Improving flexibility characteristics of 200 MW unit

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Abstract   Calculations were performed of the thermal system of a power plant with installed water pressure tanks. The maximum rise in the block electric power resulting from the shut-off of low-pressure regenerative heaters is determined. At that time, the boiler is fed with hot water from water pressure tanks acting as heat accumulators. Accumulation of hot water in water tanks is also proposed in the periods of the power unit small load. In order to lower the plant electric power in the off-peak night hours, water heated in low-pressure regenerative heaters and feed water tank to the nominal temperature is directed to water pressure tanks. The water accumulated during the night is used to feed the boiler during the period of peak demand for electricity. Drops in the power block electric power were determined for different capacities of the tanks and periods when they are charged. A financial and economic profitability analysis (of costs and benefits) is made of the use of tanks for a 200 MW power unit. Operating in the automatic system of frequency and power control, the tanks may also be used to ensure a sudden increase in the electric power of the unit. The results of the performed calculations and analyses indicate that installation of water pressure tanks is well justified. The investment is profitable. Water pressure tanks may not only be used to reduce the power unit power during

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the off-peak night hours and raise it in the periods of peak demand, but also to increase the power capacity fast at any time. They may also be used to fill the boiler evaporator with hot water during the power unit start-up from the cold state.

Keywords: Thermal power unit; Flexibility increasing; Steam boiler; Rapid start-up

Nomenclature

c_p	–	specific heat capacity at constant pressure, J/(kg K)
c_{wall}	–	specific heat capacity of a tube material, J/(kg K)
D	–	diameter, m
d	–	diameter, m
d_{in}	–	inner diameter of the tube, m
G	–	generator
h	–	specific fluid enthalpy, kJ/kg
h_{blp}	–	enthalphy of the steam at the outlet of LP-turbine
$h_{RH_1}^{inlet}$	–	steam specific enthalpy upstream the steam reheater stage I, kJ/kg
h_{SH5}^{outlet}	–	specific enthalpy of the boiler live steam, kJ/kg
h_{WLP}	–	specific enthalpy of the steam flow from the low-pressure turbine part, kJ/kg
L_s	–	tube length, m
n	–	number of tanks
N	–	number of transfer units
p	–	pressure, MPa
r	–	tube radius, m
s^+	–	dimensionless curvilinear coordinate, m
t	–	time, s
t_{peak}	–	duration of peak load, s
T	–	temperature, °C
$\dot{Q}$	–	heat flow rate, MW
$\dot{Q}_c$	–	convective heat flow rate from the water-walls to the flowing air, MW
H_{LV}	–	lower heating value (fuel calorific value), kJ/kg
H_{tank}	–	height of accumulation tank, m
$\dot{m}$	–	fluid mass flow rate, kg/s

Greek symbols

α	–	heat transfer coefficient, W/(m²K)
α_o	–	equivalent heat transfer coefficient on the air side considering the heat transfer through the longitudinal fins, W/(m²K)
η_b	–	boiler efficiency
ρ_{wall}	–	density of the tube material, kg/m³
ρ_w	–	water density, kg/m³
τ	–	time constant of water, air, and riser tube, respectively, s

Subscripts and superscripts

∞	–	ambient temperature
$I, \ldots, VII$	–	bleed steam
a	–	air
b	–	boiler
BR	–	brine
FW	–	feed water
i	–	initial
in	–	inner
IP	–	intermediate-pressure turbine
hw	–	hot water
HP	–	high-pressure turbine
LP	–	low-pressure turbine
LS	–	live steam
nom	–	nominal (design) temperature
out	–	outer
RH	–	steam reheater
SH	–	live steam superheater stage
w	–	riser tube wall, water
$wall$	–	outer

1   Introduction

Due to the rapid development of wind farms, photovoltaic cells, and other dispersed energy sources, considerable oscillations occur in electric power generation. If a power shortage is created in the electric power system, electricity needs to be supplied to the power grid quickly by thermal power plants. A requirement is also imposed on state-of-the-art power units to make it possible to raise or lower the power capacity at the rate of 2–8% of installed power per minute in the full range of control, i.e., from the minimum to the maximum load. The power unit start-up from different states should also proceed fast. The manufacturer of state-of-the-art power units is obliged to carry out the following tests:

- start-up from the cold state (after 8 h of unit standstill),

- start-up from the hot state (alter 8 to 50 h of unit standstill),

- start-up from the cold state (after more than 50 hours of unit standstill).

