$ of the specific enthalpy is calculated according to equation (5) above, wherein $K_p$ and $K_T$ are predetermined values and wherein $x_{wp}$ denotes the control deviation $(p_i - p_o)$ of the pressure and $x_{wT}$ the control deviation $(T_i - T_o)$ of the temperature.

If the control deviation $x_{wi}$ is to be determined for an extended operating range, the parameters $K_p$ and $K_T$ can no longer be considered as constants. A further embodiment of the method according to the invention consequently provides for this case and the values $K_p$ and $K_T$ are controlled as functions of the load, particularly in dependence on the reference value $P_o$ of the electric power of a turbogenerator connected to the heat exchanger. Correspondingly, the reference value $p_o$ of the pressure and the reference value $T_o$ of the temperature can also be controlled. In this manner, control in the varying pressure mode can also be realized. In the special case that all four values $K_p$, $K_T$, $p_o$ and $T_o$ are simultaneously controlled as functions of the load, for example, of the reference value $P_o$ of the electric power of the turbogenerator, equation (5) assumes the form:

$$x_{wi} = K_p(P_o)\,(p_i - p_o(P_o)) + K_T(P_o)\,(T_i - T_o(P_o)) \quad (6)$$

The enthalpy deviation $x_{wi}$ can therefore be determined for this special case according to equation (6).

In the following, further possibilities for the continuous determination of a small control deviation $x_{wi}$ from the operating point A (reference state $i_o$, $p_o$, $T_o$) of the slightly superheated steam will be illustrated. Again, the starting point is the total differential quotient, equation (2), of the specific enthalpy $i$. Since the following applies as general:

$$(\delta i/\delta T)\cdot(\delta T/\delta p)\cdot(\delta p/\delta i) = -1 \quad (7)$$

there is obtained after substitution into equation (2) and considering a small control deviation $x_{wi} = i_i - i_p$, in approximation:

$$x_{wi} = (\Delta\, i/\,\Delta\, T)_{p_0}\cdot(T_i - (T_o + (\delta T/\delta p)_{i_0}\cdot(p_i - p_o))) \quad (8)$$

The expression in the bracket on the right-hand side in equation (8) is a pressure-dependent quantity, which can be considered as a pressure-dependent auxiliary or reference temperature $T_s$:

$$T_s = T_s\,(p_i) = T_o + a_{T_0\,,\,p_0}\,(p_i - p_o) \quad (9)$$

with

$$a_{T_0\,,\,p_0} = (\delta T/\delta p)_{i_0}. \quad (10)$$

The approximation consists in the fact that instead of the curve of equal heat content $i_o = i_o\,(p,T) =$ constant, its tangent at the operating point A ($i_o$, $p_o$, $T_o$) is used for forming the reference value.

By setting

$$x'_{wT} = T_i - T_s = T_i - (T_o + a_{T_0\,,p_0}(p_i - p_o)) \quad (11)$$

one obtains for the control deviation $x_{wi}$ of the specific enthalpy:

$$x_{wi} = (\Delta\, i/\,\Delta\, T)_{p_0}\cdot(T_i - T_s)$$
$$= (\Delta\, i/\,\Delta\, T)_{p_0}\cdot x'_{wT}\,. \quad (12)$$

The quantity $(\Delta i/\,\Delta T)_{p_0}$ therein cannot be assumed as constant; it depends on the magnitude and the sign of $x'_{wT} = T_i - T_s(p_i)$. This will be illustrated by an example:

Example 4

Let the slightly superheated steam be in a state d defined by the pressure $p_d = 220$ atm and by the specific enthalpy $i_d = 630$ kcal/kg. When the steam is subjected to a negative temperature change of $\Delta\, T_d = -7°C$ with the pressure $p_d$ held constant, it is accompanied by an enthalpy change $\Delta\, i_d = -20$ kcal/kg. In this way, the quantity $(\Delta i_d/\Delta T_d)_{p_0} = 2.86$ kcal/°C · kg. For the same operating point $p_d$, $i_d$ a positive temperature change $\Delta T_{d'} = +9°C$ is, on the other hand, equivalent to an enthalpy change of the same absolute magnitude of $\Delta i_{d'} = 20$ kcal/kg $= -\Delta i_{d'}$, that is, one obtains in this instance for the quantity: $(\Delta i_{d'}\ /\ \Delta T_{d'})_{p_0} = 2.22$ kcal/kg $(\Delta i_d/\Delta\, T_d)$.

