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(54) A METHOD OF CONTROLLING A SUPPLY OF FEED WATER INTO A BOILER

(57) The present invention relates to a system and method of controlling a supply of feed water into a boiler (10). The boiler (10) comprising a feed water inlet (20) for supplying feed water into the boiler (10), a steam outlet (22) for taking steam from the boiler (10) and a liquid level sensor (14) for measuring a liquid level in the boiler (10). The steam outlet (22) comprising a steam valve (26) defining a steam valve (26) opening degree, the method comprising measuring the liquid level in the boiler (10) using the liquid level sensor (14), determining a rate of change of the steam valve (26) opening degree and controlling the supply of feed water into the boiler (10) via the feed water inlet (20) based on the liquid level in the boiler (10), a reference liquid level for the boiler (10) and the rate of change of the steam valve (26) opening degree.

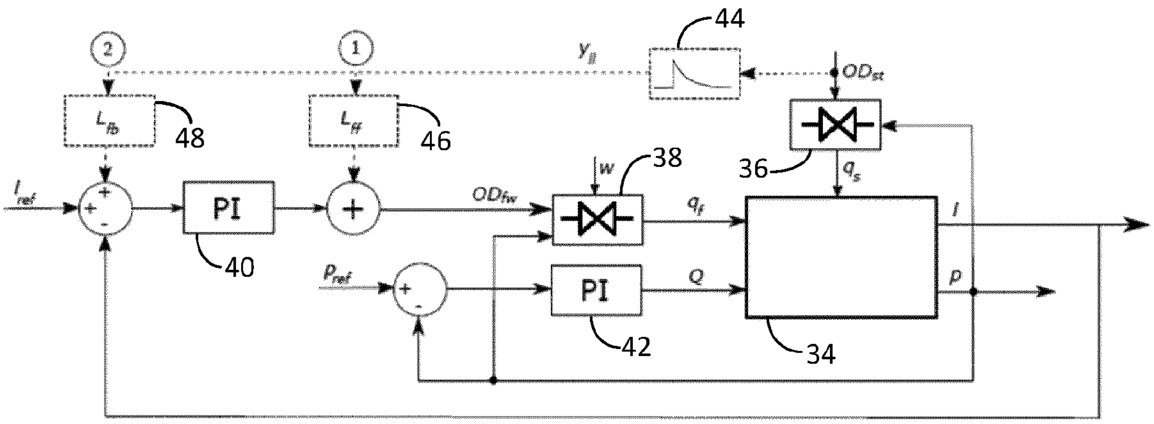

FIG. 2

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Description

[0001] The present invention relates to a method of controlling a supply of feed water into a boiler, a system for controlling a supply of feed water into a boiler, a computer program and a computer-readable medium.

Background of the invention

[0002] The present invention concerns a strategy for controlling the water level in a boiler subject to the shrink and swell phenomena. These phenomena can occur when there is a change in the steam load on the boiler (the main disturbance in the system). Such a change in steam load will affect the steam pressure in the boiler which in turn affects the volume of steam suspended in the boiler water. This leads to a so-called inverse response of the water level (non-minimum phase behaviour) where the initial response of the level is opposite to the long-term behaviour.

[0003] For example: if the steam load is increased the boiler pressure will drop which leads to a swell of the steam bubbles suspended in the water. This swelling leads at first to an increase in the water level and subsequently a re-distribution of steam and water in the boiler. The re-distribution leads to the long-term behaviour which is a decrease in the water level. A water level control strategy is designed to accommodate an adverse effect of the water levels inverse response to the disturbance.

[0004] This adverse effect can be illustrated as follows: due to the initial rise in water level resulting from the pressure drop during a load increase the control will decrease the feed water flow when actually an increase is needed. This initial decrease in feed water flow exacerbates the following water level decrease. There is therefore a need to reduce fluctuations in boiler water level by avoiding such an initial response of the control.

[0005] Boiler drum level control systems are known in the prior art. US 9476584 describes a boiler drum level control system using the position of a bypass valve configured to control the steam flow. The controller commands the feed-water flow and heat input to the evaporator based on sensor signals. The sensor signals are generated by sensors that measure fluid flow, steam flow, drum pressure, drum temperature, and bypass position. The drum pressure may be measured directly by detecting the position of the by-pass valve providing leading indicators of a pressure change in the boiler which may result in an adjustment of the water level in the drum.

[0006] JP 2504939 describes a boiler level control device controlling the opening degree of a bypass valve for branching surplus steam to the condenser thereby bypassing the steam turbine. Pressure sensors are used for determining the steam flow.

[0007] US 10185332 describes a boiler drum level control method using the difference between a steam flow signal and a feed water flow signal. A transient controller calculates the gain parameter based on the absolute flow difference. Additional parameters include a bypass valve position.

[0008] CN 109028023 describes how a change of the steam load of a marine boiler is controlled by sending signals to a PLC regulating the feed water valve. The water level and the steam flow are measured. The steam flow rate is introduced as a feed forward control signal. When the steam load suddenly changes, the steam flow rate signal causes the feed water regulating valve to initially move in the correct direction, i.e. when steam flow is increased, the feed water regulating valve is opened. A vortex flow meter is used for monitoring the load.

[0009] US 7931041 describes a method for controlling a liquid level in a boiler using filtered output signals representing liquid level, gas/steam flow rate, feed-liquid flow rate, vessel pressure and vessel temperature.

[0010] US 10323547 describes a steam level control system of a boiler measuring the position of a bypass valve bypassing a heat recovery steam generator.

[0011] JP 2018080672 describes a steam turbine control device having a steam control valve opening degree detector. It does not relate to the supply of feed water into the boiler.

[0012] K. J. Åström and R. D. Bell, "Drum-boiler dynamics," Automatica, vol. 36, pp. 363-378, 2000, describes a nonlinear dynamic model for natural circulation drum-boilers.

[0013] S. W. Smith, The Scientist and Engineer's Guide to Digital Signal Processing, 2nd ed. California Technical Publishing, 1999, describes edge detection in signal processing.

[0014] G. F. Gilman, Boiler Control Systems Engineering, 1st ed. ISA - The Instrumentation, Systems and Automation Society, 2005, describes a feed forward water level control scheme using the steam flow.

[0015] D. Lindsley, Power-plant Control and Instrumentation - The control of boilers and HRSG systems, 1st ed. The Institution of Electrical Engineers, 2000, also describes a water level control scheme using the steam flow.

[0016] It is an object of the invention to reduce fluctuations in boiler water level by avoiding a negative initial response of the control while avoiding relying on steam flow sensors. Such sensors will increase the costs of the system and decrease the reliability.

Summary of the invention

[0017] The above object is realized in a first aspect of the present invention by a method of controlling a supply of feed water into a boiler, the boiler comprising a feed water inlet for supplying feed water into the boiler, a steam outlet for taking steam from the boiler and a liquid level sensor for measuring a liquid level in the boiler, the steam outlet comprising a steam valve defining a steam valve opening degree, the method comprising:

measuring the liquid level in the boiler using the liquid level sensor,
determining a rate of change of the steam valve opening degree, and
controlling the supply of feed water into the boiler via the feed water inlet based on the liquid level in the boiler, a reference liquid level for the boiler and the rate of change of the steam valve opening degree.

[0018] The boiler includes a vessel for accommodating water and steam. The water is supplied to the boiler via the feed water inlet. The stream is generated by heat input into the vessel. The steam is taken out of the boiler via the steam outlet. The steam outlet is controlled by a steam valve defining a steam valve opening degree. The steam generated may be used for operating a steam turbine or other types of steam consumers.

[0019] The boiler also including the liquid level sensor. The liquid level sensor measures the liquid level in the boiler. Below the liquid level the vessel comprises a two-phase flow comprising liquid water and steam bubbles and above the liquid level the vessel essentially comprises steam.