This paper presents an analysis of the possibility of using hot water pressure tanks to improve a 200 MW power unit flexibility. The tanks may be used in the off-peak night hours to reduce the power unit power capacity due to

low demand for electricity. In the period of low demand, the boiler may operate at the minimum permissible load (at the level of the boiler technical minimum), and steam is then used both to generate electrical energy and to heat up hot water accumulated in the tanks.

In the period of peak demand for electricity, which in Poland is between 4 p.m. and 10 p.m., the power unit capacity may be raised. Low-pressure regenerative bleeds are then shut off, which involves a rise in the electric power of the block due to a bigger mass flow of steam through the turbine. The boiler is fed with hot water accumulated in the tanks.

Hot water tanks may also be used to fill the boiler with hot water at the beginning of the boiler start-up. According to the boiler drum optimal heating method proposed in [1–3], the boiler evaporator together with the drum may be flooded with hot water with a temperature much higher than the initial one. The pressure tank hot water may be used to feed the bottom headers of the boiler furnace chamber walls, and the water displaced from the boiler evaporator may be directed to the bottom part of the pressure tank. Owing to such heat accumulators, the boiler start-up from the cold state becomes faster and safer.

Hot water pressure tanks may also be used in the automatic system of frequency and power control to ensure a sudden increase in the power unit electric power. Shutting off low-pressure regenerative bleeds and feeding the boiler with hot water from the tanks, it is possible to raise the power unit maximum power capacity by more than 7% in several hours.

In this paper, a mathematical model for an optimum heating the boiler evaporator with hot water is presented. Also, the power increase in the peak load using water pressure accumulators and power reduction during the night by closing turbine bleeds are calculated.

2   Model of the evaporator tube heating

To simulate heating boiler evaporator mathematical models of water walls and downcomers (Fig. 1) were developed. The cold air flows through the combustion chamber during evaporator heating. The outer surfaces of the downcomers are thermally insulated.

A differential form of the energy conservation equation for water flowing through the evaporator tubes and the energy conservation equation for the evaporator tube wall will be derived first.
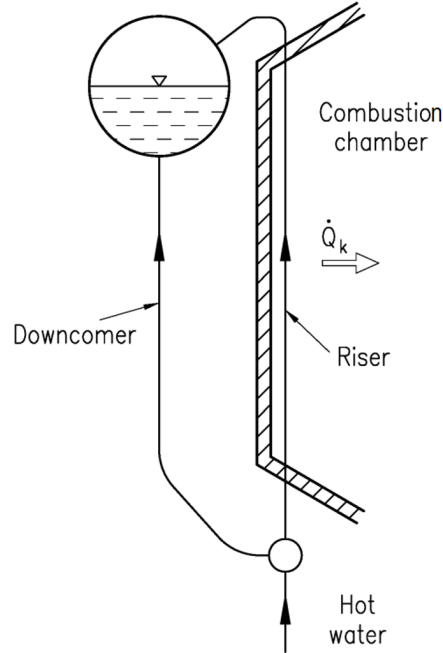
Figure 1: Diagram of water cooling and metal heating in the evaporator after it is suddenly filled with hot water.

2.1 Energy balance equation for water flowing through the evaporator and the riser tubes

Transforming the energy balance equation for a control volume with length $\Delta s \rightarrow 0$, the following is obtained

$$\tau_w \frac{\partial T_w}{\partial t} + \frac{1}{N_w} \frac{\partial T_w}{\partial s^+} = -\left(T_w - T_{wall}\right) \ , \tag{1}$$

where

$$N_w = \frac{\alpha_w \pi d_{in} L_s}{\dot{m}_w c_w} \quad \text{and} \quad \tau_w = \frac{d_{in}}{4\alpha_w} \rho_w c_w \ . \tag{2}$$

It is assumed that at the time $t = 0$ the temperature of water in the evaporator tubes is constant and equal to ambient temperature T_∞, i.e., the initial condition is expressed as

$$T_w\big|_{t=0} = T_\infty \ . \tag{3}$$

Hot water with temperature T_{hw} flows into the riser tubes through lower headers to the boiler waterwalls and the boundary condition is of the following form:

$$T_w|_{s^+=0} = T_{hw} \ . \tag{4}$$

Equation (1) with conditions (3)–(4) have been solved using the finite difference method.