For a constant reference enthalpy $i_o$, the quantity $(\Delta i/\Delta T)_{p_0}$ is practically only a function of $x'_{wT}$ and essentially independent of the pressure $p_o$, that is, one obtains for any pressure $p_o$, for a fixed reference enthalpy $i_o$, the same value for $(\Delta i/\,\Delta\, T)_{p_0}$. Inspection of the $i$-T diagram reveals that the isobaric lines are, in good approximation, parallel for fixed reference enthalpy $i_o$.

Starting from equation (12), there are, according to the invention, two further embodiments to determine the control deviation $x_{wi}$ of the specific enthalpy and to use this quantity for control purposes:

The first of these embodiments comprises the more general case and is provided for the sliding pressure mode of operation ($p_o$ variable) of the heat exchanger and for constant reference enthalpy $i_o$ of the slightly superheated steam. According to a feature of this embodiment, an auxiliary quantity, designated at a pressure-dependent reference temperature $T_s$, is formed as a function of the measured actual pressure $p_i$. Also, a temperature deviation $(T_i - T_s)$ is determined by subtracting this reference temperature $T_s$ from the measured actual temperature $T_i$, and the control deviation $x_{wi}$ of the specific enthalpy is determined as a function of the temperature deviation $(T_i - T_s)$. In a circuit arrangement for carrying out this method embodiment, each of the quantities $T_s$ and $(\,\Delta\, i/\,\Delta\, T)_{p_0}$ are most advantageously formed in respective function generators.

The second embodiment is suited particularly for fixed-pressure operation ($p_o$ approximately constant) of the heat exchanger and for constant reference enthalpy $i_o$ of the slightly superheated steam. According to a feature of this embodiment, the control deviation $x_{wi}$ of the specific enthalpy is calculated according to equation (12) as:

$$x_{wi} = (\,\Delta i/\,\Delta\, T)_{p_0}\,(T_i - T_s),$$

wherein the quantity $(\,\Delta i/\Delta T)_{p_0}$ is predetermined as a quantity dependent on the operating point ($i_o$, $p_o$, $T_o$) of the slightly superheated steam, and the pressure-dependent reference temperature $T_s$ is determined according to equation (9) as:

$$T_s = T_o + a_{T_0\,,p_0}\,(p_i - p_o)$$

with fixed $a_{T_0\,,p_0}$. In a circuit arrangement with implementing this method, the dependence of the quantity $(\Delta i/\,\Delta\, T)_{p_0}$ is taken into consideration by a function generator. The pressure-dependent auxiliary quantity $T_s$ on the other hand, can be determined according to equation (9) in a simple computing circuit.

There is also the further embodiment in which the reference enthalpy $i_o$ of the slightly superheated steam is assumed not to be constant. Instead, the reference enthalpy $i_o$ is assumed as fluctuating about a mean reference value $\bar{i}_o$. A change $\Delta i_o = i_o - \bar{i}_o$ from the mean reference enthalpy $\bar{i}_o$ can be brought about intentionally in the operation of a heat exchanger. Such an intentional change $\Delta i_o$ can occur, for example, through control, if the reference enthalpy $i_o$ is controlled in dependence on the load; however, it can also be caused by the action of a superordinated control if, for example, after a soot blowing operation, the distribution of the heat flow over the individual heating surfaces of the heat exchanger has changed.