[0020] The liquid level in the boiler is normally controlled by adjusting the supply of feed water into the boiler by means of a feed pump and/or valve in response to the measured liquid level in the boiler using a control scheme. However, when the steam load on the boiler is increased, the boiler pressure will drop. This leads to steam bubbles suspended in the liquid water being released, whereby the liquid level will initially swell. Thus, the liquid level in the boiler rises initially and then drops as more steam is taken out of the boiler. Using a naive controller, e.g. simple PID which does not take the swell phenomenon into consideration, the response to the initial increased liquid level in the boiler will be that the water feed into the boiler is decreased, which will subsequently lead to too low liquid level of water in the boiler as more steam is taken out of the boiler. This may potentially lead to a damage of the boiler due to low liquid level. Instead the initial response should be to increase the water feed to counter the increased taking out of steam from the boiler.

[0021] By the present solution the signal representing the opening degree of the steam valve and the signal representing the liquid level in the boiler is used to determine the supply of feed water into the boiler. These two signals are readily available and there is thus no need for additional sensors, such as boiler steam flow sensors. The reference liquid level for the boiler is a constant which represents the normal liquid level under steady state conditions and is determined by the design of the boiler. From the signal representing the opening degree of the steam valve a rate of change of the steam valve opening degree is determined and used to compensate the inverse response to the disturbance, i.e. the drop of the liquid level when the steam load increases. The rate of change of the steam valve opening degree is zero when the steam valve opening degree is constant, i.e. when the steam valve is still and the steam load is constant. When the steam valve opening degree is changing because of changing load, i.e. when the steam valve is moving, the rate of change of the steam valve opening degree is non-zero.

[0022] By basing the supply of feed water into the boiler on the measured liquid level in the boiler, the reference liquid level for the boiler and the rate of change of the steam valve opening degree, the inverse response to the disturbance can be avoided or reduced.

[0023] According to a further embodiment, the feed water inlet comprises a feed water valve defining a feed water valve opening degree, wherein the method comprises determining the supply of feed water into the boiler by the feed water valve opening degree.

[0024] In order to control the supply of feed water to the boiler, a feed water valve can be used. The opening degree of the feed water valve is available as the actuation signal for the boiler water level controller.

[0025] According to a further embodiment, the feed water inlet is connected to a pump, the pump defining a flow rate, the supply of feed water into the boiler is determined by the flow rate.

[0026] By using a flow-controlled pump the feed water valve in the feed water line can be omitted.

[0027] According to a further embodiment, the flow rate is based on the rotational speed of a pump.

[0028] To change the supply of feed water, the rotational speed of a pump may be changed,

[0029] According to a further embodiment, the controlling of the supply of feed water into the boiler is performed using a PI control scheme.

[0030] The control action is designed to minimize the adverse effect of a change in the disturbance. The PI (Proportional-Integral) controller performs the calculations for a proportional-integral algorithm based on an integral parameter and a proportional or gain parameter and the generated output is a flow control signal used to control the supply of feed water to the boiler.

[0031] According to a further embodiment, controlling the supply of feed water into the boiler including: generating a feed water control action based on the difference between the liquid level in the boiler and the reference liquid level for the boiler, and, determining the supply of feed water into the boiler based on the sum of the feed water control action and the rate of change of the steam valve opening degree.

[0032] The rate of change of the steam valve opening degree signal can be added to the control action in a feed-forward manner, i.e. after the controller, on basis of which the opening degree of the feed valve (or alternatively the flow/speed of the feed pump) is controlled. In this way the corrective term to the feed water control action is introduced immediately when the disturbance occurs without having to wait for the water level to drop before the controller takes corrective action. The controller typically use a linear siso control scheme to generate the control action. The controller is preferably a PI controller and the control action is preferably a PI control action.

[0033] According to a further embodiment, controlling the supply of feed water into the boiler including: generating a feed water control action based on the sum of the rate of change of the steam valve opening degree and the difference between the liquid level in the boiler and the reference liquid level for the boiler, and, determining the supply of feed water into the boiler by the feed water control action.

[0034] The rate of change of the steam valve opening degree signal can alternatively be added in a feed-back manner, i.e. added to the measured liquid level before the controller, on basis of which the opening degree of the feed valve (or alternatively the speed of the feed pump) is controlled. In this way the corrective term to the feed water control input is introduced into the controller which takes corrective action. The controller typically use a linear siso control scheme to generate the control action. The controller is preferably a PI controller and the control action is preferably a PI control action.

[0035] According to a further embodiment, the method comprises determining the rate of change of the steam valve opening degree by using a phase-lead filter on the steam valve opening degree.

[0036] The opening degree of the water feed is controlled by disturbance compensation in the water level control provided by a lead filter. The lead filter provides a zero output in case of constant inputs to the filter, but a non-zero output, when the input changes, i.e. when the steam load suddenly changes. The filtered rate of change of the steam valve opening degree replaces the rate of change of the steam valve opening degree in the above feed-forward and feed-back schemes.

[0037] According to a further embodiment, the method further comprising the steps of:

measuring a pressure in the boiler using a pressure sensor, and
controlling a heat input into the boiler based on the pressure in the boiler and a reference pressure for the boiler.

[0038] The heat input into the boiler may be controlled by a second controller. The heat input based on the pressure measurement and a reference pressure for the boiler. The pressure measurement is made by a pressure sensor in the vessel. The pressure thus represents the total energy in the boiler. The reference pressure for the boiler is a constant which represents the normal operating pressure under steady state conditions and is determined by the design of the boiler.

[0039] According to a further embodiment, controlling a heat input into the boiler including: generating a heat input control action based on the difference between the pressure in the boiler and a reference pressure for the boiler, and, determining the heat input into the boiler by the heat input control action.

[0040] The heat input into the liquid in the vessel is based on the control action. A higher heat input will cause more steam to be generated resulting in a higher pressure and vice versa.

[0041] According to a further embodiment, the controlling of the heat input into the boiler is performed using a PI control scheme.

[0042] The control action is designed to minimize the adverse effect of a change in the disturbance. The PI (Proportional-Integral) controller performs the calculations for a proportional-integral algorithm based on an integral parameter and a proportional or gain parameter and the generated output is a flow control signal.

[0043] The above object is realized in a second aspect of the present invention by a boiler having a control system for controlling a supply of feed water into a boiler, the boiler comprising a feed water inlet for supplying feed water into the boiler, a steam outlet for taking steam from the boiler and a liquid level sensor for measuring a liquid level in the boiler, the steam outlet comprising a steam valve defining a steam valve opening degree, the control system controlling the supply of feed water into the boiler via the feed water inlet based on the liquid level in the boiler, a reference liquid level for the boiler and a rate of change of the steam valve opening degree.

[0044] According to a further embodiment, the above boiler according to the second aspect may comprise any of the features of the method according to the first aspect.

[0045] The above object is realized in a third aspect of the present invention by a computer program comprising instructions which, when the program is executed by a computer, cause the computer to carry out the method according to the first aspect.

[0046] The control solution including the feed-back disturbance compensation according to the previous aspects can preferably be implemented as software in a programmable logic controller (PLC).

[0047] The above object is realized in a fourth aspect of the present invention by a computer-readable medium having stored thereon the computer program of the third aspect.

Brief description of the drawings

[0048]

FIG. 1	shows a schematic view of the boiler.
FIG. 2	shows a block diagram illustrating the feed water level control strategy.
FIG. 3.	shows the step response of the phase-lead filter.
FIG. 4	shows the simulation results using feed water flow and no disturbance compensation.
FIG. 5	shows the simulation results using feed water flow and feed-forward compensation.
FIG. 6	shows the simulation results using feed water flow and feed-back compensation.
FIG. 7	shows the simulation results with valve opening and no disturbance compensation.
FIG. 8	shows the simulation results with valve opening and feed-forward compensation.
FIG. 9	shows the simulation results with valve opening and feed-back compensation.
FIG. 10	shows the simulation results of FIG. 9 using PLC simulation software.