2.2 Energy balance equation for the waterwall tubes

Transforming the energy balance equation derived for a wall, assuming that the wall is an element with a lumped thermal capacity, the following is obtained:

$$\tau_{wall}\frac{dT_{wall}}{dt} + T_{wall} = \frac{2r_{in}\alpha_w T_w + r_{out}\alpha_o T_a}{2r_{in}\alpha_w + r_{out}\alpha_o} \ , \tag{5}$$

where the time constant, τ_{wall} is expressed as

$$\tau_{wall} = \frac{\left(r_{out}^2 - r_{in}^2\right)\rho_{wall}c_{wall}}{2r_{in}\alpha_w + r_{out}\alpha_o} \ . \tag{6}$$

The value of the waterwall tube time constant is highly dependent on the tube wall thickness and on the weighted heat transfer coefficient on the air side, which is much lower than on the water side.

The initial condition for Eq. (5) has the following form:

$$T_w|_{t=0} = T_\infty \ , \tag{7}$$

where T_∞ denotes ambient temperature.

2.3 Energy balance equation for air in the combustion chamber

Transforming the energy balance equation for the ith control volume on the air side, the following is obtained:

$$\tau_a\frac{\partial T_a}{\partial t} + \frac{1}{N_a}\frac{\partial T_a}{\partial s^+} = (T_{wall} - T_a) \ , \tag{8}$$

where

$$N_a = \frac{n_t\pi\, r_{out}\alpha_o L_s}{\dot{m}_a\, c_p} \quad \text{and} \quad \tau_a = \frac{A_c\,\rho_a\, c_{p,a}}{n_t\pi\, r_{out}\alpha_o} \ . \tag{9}$$

The initial and the boundary conditions are as expressed as

$$T_a|_{t=0} = T_\infty \quad \text{and} \quad T_a|_{s^+=0} = T_\infty \ .$$ (10)

Equation(8) with conditions (10) will be solved using the finite difference method. In the same way downcomers were modeled.

3   Analysis of the possibility of using water tanks to fill the evaporator with hot water during start-up from the cold state
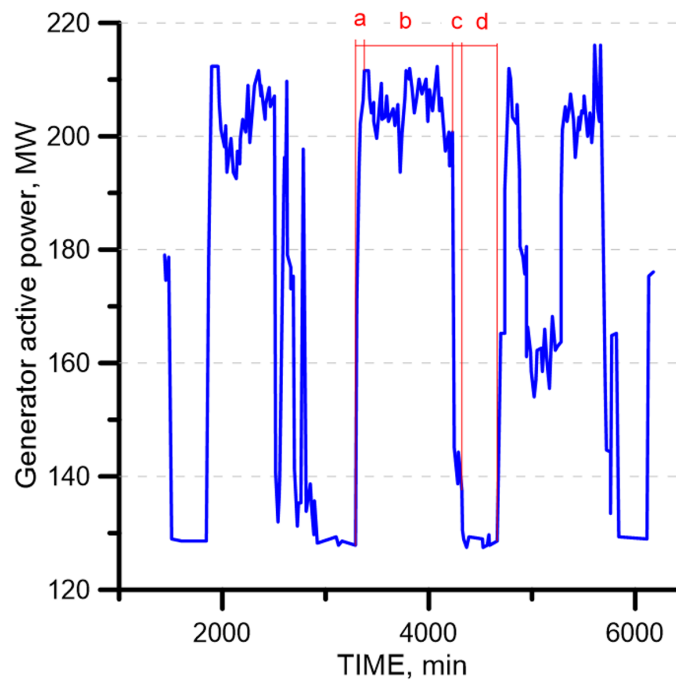

Figure 2: History of changes in power, fuel mass flow, and the boiler efficiency in a three-day operating cycle of the power unit of the power plant: a – increase in power from the minimum to the maximum value 1.5 h, 2015-06-10 06:45–08:15, b – power unit operation under a nominal load during the day 14.25 h, 2015-06-10 08:15–22:30, c – decrease in power from the maximum to the minimum value 1.5 h, 2015-06-10 22:30–2015-06-11 00:00, d – power unit operation under the minimum load during the night 6 h, 2015-06-11 00:00–06:00.

Figure 2 presents charts of basic parameters of the power unit operation in the power plant. The presented period covers 5 days of the power unit continuous operation: from 2015-06-06 (00:00) to 2015-06-12 (08:00), Monday to Friday. Characteristic periods of the power unit operation (a, b, c, d) are marked in the Fig. 2.