A still further embodiment of the invention for the case where the heat exchanger is operated with a reference enthalpy $i_o$ which varies about a mean reference value $\bar{i}_o$. In this embodiment, a pressure dependent reference temperature $T_s$ is formed as a function of the measured actual pressure $p_i$ and a temperature deviation $(T_i - T_s)$ is determined by subtracting the pressure-dependent reference temperature $T_s$ from the measured actual temperature $T_i$. Also, an enthalpy deviation $x^{=}_{wi}$ is determined as a function of this temperature deviation $(T_i - T_s)$, and, for the purpose of forming an effective deviation $x_{wi}$ for use as an auxiliary control quantity, the intended enthalpy deviation $\Delta i_o = i_o - i_o$ is subtracted from the enthalpy deviation $x^{=}_{wi}$ determined in the above manner. The intended enthalpy change $\Delta i_o$ can here be controlled as a function of the load, for example, as a function of the reference value $P_o$ of the electric power of a turbogenerator connected to the heat exchanger.

Although the invention is illustrated and described herein as a method and apparatus for controlling a heat exchanger, it is nevertheless not intended to be limited to the details shown, since various modifications may be made therein within the scope and the range of the claims. The invention, however, together with additional objects and advantages will be best understood from the following description and in connection with the accompanying drawing.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the method and apparatus are illustrated in the following eight FIGS. described below. Similar or like components are designated by the same reference numeral in each FIG. in which they appear.

FIG. **1** is a signal flow diagram for controlling the feedwater in a Benson boiler according to the method and apparatus of the invention.

FIG. **2** illustrates a computing circuit for determining the control deviation $x_{wi}$ of the specific enthalpy for a fixed operating point $p_o$, $T_o$ of the slightly superheated steam.

FIG. **3** is a computing circuit for determining the control deviation $x_{wi}$ of the specific enthalpy for load-dependent control of the reference values $p_o$ and $T_o$ for pressure and temperature.

FIG. **4** is a further computing circuit for determining the control deviation $x_{wi}$ for a variable operating point of the slightly superheated steam.

FIG. **5** is a computing circuit for determining the control deviation $x_{wi}$ for constant reference enthalpy $i_o$ and variable pressure $P_o$ for the sliding pressure mode of operation.

FIG. **6** is a computing circuit for determining the control deviation $x_{wi}$ for constant reference enthalpy $i_o$ and fixed pressure $p_o$ for fixed-pressure operation.

FIG. **7** illustrates a computing circuit for determining the effective control deviation $x_{wi}$ in view of an intended change $\Delta i_o$ of the mean reference enthalpy $i_o$.

FIG. **8** is a signal flow diagram for the feedwater control in a Benson boiler which includes superimposing the effective specific enthalpy deviation obtained according to FIG. **7**.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. **1**, a Benson boiler **1** is supplied with thermal energy by means of an energy carrier **2** for evaporating the inflowing feedwater **3**. The energy carrier, for example, can be oil, gas or coal. After passing through a feedwater valve **4** that is connected to a positioning drive **5** controlled by an electric motor, an injection water stream **6** is diverted away from the feedwater **3**. The feedwater flow less the injection water **6** is designated by reference numeral **7** and is determined at a flow meter **8**, and converted into an electrically measured quantity $M_W$ by a measuring transducer **9**. The flow meter **8** can be in the form of a measuring orifice. After passing through the flow meter **8**, the feedwater throughput **7** is preheated in a preheater **10** of the Benson boiler **1** and is vaporized in an evaporation **11**. The steam leaving the evaporator **11** is slightly superheated. It is then conducted to a first steam superheater **12**. From there the steam is fed to an injection cooler **13**, into which the diverted injection water **6** is fed through an injection water valve **14**. The steam then flows to a further steam superheater **15**. The steam **16** leaving the Benson boiler **1** is subsequently fed to a turbogenerator (not shown).

A temperature transmitter **17** is placed between the evaporator **11** and the first steam superheater **12** for continuously measuring the actual value of the temperature of the slightly superheated steam. A temperature transducer **18** connected to the transmitter **17** converts this value into an electrical quantity $T_i$. At the same location, there is placed a pressure transmitter **19** for continuously measuring the actual pressure value. A pressure transducer **20** is connected to the pressure transmitter **19** that converts the pressure into a corresponding electrical quantity $p_i$.