Detailed description of the drawings

[0049] FIG. 1 is a simplified schematic view of a boiler 10. The boiler 10 comprises a vessel 12. The vessel defines a liquid level illustrated by a corrugated line. The liquid level is measured by a liquid level sensor 14. Below the liquid level there is a two-phase flow 16 of liquid water and steam bubbles, whereas above the liquid level there is mainly steam 18. The boiler 10 further comprises a feed water inlet 20 for supplying feed water into the vessel 12 and a steam outlet 22 for taking out steam from the vessel 12. The feed water inlet 20 is supplied via a pump 24' and controlled by a feed water inlet valve 24 and the steam outlet is controlled by a steam outlet valve 26.

[0050] The boiler 10 further comprises a riser 28 and a downcomer 30 forming a closed loop together with the vessel 12. Heat is supplied to the riser causing boiling. The steam rises to the vessel and causes a circulation in the riser 28 - vessel 12 - downcomer 30 loop. In the present schematic view only one riser and one downcomer are presented, however, in practice many risers and downcomers are used. The boiler 10 further comprising a pressure sensor 32 for measuring the pressure in the vessel 12.

[0051] FIG. 2 is a block diagram illustrating the feed water level control strategy according to the present invention. The block having the reference numeral 34 is the block representing the plant, i.e. the boiler. Thus, the inputs to the block 34 are the supply of feed water q_f and the supply of heat Q while the outputs from the block 34 are the measured liquid level l and the measured pressure p in the vessel. The disturbance is the outflow of steam q_s however, according to the present invention, the outflow of steam q_s is not directly measured. The outflow of steam q_s from the boiler is controlled by the steam valve having the reference numeral 36, and the measurable disturbance is then the opening degree OD_{st} of the steam valve 36. The supply of feed water q_f is controlled by the feed water valve/pump 38 which has the opening degree OD_{fw} of the feed water valve 38 as input, and optionally the pressure p in the boiler and the rotational speed of the pump ω. The boiler pressure p can affect the feedwater flow into the boiler since it is the pressure on the secondary side of the feedwater valve/pump

[0052] The blocks marked" PI" having the reference numerals 40 and 42, respectively, implement the proportional-integral control actions for the water level l and boiler pressure p. The control action should be designed to minimize the adverse effect of a change in the disturbance, i.e. the change of steam load, on the water level in the boiler. As a baseline, the control system is fitted with two independent PI controllers: one controls the heat input based on the pressure measurement and the other controls the feed water input based on the water level measurement. The following standard PI control expressions are used for the two system inputs q_f and Q:

$$q_f = \xi_{wl} - N_{wl}\left(l - l_{ref}\right) \quad \text{[eq. 1]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l - l_{ref}) \quad \text{[eq. 2]}$$

$$Q = \xi_p - N_p\left(p - p_{ref}\right) \quad \text{[eq. 3]}$$

$$\dot{\xi}_p = -K_p(p - p_{ref}) \quad \text{[eq. 4]}$$

where $\xi_{(\cdot)}$ denotes the respective controller states; $K_{(\cdot)} > 0$ the integral gain; $N_{(\cdot)} > 0$ the proportional gain; $(\cdot)_{ref}$ the reference values for the respective outputs. The response of the closed loop system using this baseline control is exactly the opposite of what is needed, and it aggravates the subsequent drop in the boiler water level, see FIG. 4. The initial response of the PI controller to an increase in the steam load is to decrease the flow of feed water. This can be particular problematic if the boiler volume is relatively small.

[0053] The main strategy to improve the closed loop system response to changes in the steam load is to detect the (rising/falling) edge of the disturbance using a filter which has zero output for constant inputs and gives a non-zero output whenever the input signal to the filter changes value.

[0054] The opening degree OD_{st} of the steam valve is fed to a lead filter 44 which generates a filter output y_{ll}. These parts are marked in dashed blocks and wires. The path leading to the block having reference numeral 46 is the feed-forward strategy L_{ff} while the path leading to the block having reference numeral 48 is the feed-back strategy L_{fb}.

[0055] FIG. 3. shows the step response of the phase-lead filter. To detect the edge of the change in the disturbance k_v a phase-lead filter with zero dc gain is used which is described by the following continuous time differential equation:

$$\dot{y}_{ll} = -p_{ll} y_{ll} + \dot{k}_v \quad \text{[eq. 5]}$$

where $p_{ll} > 0$ is the pole of the filter. Now, the term $\dot{k}_v$ is not well defined for piecewise constant k_v. However, to illustrate the intuition behind the filter it can be assumed that it can be defined as something like an impulse (Diracs delta) at the time instance where k_v changes value. Since the unforced equation above describes an integrator, the output response of the filter to this impulse is to initially rise to one at the time of the impulse and subsequently decay to zero. The speed of this decay is determined by the pole p_{ll}.

[0056] While the continuous time implementation of [eq. 5] is somewhat problematic for nondifferentiable k_v in the end the filter needs to be implemented in discrete time on a computer which is not problematic as long as the change in k_v between samples is finite. In discrete time [eq. 5] can be implemented at the kth sample as:

$$y_{ll}[k] = a_0 k_v[k] - a_1 k_v[k-1] + b_1 y_{ll}[k-1] \quad \text{[eq. 6]}$$

where a_0, a_1, $b_1 > 0$ are parameters of the filter. The parameters of [eq. 6] can be calculated based on the suggestions given in the publication by S. W. Smith, "The Scientist and Engineer's Guide to Digital Signal Processing", 2nd ed. California Technical Publishing, 1999: $a_0 = a_1 = \frac{(1+b_1)}{2}$ and $0 < b_1 = 1$ where $1 - b_1$ is the desired decay between samples. That is, within x samples, the filter has decayed to $(b_1)^x$ of the initial value. Thus, parameter b_1 is related to the pole p_{ll} of the continuous time filter. The decay parameter b_1 has in the present case been chosen in the following way: It may be desired to design the filter to decay to 10% of the initial value within T seconds. With a sample-time of T_{s1} this corresponds to T/T_s samples until the filter has decayed to 0.1 times the initial value. Then, b_1 is given by: $b_1 = (0.1)^{T_s/T}$. In the following, two strategies are described to use the output of the filter to compensate for the disturbance.

[0057] The first strategy to improve the response of the level control is to add the output of the filter of [eq. 5] in a feed-forward manner to the control signal from the PI control. The intention is to add a corrective term to the feed water control input immediately when the disturbance occurs without having to wait for the water level to drop before the PI controller takes corrective action. By adding the term as feed-forward, any tampering with the PI loop can be avoided. The feed water control input thus takes the following form:

$$q_f = \xi_{wl} - N_{wl}(l - l_{ref}) - \overbrace{L_{ff} y_{ll}}^{\text{added term}} \quad \text{[eq.7]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l - l_{ref}) \quad \text{[eq.8]}$$

where $L_{ff} > 0$ is the feed-forward gain. The gain L_{ff} should be in the region where $L_{ff} y_{ll}$ is in the same order of magnitude as the output of the PI controller.

[0058] The second strategy to improve the response of the level control is to add the output of the filter of [eq. 5] to the level measurement in a feed-back manner. The intention is to compensate directly in the water level measurement the immediate increase (decrease) of the water level in which the increased (decreased) steam load results.

$$q_f = \xi_{wl} - N_{wl}\left(l + \overbrace{L_{fb}y_{II}}^{\text{added term}} - l_{ref}\right) \qquad \text{[eq.9]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l + \overbrace{L_{fb}y_{II}}^{\text{added term}} - l_{ref}) \qquad \text{[eq.10]}$$

where L_{fb}> 0 should be in the region where l and $L_{fb}y_{II}$ are in the same order of magnitude.

[0059] Simulations have been made to validate the control scheme. The simulation model used for the simulations has been described in the publication by K. J. Åström and R. D. Bell. The boiler used in the simulation model is principally shown in FIG. 1.

[0060] Two water level control strategies designed to accommodate an adverse effect of the water levels inverse response to the disturbance have been used for the simulations. This adverse effect is exhibited by the baseline control strategy which is included for comparison and can be illustrated as follows: due to the initial rise in water level resulting from the pressure drop during a load increase the control will decrease the feed water flow when actually an increase is needed. This initial decrease in water flow exacerbates the following level decrease, see FIG. 4.. Therefore, it is desired to avoid such an initial response of the control.