Diagram of the power unit with a hot water storage tank, in the period of peak demand for electricity and low demand for electricity, are shown in Fig. 3. Pressure tanks may be used to flood the boiler evaporator with hot water during the power unit start-up from the cold state (Fig. 3a). Filling the evaporator and then the drum with the initial temperature T_{wi} with hot water with temperature $T_{wi} + \Delta T_w$ (Fig. 4), the drum heating rate may be reduced in further stages of the start-up. If the start-up time is a bit shorter compared to the time obtained based on PN-EN 12952-3 standard, stresses on the edge of the hole in the drum-downcomer tube interface do not exceed permissible values [1–3]. If the boiler evaporator is heated at rates determined according to PN-EN 12952-3 standard, permissible stress values are exceeded on a part of the hole perimeter [4]. This may quickly give rise to cracks on the downcomer tube hole edge. The method of the boiler start-up proposed in [1-3], where the boiler evaporator is flooded with hot water, is safe. Unlike Standard PN-EN 12952-3, the method allows an abrupt rise in the working medium temperature in the drum at the beginning of the drum heating process. The water temperature in the boiler drum may be raised even up to 100 °C, which makes it possible to reduce the consumption of mazut fired in the boiler. In the start-up, first, phase the temperature of the medium is raised to the nominal temperature of about 315 °C from 100 °C but not from 20 °C to 315 °C.

3.1   Calculations of the water tank capacity

Calculations of the capacity of hot water tanks was conducted for preliminary assumptions:

- absolute pressure: $p = 0.7$ MPa,
- saturation temperature: $T = 164.9\,°$C,
- water density: $\rho_w = 902.56$ kg/m^3,
- power unit power: 200 MW,
- boiler output: $\dot{m}_w = 650$ t/h $= 180.5$ kg/s,
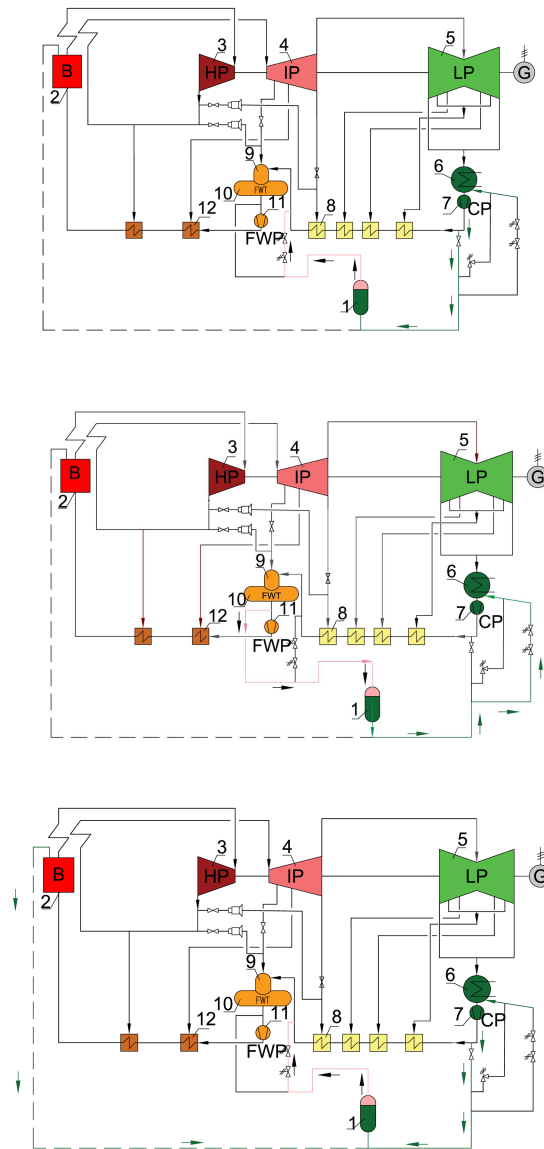- inner diameter of a single tank: $d_{in} = 3$ m.