A computing circuit **21** is supplied with the two electrical quantities $T_i$ and $p_i$ and continuously forms an electrical output quantity $x_{wi}$ using these quantities. The quantity $x_{wi}$ is a measure of the deviation of the specific actual enthalpy $i_i$ from the specific reference enthalpy $i_o$. In the basic flow diagram shown in FIG. **1**, the formation of the output quantity $x_{wi}$ takes place with the aid of two fixed, predetermined electrical quantities $T_o$ and $p_o$, which are generated in respective reference value transmitters **22** and **23** according to the desired temperature and pressure of the slightly superheated steam.

Embodiments of the computing circuit **21** which are adapted to a given requirement are described below with reference to the following FIGS.

According to FIG. **1**, the output quantity $x_{wi}$ of the computing circuit **21** is fed to a comparator **24** which in turn is connected to a regulator **25**. The regulator **25** controls the positioning drive **5** of the feedwater valve **4** in dependence upon its input quantity $e$. In the comparator **24**, the measured quantity $M_W$ for the feedwater throughput, supplied by the measuring transducer **9**, is compared with a reference value $M_{Wo}$ that is either set as a fixed value by a reference setting device (not shown) or is controlled as a function of the load. The input quantity $e$ of the regulator **25** is a measure of the deviation of the measured throughput from the adjusted reference throughput. The positioning quantity $y$ delivered by the regulator **25** acts on the feedwater valve **4** in a direction minimizing the deviation of the feedwater throughput from its reference value.

Should a heating disturbance as, for example, a temporary change in the calorific power of the energy carrier **2** occur; this is noted very quickly as a change of the specific enthalpy $i_i$ of the slightly superheated steam at the output of the evaporator **11**, and the output quantity $x_{wi}$ of the computing circuit **21** fed to the comparator **24** causes, via the regulator **25**, a change in the feedwater throughput in a direction to keep the specific enthalpy constant $i_i$. In the embodiment according to FIG. **1** the output quantity $x_{wi}$ of the computing circuit **21** thus serves, as a correction quantity for the input quantity $e$ of the regulator **25**.

FIG. **2** illustrates a computing circuit designated **21***a* which can be used with a heat exchanger or once-through, forced-flow boiler in which the operating point of the slightly superheated steam is determined by pressure and temperature and is essentially fixed, that is, not controlled. In order to simplify the description, the electrical quantities of current and voltage occurring in the electrical circuits which are proportional or correspond to the physically measured values of pressure, temperature or quantities of specific enthalpy are designated here and with reference to the remaining FIGS. as the physically measured values and quantities to which they refer.

The control deviation $x_{wi}$ of the specific enthalpy is determined in the computing circuit **21***a* of FIG. **2** by equation (5):

$$x_{wi} = K_p\, x_{wp} + K_T\, x_{wT} \tag{5}$$

The values $K_p$ and $K_T$ are here constants adapted to the operating point. The preset reference value $p_o$ of the pressure is subtracted from the continuously measured actual value $p_i$ of the pressure at the subtraction circuit **26.** The difference $x_{wp} = p_i - p_o$ is multiplied by the constant $K_p$ at the multiplier **27.** The product $K_p\, x_{wp}$ is fed to the first input of an adder **28.** At the same time, the reference value $T_o$ is subtracted from the continuously measured actual value $T_i$ of the temperature at the subtraction circuit **29**; and the difference $x_{wT} = T_i - T_o$ is multiplied by the constant $K_T$ at another multiplier **30.** The product $K_T\, x_{wT}$ is fed to the other input of the adder **28.** At the output of the adder, and therefore at the output of the computing circuit **21,** there is provided the control deviation $x_{wi}$ of the specific enthalpy, determined according to equation (5). Example 4 below will illustrate how the constant $K_p$ and $K_T$ are determined for a fixed operating point.