[0061] In addition to the two control strategies, two cases which differs in which sensors and actuators are available have been simulated. In the first case an ideal scenario has been simulated in which the feed water flow can be directly actuated, and the steam valve resistance is the measurable disturbance. In the second case a more realistic scenario has been simulated in which the feed water flow is controlled by the opening degree of a valve and where the opening degree of the steam valve is the measurable disturbance.

[0062] The system model derived in the publication by K. J. Åström and R. D. Bell is a non-linear state-space model with four state variables. These state variables are: the drum pressure p; the total volume of water V_{wt} in the drum, risers and down-comers; the steam quality (i.e. the mass fraction of steam) α_r at the riser outlet; the volume of steam V_{sd} under the water level in the drum. Exogenous inputs to the system are: the feed water mass flow q_f into the boiler; the heat input Q to the riser; the steam mass flow q_s out of the boiler, see FIG. 1.

[0063] FIG. 4 - FIG. 6 show the results of the simulation of the more ideal case where the feed water flow is directly available for actuation and the steam valve resistance is the measurable disturbance. In each simulation, a step is added to the disturbance (here the valve resistance parameter) and the closed loop system response is observed. In all three cases, the disturbance step is carried out at time t = 10000 s and corresponds to an increase of approximately 30 % in desired energy/steam production. It should be noted that the results obtained with each individual control action could potentially be improved since little time has been spent on tuning them.

[0064] FIG. 4 shows the simulation results when the boiler water level is controlled using the standard/baseline proportional-integral control action in [eq. 1]. Four plots of different time series are given. The upper left plot shows the boiler water level l relative to some desired reference. The upper right plot shows the control signal q_f or the feed water input. The lower left plot shows the boiler pressure p. The lower right plot shows the control signal Q for the heat input. The setup here is that the feed water control should hold the relative boiler water level at a reference of 0 m while the heat control should hold the boiler pressure at a reference value of 8 MPa.

[0065] The initial response of the feed water control to the disturbance is to decrease the feed water input due to the swelling phenomenon evident from the plot of the water level which reaches a maximum of 1.8[cm] approximately at time t = 10100 s. This control response exacerbates the following dip in the water level which reaches a minimum of -8.5 cm below the desired level approximately at time t = 12900 s.

[0066] Note that minimal effort has been put into tuning the gains of these baseline controllers. However, for illustration, they serve the purpose.

[0067] FIG. 5 shows the simulation results when the feed-forward action described by [eq. 7] is added to the boiler water level control. The layout in the figure is the same as in FIG. 4. The initial response of the feed water control to the disturbance has now been changed such that an increased steam demand now leads to an increase in feed water despite of the initial inverse response of the water level. Furthermore, the subsequent dip in the water level has now been decreased with approximately 37 % to a minimum of -5.3 cm approximately at time t = 15600 s. However, the increase in boiler water level preceding the dip has now been increased with 370 % to a maximum of 8.4 cm approximately at time t = 10700 s.

[0068] FIG. 6 shows the simulation results when the disturbance feed-back action described by [eq. 9] is added to the boiler water level control. Again, the layout is the same as in FIG. 4 and FIG. 5. The initial response of the control is to increase the feedwater input despite the initial increase in the water level due to swelling. Compared to the baseline control the subsequent dip in the boiler water level has been decreased with approximately 90 % to -0.8 cm. Furthermore, compared to the baseline control, the preceding rise in the boiler water level is increased by 172 % to 4.9 cm at time t = 10100 s which is less than half of the increase obtained using the feed-forward corrective action.

[0069] FIG. 7 - FIG. 10 show the results of the simulation of the more realistic second case mentioned above. In the simulation results presented in FIG. 4 - FIG. 6 it was assumed that the PI controller used to control the boiler water level had access to measurements of the steam flow valve resistance and that the controller could actuate the feed water flow directly. Such actuation could potentially be realized using an inner loop flow controller. However, such an inner loop controller would be dependent on a measurement of the feed water flow.

[0070] The setup is the one illustrated in FIG. 1 Here the equipment which feeds water to the boiler as well as the valve which determines the steam flow are shown. It will be assumed: 1) that the opening degree of the steam valve OD_{st} is known and can be used as input to the boiler water level controller, 2) that the feed water pump operates at a constant speed and 3) that the opening degree of the feed water valve OD_{fw} is available as the actuation signal for the boiler water level controller.

[0071] Again, three scenarios for the boiler setup has been simulated:

1) The first simulated scenario is with the baseline PI boiler level control according to [eq. 1] and [eq. 2] which now controls the opening degree of the feed water valve based on the measurement of the boiler water level, that is:

$$OD_{fw} = \xi_{wl} - N_{wl}\left(l - l_{ref}\right) \qquad \text{[eq. 11]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l - l_{ref}) \qquad \text{[eq.12]}$$

where OD_{fw} denotes the opening degree of the feed water valve.

2) The second simulated scenario is with the feed-forward disturbance compensation using the lead filtered version of the steam valve opening degree signal OD_{st}, that is

$$y_{ll}[k] = a_0 OD_{st}[k] - a_1 OD_{st}[k-1] + b_1 y_{ll}[k-1] \qquad \text{[eq. 13]}$$

and the feed-forward disturbance compensated control according to can be described by

$$OD_{fw} = \xi_{wl} - N_{wl}\left(l - l_{ref}\right) - \overbrace{L_{ff} y_{ll}}^{\text{added term}} \qquad \text{[eq.14]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l - l_{ref}) \qquad \text{[eq.15]}$$

3) The third simulated scenario is with the feed-back disturbance compensation again using the filtered OD_{st} signal such that the disturbance compensating control can be described by the following equation:

$$OD_{fw} = \xi_{wl} - N_{wl}\left(l + \overbrace{L_{fb} y_{ll}}^{\text{added term}} - l_{ref}\right) \qquad \text{[eq.16]}$$

$$\dot{\xi}_{wl} = -K_{wl}(l + \overbrace{L_{fb} y_{ll}}^{\text{added term}} - l_{ref}) \qquad \text{[eq.17]}$$

[0072] FIG. 7 shows the simulation results obtained using the baseline boiler water level controller defined in the controller equation [eq. 11]. Again, a step in the disturbance, here OD_{st} is introduced at time t = 10000 s. As previously simulated, the immediate response of the boiler water level to the disturbance is a rise to 1.7[cm] approximately at time t = 10060 s. As it can be seen the subsequent response of the boiler water level is a dip to -3.25 cm approximately at time t = 10200 s. Following this dip there is a recovery and then a subsequent dip in the level to -1.55 cm approximately at time t = 12000 s.

[0073] Note again that not much time has been spent tuning the gains of the baseline controller. However, all in all, the baseline controller here appears to be tuned to react more aggressively than in the first round of simulations.

[0074] FIG. 8 shows the simulation results obtained using the feed-forward disturbance compensation as defined in the controller equation [eq. 14]. Here it is seen that, compared with the baseline controller, the initial rise in the boiler water level is exacerbated by approximately 130 % such that it reaches a maximum of 3.88 cm approximately at time t = 10060 s. This is later followed by a dip in the boiler water level which compared with the largest dip in the baseline case has been reduced by 40 % such that it reaches a minimum of -1.92 cm approximately at time t = 12050 s.

[0075] FIG. 9 shows the simulation results obtained using the feed-back disturbance compensation as defined in the controller equation [eq. 16]. It can again be seen that, compared to the baseline control, the rise in level is exacerbated. Here the largest (second) rise is increased with 96 % such that it reaches a maximum of 3.34 cm approximately at time t = 10600 s. The largest dip in boiler water level occurs approximately at time t = 10180 s with a minimum level of -0.72 cm which is a reduction of 78 % compared to the baseline case.

[0076] FIG. 10 shows the results of a simulation of the above control solution including the feed-back disturbance compensation implemented in PLC (Programmable Logic Controller) software. The implementation has been tested in closed loop using the "PLCSim" software by Siemens to emulate the PLC. The results shown in FIG. 10 may be compared to the results shown in FIG. 9 to verify the correctness of the PLC implementation. Overall, the results are the same except for some quantization noise due to rounding errors arising from the finite representation of the control outputs in the PLC. This quantization is indicated in the zoomed areas in FIG. 10.

Claims

1. A method of controlling a supply of feed water into a boiler (10), the boiler (10) comprising a feed water inlet (20) for supplying feed water into the boiler (10), a steam outlet (22) for taking steam from the boiler (10) and a liquid level sensor (14) for measuring a liquid level in the boiler (10), the steam outlet (22) comprising a steam valve (26) defining a steam valve (26) opening degree, the method comprising:

measuring the liquid level in the boiler (10) using the liquid level sensor (14),
determining a rate of change of the steam valve (26) opening degree, and
controlling the supply of feed water into the boiler (10) via the feed water inlet (20) based on the liquid level in the boiler (10), a reference liquid level for the boiler (10) and the rate of change of the steam valve (26) opening degree.

2. The method according to claim 1, wherein the feed water inlet (20) comprises a feed water valve (24) defining a feed water valve (24) opening degree, wherein the method comprises determining the supply of feed water into the boiler (10) by the feed water valve (24) opening degree.

3. The method according to any of the previous claims, wherein the feed water inlet (20) is connected to a pump (24'), the pump (24') defining a flow rate, wherein the method comprises determining the supply of feed water into the boiler (10) by the flow rate.

4. The method according to claim 4, the flow rate is based on the rotational speed of the pump (24').

5. The method according to any of the preceding claims, wherein the controlling of the supply of feed water into the boiler (10) is performed using a PI control scheme (40).

6. The method according to any of the preceding claims, wherein controlling the supply of feed water into the boiler (10) including: generating a feed water control action based on the difference between the liquid level in the boiler (10) and the reference liquid level for the boiler (10), and, determining the supply of feed water into the boiler (10) based on the sum of the feed water control action and the rate of change of the steam valve (26) opening degree.

7. The method according to any of the claims 1-5, wherein controlling the supply of feed water into the boiler (10) including: generating a feed water control action based on the sum of the rate of change of the steam valve (26) opening degree and the difference between the liquid level in the boiler (10) and the reference liquid level for the boiler (10), and, determining the supply of feed water into the boiler (10) by the feed water control action.

8. The method according to any of the preceding claims, wherein the method comprises determining the rate of change of the steam valve (26) opening degree by using a phase-lead filter (44) on the steam valve (26) opening degree.

9. The method according to any of the claims, further comprising the steps of:

measuring a pressure in the boiler (10) using a pressure sensor (32), and
controlling a heat input into the boiler (10) based on the pressure in the boiler (10) and a reference pressure for the boiler (10).

10. The method according to claim 9, wherein controlling a heat input into the boiler (10) including: generating a heat input control action based on the difference between the pressure in the boiler (10) and a reference pressure for the boiler (10), and, determining the heat input into the boiler (10) by the heat input control action.

11. The method according to any of the claims 9-10, wherein the controlling of the heat input into the boiler (10) is performed using a PI control scheme (43).

12. A boiler (10) having a control system for controlling a supply of feed water into a boiler (10), the boiler (10) comprising a feed water inlet (20) for supplying feed water into the boiler (10), a steam outlet (22) for taking steam from the boiler (10) and a liquid level sensor (14) for measuring a liquid level in the boiler (10), the steam outlet (22) comprising a steam valve (26) defining a steam valve (26) opening degree, the control system controlling the supply of feed water into the boiler (10) via the feed water inlet (20) based on the liquid level in the boiler (10), a reference liquid level for the boiler (10) and a rate of change of the steam valve (26) opening degree.

13. The system according to claim 12, further comprising any of the features of claims 1-11.

14. A computer program comprising instructions which, when the program is executed by a computer, cause the computer to carry out the method of any of the claim 1-11.

15. A computer-readable medium having stored thereon the computer program of claim

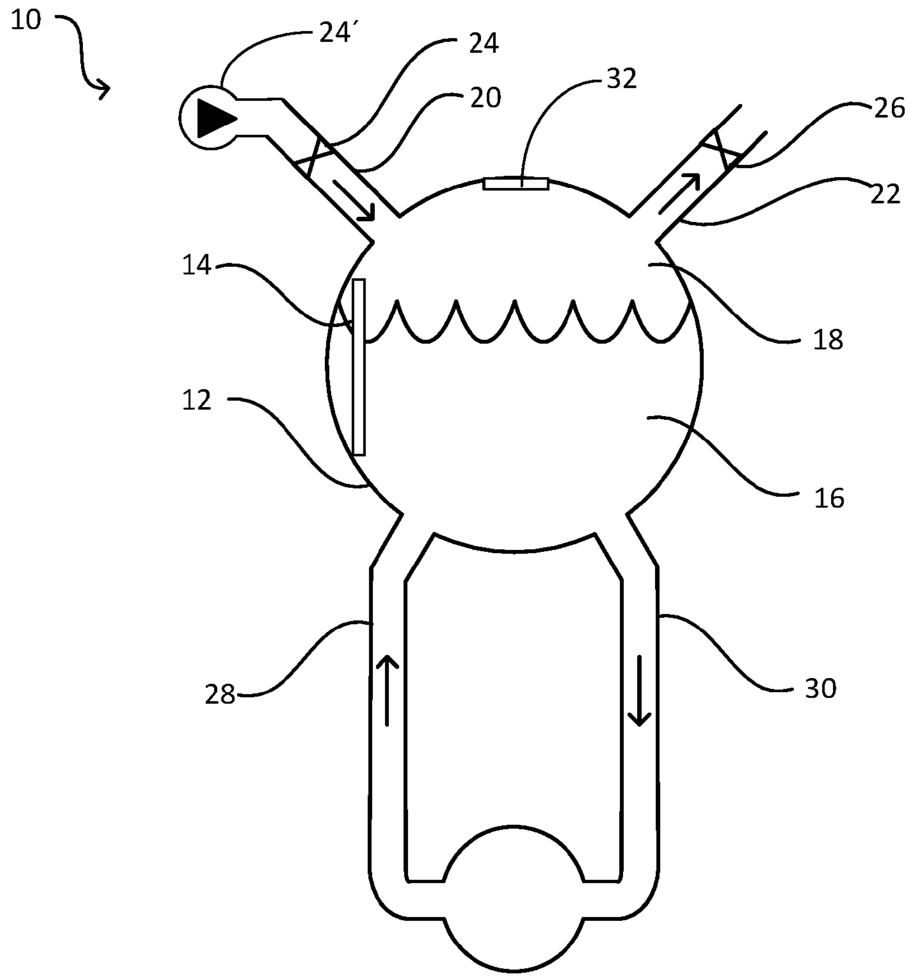

10
24´
24
20
32
26
22
14
18
12
16
28
30

FIG. 1

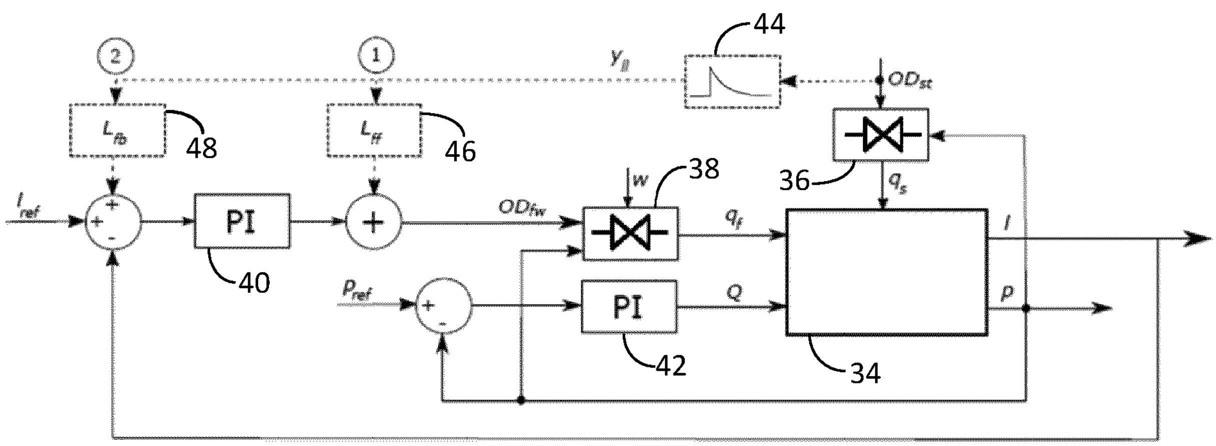

2
1
y_{ll}
44
OD_{st}
L_{fb}
48
L_{ff}
46
w
38
36
q_s
l_{ref}
PI
OD_{fw}
q_f
l
40
p_{ref}
PI
Q
p
42
34