Example 4

The operating point A of the slightly superheated steam will be assumed as given by the temperature $T_e = 370°C$, by the pressure $p_e = 180$ atm and so, by the specific enthalpy $i_e = 650$ kcal/kg. From the *i*-T diagram it is determined that at constant pressure $p_e = 180$ atm, a temperature change $\Delta T = 1°C$ results in an enthalpy change of 2.18 kcal/kg. Thus, for the constant $K_T$, a value of $K_T / (\Delta i/\Delta T)_{p_e} = 2.18$ kcal/kg/deg is obtained. And, from the *i*-T diagram, at constant temperature $T_e = 370°C$, the enthalpy change occurring as the result of a pressure change of $\Delta p = 1$ atm, is $\Delta i = -1.45$ kcal/kg. From this, a value of $-1.45$ kcal/kg per atmosphere is obtained for the constant $K_p$. After entering these values in equation (5), one obtains as the defining equation for $x_{wi}$:

$$x_{wi}\ [\text{kcal/kg}] = -1.45\ x_{wp}\ [\text{atm}] + 2.18\ x_{wT}\ [\text{deg}].$$

FIG. **3** shows a computing circuit designated **21***b* for determining the control deviation $x_{wi}$ in which the pressure reference value $p_o$ and the temperature reference value $T_o$ are no longer fixed, preset constants of the slightly superheated steam; they are rather controlled via respective function generators **31** and **32** as functions of the electric power $P_o$ which a turbogenerator connected to the heat exchanger is to deliver.

In FIG. **4** is shown a computing circuit designated **21***c*. with this circuit, the enthalpy deviation $x_{wi}$ $(P_o)$ according to equation (6) given above is determined. In contrast to the computing circuit of FIG. **3,** the values $K_p$ and $K_T$ are now also controlled as functions of the desired electric power $P_o$ via respective function generators **33** and **34.** The computing circuit is of particular importance for the case that the control deviation $x_{wi}$ is to be determined for an extended range of operation, where the values of $K_p$ and $K_T$ can no longer be considered as constant.

FIG. **5** shows a computing circuit designated **21***d*, in which the control deviation $x_{wi}$ of the specific enthalpy is determined on the basis of equation (12) for varying pressure operation ($p_o$ variable) and constant reference enthalpy $i_o$ of the heat exchanger. A reference temperature $T_s$, which is a function of the actual pressure $p_i$, is determined as an auxiliary quantity with the aid of the function generator **35.** This pressure-dependent reference temperature $T_s$ is subsequently subtracted in a subtraction circuit **36** from the measured actual temperature $T_i$. A further function generator **37** forms the quantity $(\Delta i/\Delta T)_{p_0} \cdot (T_i - T_s)$ which is a function of the determined temperature difference $(T_i - T_s)$ alone.

The computing circuit designated **21***e* in FIG. **6** differs from the foregoing embodiments only with respect to the realization of the pressure-dependent reference temperature $T_s$. It is applicable for fixed-pressure operation ($p_o$ = const), specifically, if the heat content of the slightly superheated steam is to be kept constant, for example, the steam at the output of the evaporator **11** in FIG. **1.** The pressure is switched in here linearly without the use of the function generator **35** shown in FIG. **5.** For this purpose, the measured actual pressure $p_i$ is first multiplied by a constant $a_{T_0,\,p_0}$ in a multiplier **38.** In an adder **39,** the summation $a_{T_0,\,p_0} p_i + T_o - a_{T_0,\,p_0}\, p_0$ according to equation (9) is subsequently made. The sum formed in this manner is equal to the pressure-dependent reference temperature $T_s$ and is fed to the subtraction circuit **36** as shown in FIG. **5.**

There are applications, in which the reference enthalpy $i_o$ of the slightly superheated steam cannot be assumed as constant, but is intentionally changed, for example, by superordinated controls. For such cases the circuit configuration shown in FIG. **7** and designated **21***f* is provided. An enthalpy deviation designated by the symbol $x^{=}_{wi}$ is determined in the computing circuit **21***f*, which corresponds to the computing circuit **21***d* shown in FIG. **5.** The control deviation $x_{wi}$ is effective as an auxiliary control quantity and is generated in a subtraction circuit **40** by subtracting an intended enthalpy change $\Delta i_o$ from the enthalpy deviation $x^{=}_{wi}$ determined by electronic circuits from the values of $p_i$ and $T_i$.