FIG. 2

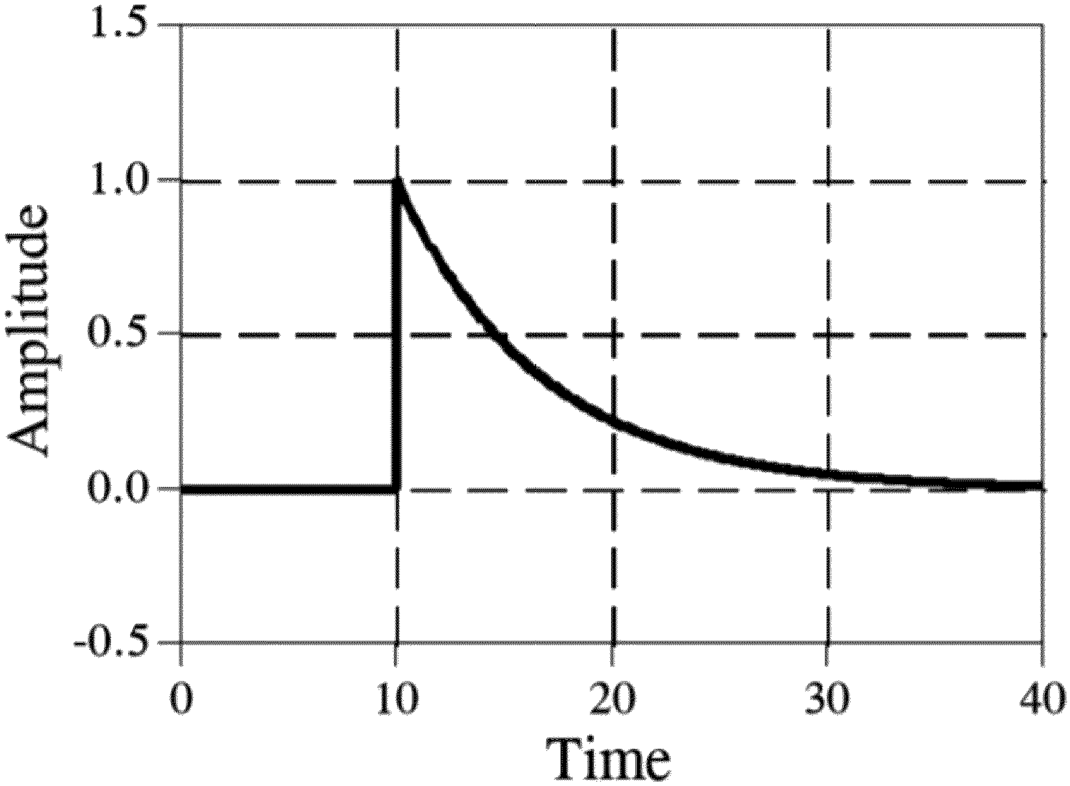
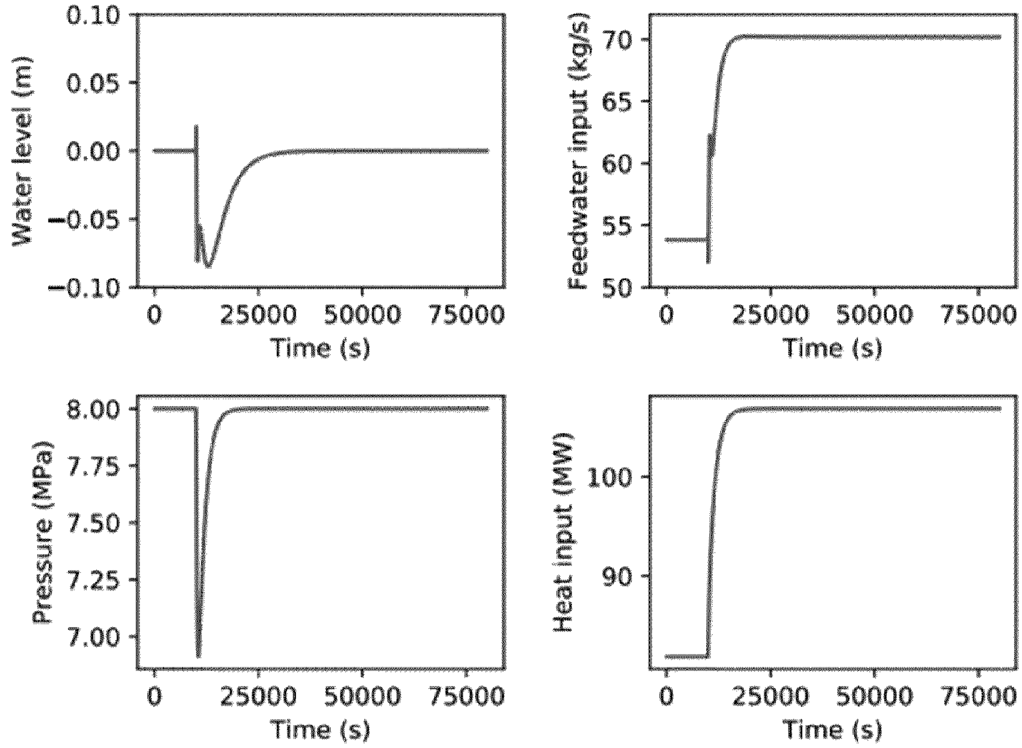
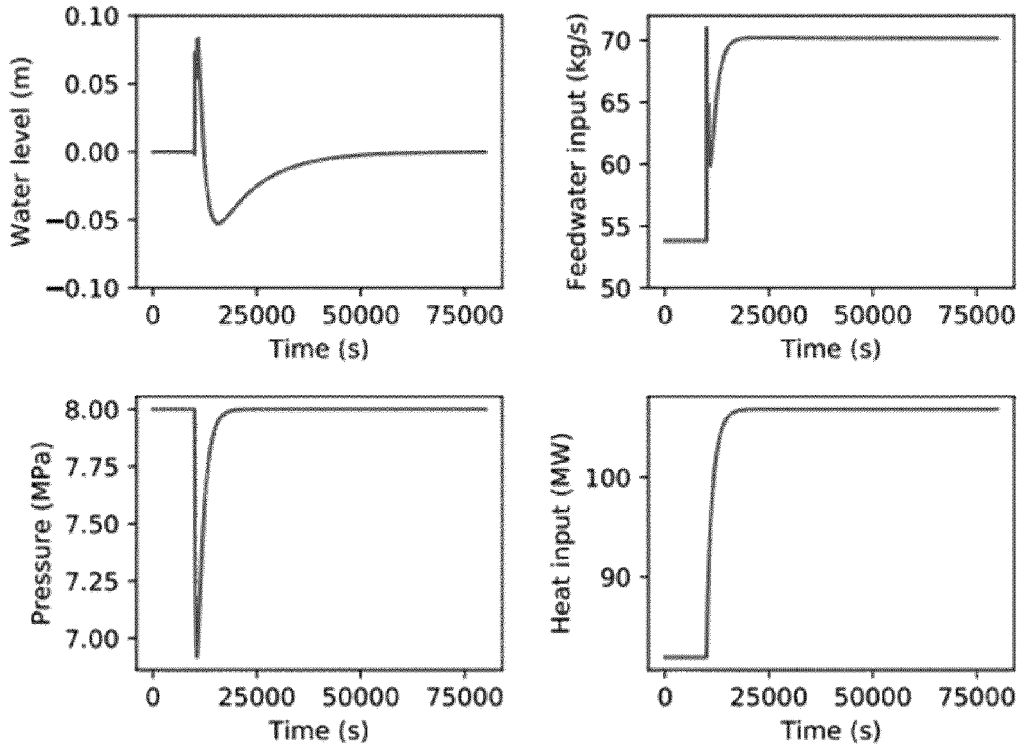