The intended enthalpy change $\Delta i_o$ is formed in turn in an adder **41** from a first enthalpy value $\Delta i_o'$ and a second enthalpy value $\Delta i_o''$. The first enthalpy value $\Delta i_o'$ is delivered to the adder **41** by a control **42** according to an enthalpy deviation $x^{==}_{wi}$, which is formed in the circuit **44** from values of $P'_i$ and $T'_i$ measured, for example, at the output of the steam superheater **12** following the evaporator **11** of FIG. **1**. The second enthalpy quantity $\Delta i_o''$ is determined, for example, by a function generator **43** as a function of the desired value of the power $P_o$ of the turbogenerator connected to the heat exchanger.

FIG. **8** shows a control circuit in a heat exchanger; this configuration constitutes a variant of the usual feedwater control system in a Benson boiler **1** and uses the specific enthalpy for control purposes. The flow diagram of the control circuit shown in principle in FIG. **1** is supplemented and modified essentially by the circuit configuration shown in FIG. **7**. Referring to FIG. **8**, an enthalpy quantity $\Delta i_o'$ is provided at the output of the PI (proportional-integrating) control **42**. The enthalpy quantity $\Delta i_o'$ is formed with the PI control **42** from the deviation $x'_{w\,\Delta\,T}$ of the temperature difference $(T_i' - T_o')$ from its reference value, the temperature pertaining to the intensely superheated steam and being measured at the injection cooler **13**.

The effective enthalpy deviation $x_{wi}$ determined in the circuit configuration of FIG. **7** is linked at a multiplier **44** with a reference value $P_o$ to the reference value $M_{Wo}$ of the feedwater throughput. The value $P_o$ is equal, for example, to the desired value of the power output of the turbogenerator following the Benson boiler **1**. The measured feedwater flow $M_W$ is compared in a subtraction circuit **45** with this reference value $M_{Wo}$, and the difference $(M_W - M_{Wo})$ formed there is fed to a PI control **46**. The positioning drive **5** of the feedwater valve **4** is controlled in accordance with the positioning quantity $y$ delivered by the PI control **46**.

What is claimed is:

**1.** Method of controlling a heat exchanger such as a forced-flow boiler or the like wherein slightly superheated steam is generated, comprising continuously determining the specific actual enthalpy $(i_i)$ of the slightly superheated steam, and utilizing the specific actual enthalpy as an auxiliary control quantity.

**2.** The method of claim **1** wherein the heat exchanger is supplied with the operating mediums of fuel and feedwater and is equipped with adjusting means for adjusting the flow of at least one of the operating mediums to the heat exchanger, comprising continuously measuring the actual pressure $(p_i)$ and actual temperature $(T_i)$ of the slightly superheated steam in the heat exchanger, supplying the measured actual values of pressure $(p_i)$ and temperature $(T_i)$ to a computation circuit for determining the control deviation $(x_{wi})$ of the specific actual enthalpy $(i_i)$ from the reference value of the enthalpy $(i_o)$, and supplying the control deviation $(x_{wi})$ of the specific enthalpy as a correction quantity for the input quantity of the adjusting means.

**3.** The method of claim **2** wherein the adjusting means includes a controller connected to a positioning device for adjusting the flow of one of the operating mediums to the heat exchanger, comprising supplying the control deviation $(x_{wi})$ of the specific enthalpy as a correction quantity for the input quantity $(e)$ of the controller.

**4.** The method of claim **2** comprising supplying respective predetermined reference values of pressure $(p_o)$ and temperature $(T_o)$ for the slightly superheated steam to the computation circuit, and determining the control deviation $(x_{wi})$ of the specific enthalpy from the measured actual values of the pressure $(p_i)$ and temperature $(T_i)$ and the predetermined refernce values of pressure $(p_o)$ and temperature $(T_o)$.