FIG. 3



Water level (m)
0.10
0.05
0.00
−0.05
−0.10
0
25000
50000
75000
Time (s)
Feedwater input (kg/s)
70
65
60
55
50
Pressure (MPa)
8.00
7.75
7.50
7.25
7.00
Heat input (MW)
100
90

FIG. 4



Water level (m)
0.10
0.05
0.00
−0.05
−0.10
0
25000
50000
75000
Time (s)
Feedwater input (kg/s)
70
65
60
55
50
Pressure (MPa)
8.00
7.75
7.50
7.25
7.00
Heat input (MW)
100
90

FIG. 5

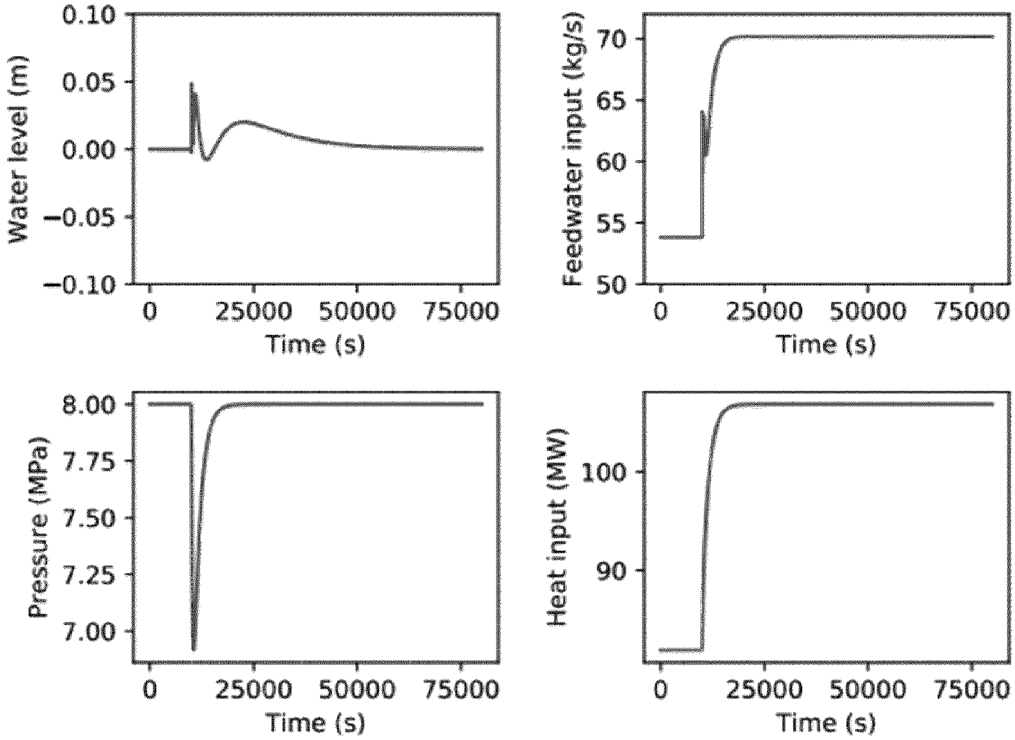

0.10
0.05
0.00
−0.05
−0.10
Water level (m)
0
25000
50000
75000
Time (s)
70
65
60
55
50
Feedwater input (kg/s)
8.00
7.75
7.50
7.25
7.00
Pressure (MPa)
100
90
Heat input (MW)

FIG. 6

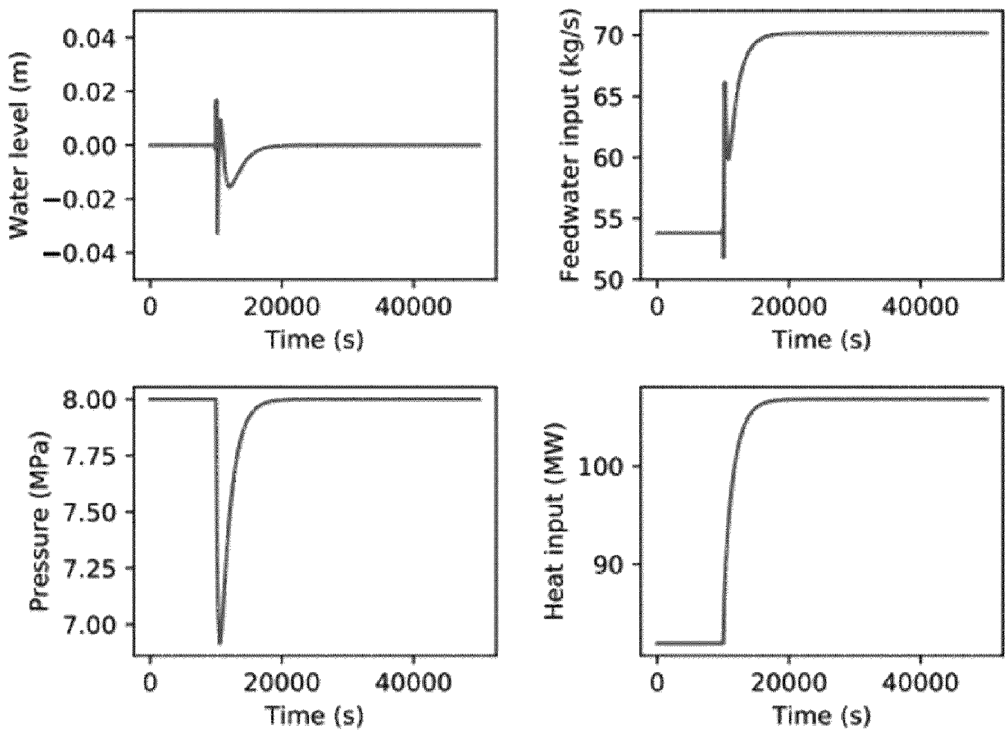

0.04
0.02
0.00
−0.02
−0.04
Water level (m)
0
20000
40000
Time (s)
70
65
60
55
50
Feedwater input (kg/s)
8.00
7.75
7.50
7.25
7.00
Pressure (MPa)
100
90
Heat input (MW)