**5.** The method of claim **4** comprising determining the specific enthalpy $(x_{wi})$ according to the equation:

$$x_{wi} = K_p\, x_{wp} + K_T\, x_{wT}$$

wherein $K_p$ and $K_T$ are predetermined values and wherein $(x_{wp})$ is the control deviation $(p_i - p_o)$ of the pressure and $(x_{wT})$ is the control deviation $(T_i - T_o)$ of the temperature.

**6.** The method of claim **5** wherein the heat exchanger supplies a load and wherein the values of pressure $(p_o)$ and temperature $(T_o)$ are functions of the load.

**7.** The method of claim **5** wherein the heat exchanger supplies a load and wherein the values of $(K_p)$ and $(K_T)$ are functions of the load.

**8.** The method of claim **5** wherein the heat exchanger supplies a load and wherein the values of pressure $(p_o)$ and temperature $(T_o)$ and the values of $(K_p)$ and $(K_T)$ are all functions of the load.

**9.** The method of claim **5** wherein the heat exchanger is connectable to a turbogenerator for supplying the same, the turbogenerator having a specified value $(P_o)$ of electric capacity, and wherein the values of pressure $(p_o)$ and temperature $(T_o)$ are functions of $(P_o)$.

**10.** The method of claim **5** wherein the heat exchanger is connectable to a turbogenerator for supplying the same, the turbogenerator having a reference value $(P_o)$ of electric capacity, and wherein the values of $(K_p)$ and $(K_T)$ are functions of $(P_o)$.

**11.** The method of claim **5** wherein the heat exchanger is connectable to a turbogenerator for supplying the same, the turbogenerator having a reference value $(P_o)$ of electric capacity, and wherein the values of pressure $(p_o)$ and temperature $(T_o)$ and values of $(K_p)$ and $(K_T)$ are all functions of $(P_o)$.

**12.** The method of claim **2** wherein the heat exchanger operates under the condition that the reference value of the pressure $(p_o)$ is variable and the reference value of the enthalpy $(i_o)$ of the slightly superheated steam is constant, and wherein the method comprises forming a pressure dependent auxiliary quantity as a function of the measured actual pressure $(p_i)$, said quantity being in the form of reference temperature $(T_s)$, subtracting the reference temperature $(T_s)$ from the measured actual temperature $(T_i)$ to determine a temperature deviation $(T_i - T_s)$, and determining the control deviation $(x_{wi})$ of the specific enthalpy as a function of the temperature deviation $(T_i - T_s)$.

**13.** The method of claim **2** wherein the heat exchanger operates under the condition that the reference value of the pressure $(p_o)$ is substantially constant and that the reference enthalpy $(i_o)$ of the slightly superheated steam is constant, and wherein the method comprises determining the control deviation $(x_{wi})$ of the specific enthalpy according to the equation:

$$x_{wi} = (\Delta i / \Delta T)_{p_0} (T_i - T_s)$$

wherein the quantity $(\Delta i/\Delta T)_{p_0}$ is predetermined as dependent upon the operating point $(i_o, p_o, T_o)$ of the slightly superheated steam, and wherein the quantity

$(T_s)$ is a reference temperature dependent upon pressure and determined from the equation:

$$T_s = T_o + a_{T_0,\,p_0}(p_i - p_o)$$

wherein $a_{T_0,\,p_0}$ is fixed.

**14.** The method of claim **2** wherein the heat exchanger operates at a reference enthalpy $(i_o)$ of the slightly superheated steam which varies about a mean enthalpy value $(i_o)$, comprising: forming a pressure dependent reference temperature $(T_s)$ as a function of the measured actual pressure $(p_i)$, subtracting the reference temperature $(T_s)$ from the measured actual temperature $(T_i)$ to determine the temperature deviation $(T_i - T_s)$, determining a control deviation quantity $(x^{=}_{wi})$ as a function of the temperature deviation $(T_i - T_s)$, and subtracting an intended enthalpy change $(\Delta i_o = i_o - i_o)$ from the quantity $(x^{=}_{wi})$ to form the control deviation $(x_{wi})$.

**15.** The method of claim **14** wherein heat exchanger supplies a load and wherein the intended enthalpy change $(\Delta i_0)$ is a function of the load.

**16.** The method of claim **15** wherein the heat exchanger is connectable to a turbogenerator for supplying the same, the turbogenerator having a specified value $(P_o)$ of electric capacity, and wherein the intended enthalpy change $(\Delta i_o)$ is a function of $(P_o)$.

**17.** The method of claim **14** wherein the heat exchanger is equipped with an injection cooler supplied with intensely heated steam and a superordinated controller, comprising detecting the temperature difference $(T'_i - T'_o)$ of the intensely superheated steam at the injection cooler and forming therewith the deviation quantity $(x'_{w\,\Delta\,T})$, and supplying the deviation quantity $(x'_{w\,\Delta\,T})$ to the superordinated controller to form the quantity $(\Delta i'_o)$ for correcting the enthalpy deviation $(\Delta i_0)$.

**18.** In a heat exchanger such as a forced-flow boiler or the like supplied with the operating mediums of fuel and feedwater and having an evaporator wherein slightly superheated steam is generated, the heat exchanger being equipped with an apparatus for controlling the heat exchanger, the apparatus comprising pressure detection means and temperature detection means for continuously measuring the pressure and temperature respectively of the slightly superheated steam at the output of the evaporator, computation means connected to said detection means for continuously determining the specific actual enthalpy of the slightly superheated steam, and means connected to said computation means for controlling the heat exchanger in response to said specific actual enthalpy.

**19.** The apparatus of claim **18** wherein the apparatus controls at least one of the operating mediums said last-mentioned means being adjustment means for adjusting the flow of at least one of said mediums to the heat exchanger in response to said specific actual enthalpy.

**20.** The apparatus of claim **19** wherein the heat exchanger is equipped with a conduit to supply the feedwater to the heat exchanger proper, said adjustment means comprising positioning equipment, said equipment including a valve for controlling the supply of feedwater to the heat exchanger, and a positioning device connected to said valve for adjusting the position of said valve.

**21.** The apparatus of claim **19** wherein the heat exchanger is equipped with a conduit to supply the fuel to the heat exchanger proper, said adjustment means comprising positioning equipment said equipment including a valve for controlling the supply of fuel to the heat exchanger, and a positioning device connected to said valve for adjusting the position of said valve.

**22.** The apparatus of claim **19,** said pressure detection means comprising a pressure transmitter placed at the output of the evaporator, and a pressure transducer connected to said pressure transmitter for converting said pressure to a corresponding electrical quantity; said temperature detection means comprising a temperature transmitter placed at the output of the evaporator, and a temperature transducer connected to said temperature transmitter for converting said temperature to a corresponding electrical quantity; said computation means comprising respective reference transmitters for providing respective predetermined electrical reference quantities of pressure and temperature for the slightly superheated steam, and further computation circuit means connected to said reference transmitters and said transducers for forming a control deviation signal corresponding to the deviation of the specific actual enthalpy from the reference value of the enthalpy; and said adjustment means comprising means responsive to the control deviation signal for adjusting the flow of at least one of the operating mediums to the heat exchanger.

* * * * *

# UNITED STATES PATENT OFFICE
# CERTIFICATE OF CORRECTION

Patent No. 3,774,396  Dated November 27, 1973

Inventor(s) Ladislaus Borsi, Helmuth Dingler

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In column 7, line 12, change "$x_{\overline{W}i}$" to --$x^{*}_{Wi}$-- and throughout text.

In column 7, line 15, change "$\Delta i_o = i_o - i_o$" to --$\Delta i_o = i_o - \bar{i}_o$--

In column 7, line 63, change "mean reference enthalpy $i_o$" to --mean reference enthalpy $\bar{i}_o$--

In column 9, line 63, change "$K_T/(\Delta i/\Delta T)_{pe}$= 2.18 kcal/kg/deg" to --$K_T = (\Delta i/\Delta T)_{pe}$= 2.18 kcal/kg/deg--

In column 12, line 51, change "of reference" to --of a reference--

Signed and sealed this 17th day of September 1974.

(SEAL)
Attest:

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