FIG. 7

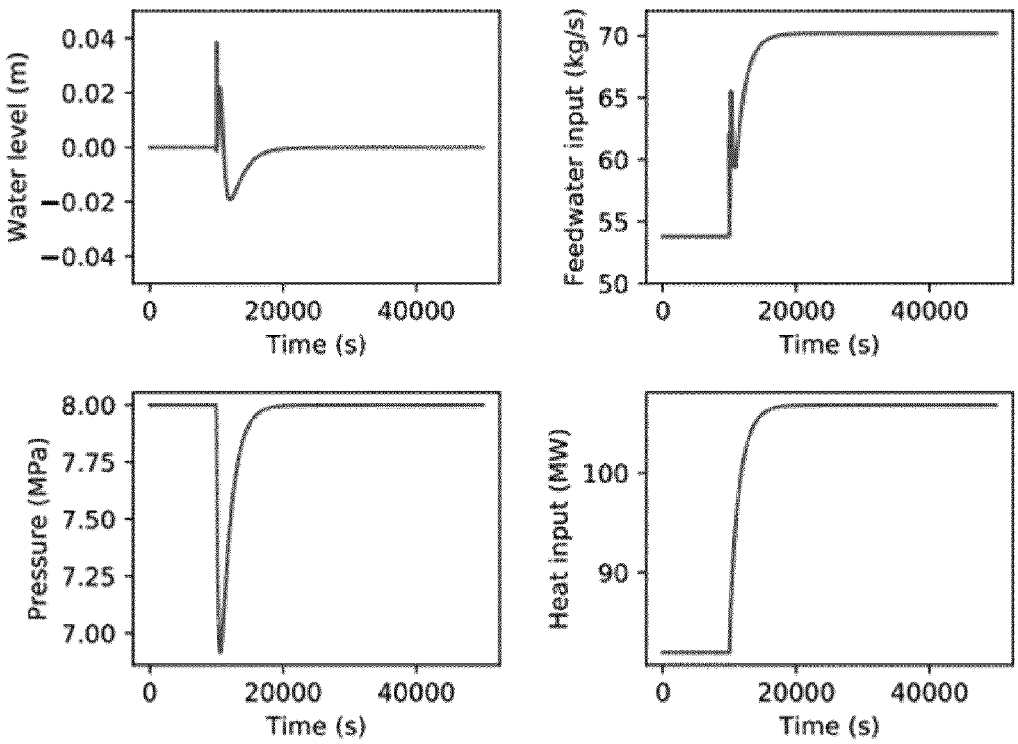

Water level (m)
Feedwater input (kg/s)
Pressure (MPa)
Heat input (MW)
Time (s)

FIG. 8

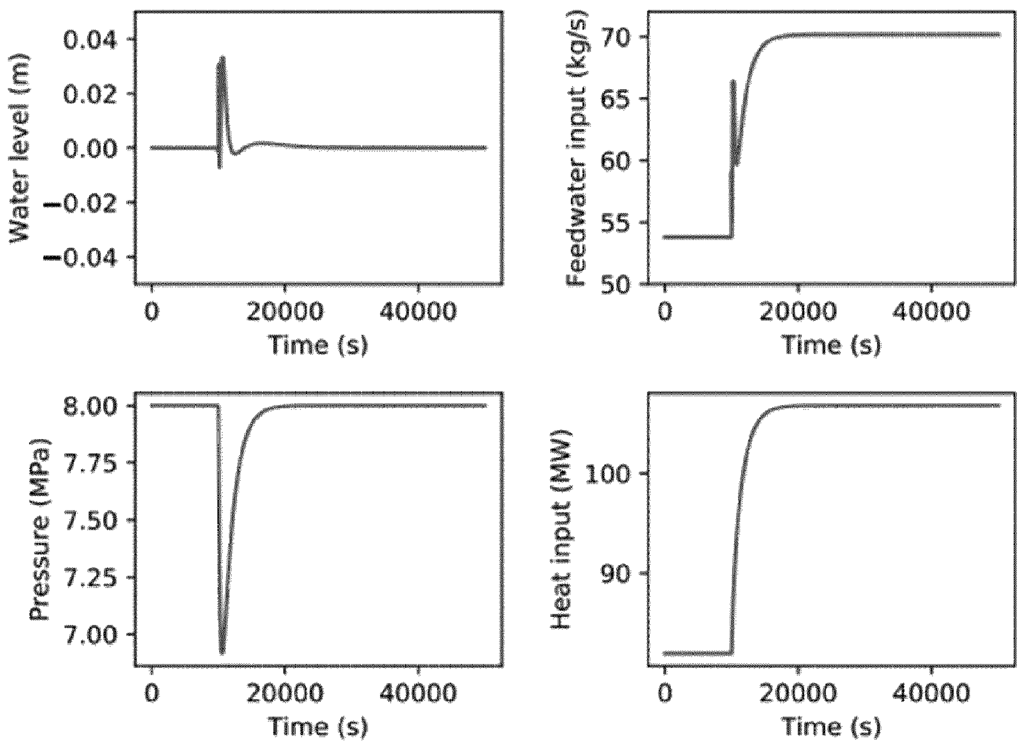

Water level (m)
Feedwater input (kg/s)
Pressure (MPa)
Heat input (MW)
Time (s)

FIG. 9

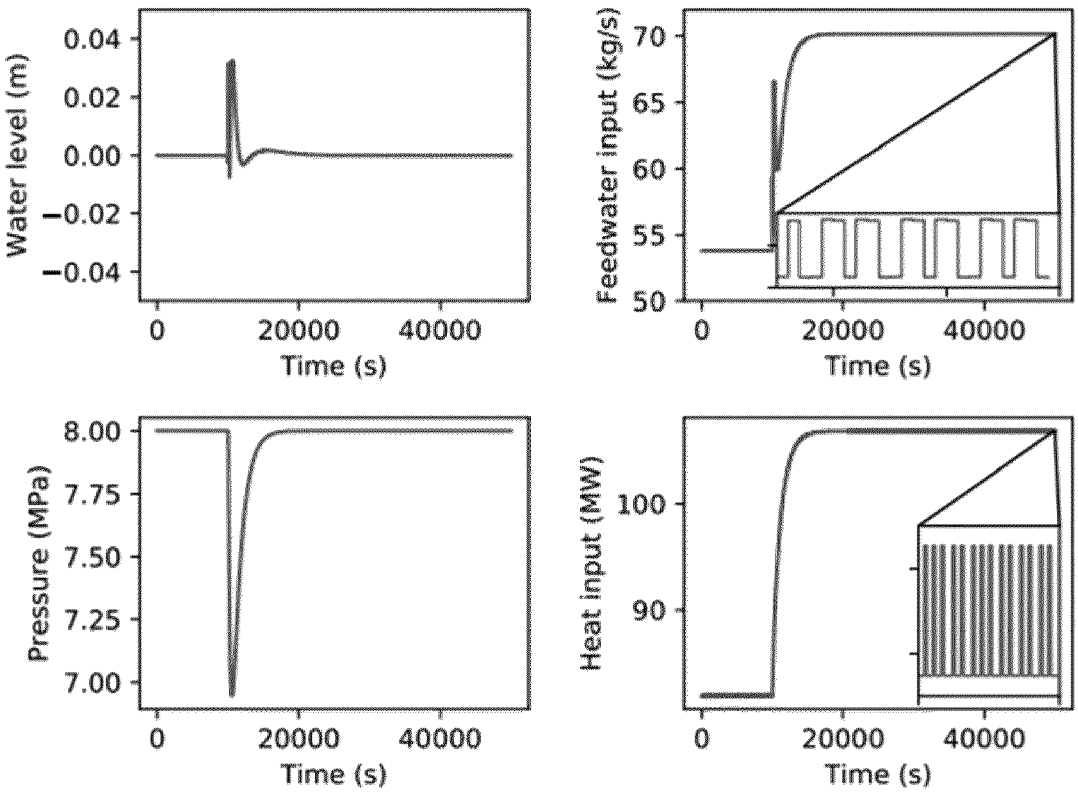

Water level (m)
0.04
0.02
0.00
−0.02
−0.04
0
20000
40000
Time (s)
Feedwater input (kg/s)
70
65
60
55
50
0
20000
40000
Time (s)
Pressure (MPa)
8.00
7.75
7.50
7.25
7.00
0
20000
40000
Time (s)
Heat input (MW)
100
90
0
20000
40000
Time (s)

FIG. 10

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EUROPEAN SEARCH REPORT

Application Number
EP 20 20 5158

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 2015/167961 A1 (TIWARI AWADESH KUMAR [IN] ET AL) 18 June 2015 (2015-06-18) * abstract; figures 1-3 * * paragraphs [0013] - [0018], [0025], [0033] - [0036] *	1-15	INV. F22D5/30 F22D5/34
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TECHNICAL FIELDS SEARCHED (IPC)

F22D

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
Munich	31 March 2021	Varelas, Dimitrios

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31-03-2021

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