Figure 3: Diagram of the thermal power plant with storage of hot water: a) rapid increase in the power block, b) reduction of the power block and filling the storage tank with hot water, c) rapid start-up of the boiler from cold and warm state; 1 – heat storage tank, 2 – boiler, 3 – high-pressure turbine, 4 – intermediate-pressure turbine, 5 – low-pressure turbine, 6 – condenser, 7 – condensate pump, 8 – low-pressure regenerative heaters, 9 – deaerator, 10 – feedwater tank, 11 – feedwater pump, 12 – high-pressure regenerative heaters.
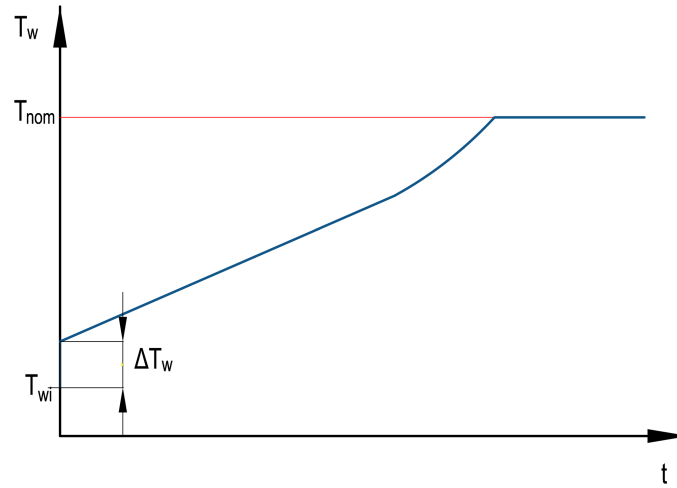
Figure 4: Proposed optimum change in the temperature of the medium in the drum.

It should be mentioned that the power unit generating capacity may be higher – it may reach as much as 225 MW at the live steam mass flow of 680–700 t/h. The results obtained from the analyses may be linearly extrapolated to higher or lower loads. The results calculations of the capacity of hot water tanks at different times of the boiler being fed from them shown in Tab. 1.

Table 1: Results for diameter $d_{in} = 3$ m.

Tank dimensions			Time of peak-demand operation	Water volume	Number of tanks
Diameter	Height	Capacity			
m	m	m^3	min	m^3	pcs
3	25.5	180.25	30	360.09	2
			60	720.17	4
			120	1440.35	8
			180	2160.52	12
			240	2880.69	16

The following relations have been used to calculations of water required volume, V_w, and height of tanks, H_{tank}

$$V_w = \frac{\dot{m}}{\rho_w} t_{peak} \; , \tag{11}$$

$$H_{tank} = \frac{V_w}{n\frac{\pi d_{in}^2}{4}} \; , \tag{12}$$

where n is the number of tanks. The tanks may be made of vertical vessels with stratification of cold and hot water and operating in a parallel system (Fig. 5). The hot water tanks may also be horizontal. In this case, they operate as a series-parallel system.
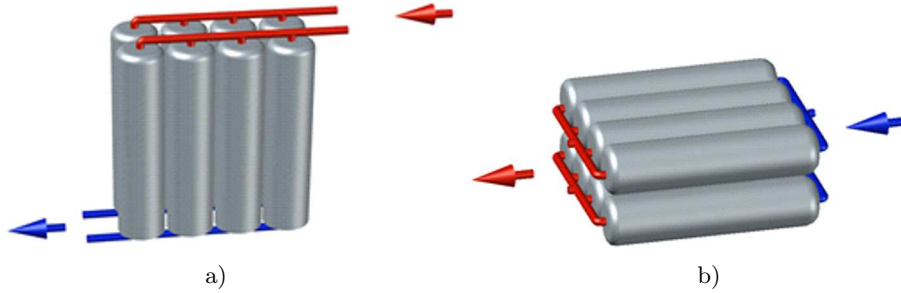

Figure 5: Several configuration variants of the hot water tanks a) vertical, parallel configuration of tanks; b) horizontal, parallel configuration.

3.2   Method of the power capacity determination for the power unit

Mass flow rates and temperatures of water and steam were determined from solving a system of equations of mass and energy balance set for all components of the thermal power plant. An example of the control region for the boiler is shown in Fig. 6, presents simplified diagram of the boiler with intake of injection water from outside the control region boundary used to write the mass and energy balance equations.

The expressions for calculating the power of the turbine set in the night off-peak are:

- internal power generated in a high-pressure part of the turbine set

$$\dot{Q}_{HP} = \dot{m}_s \left(h_{SH5}^{outlet} - h_I \right) + (\dot{m}_s - \dot{m}_I)(h_I - h_{II}) \; , \tag{13}$$
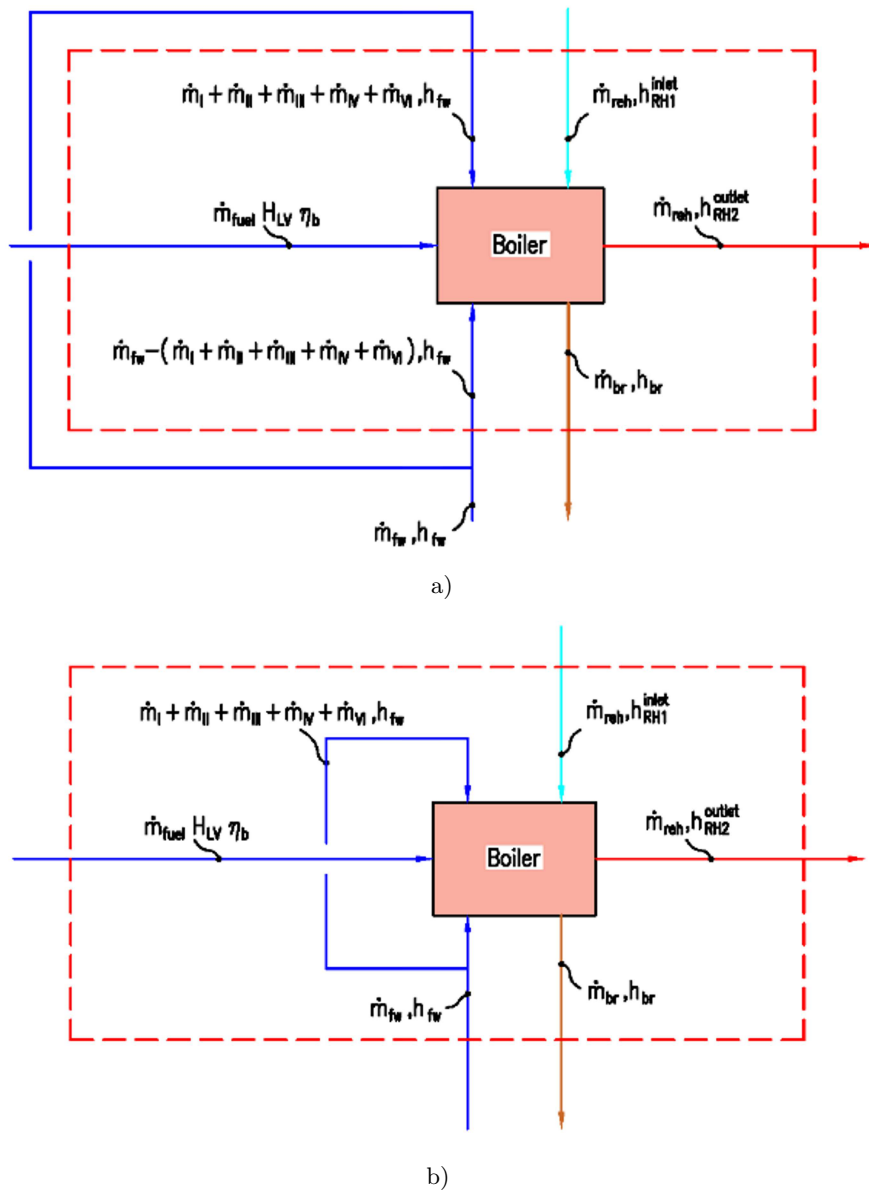
a)

b)

Figure 6: Simplified diagram of the boiler a) intake of injection water beyond the balance boundary, b) intake of injection water and injection into steam temperature regulators are included inside the balance boundary.

- internal power generated in an intermediate-pressure part of the turbine set

$$
\begin{aligned}
\dot{Q}_{IP} =\ & \dot{m}_{IP}\left(h_{IP} - h_{III}\right) + \left(\dot{m}_{IP} - \dot{m}_{III}\right)\left(h_{III} - h_{IV}\right) + \\
+\ & \left(\dot{m}_{IP} - \dot{m}_{III} - \dot{m}_{IV}\right)\left(h_{IV} - h_{V}\right) + \\
+\ & \left(\dot{m}_{IP} - \dot{m}_{III} - \dot{m}_{IV} - \dot{m}_{V}\right)\left(h_{V} - h_{VI}\right),
\end{aligned}
\tag{14}
$$

- internal power generated in a low-pressure part of the turbine set

$$
\dot{Q}_{LP} = \dot{m}_{LP}\left(h_{LP} - h_{VII}\right) + \left(\dot{m}_{LP} - \dot{m}_{VII}\right)\left(h_{VII} - h_{blp}\right),
\tag{15}
$$

- the total internal power of the turbine set

$$
\dot{Q}_{t} = \dot{Q}_{HP} + \dot{Q}_{IP} + \dot{Q}_{LP},
\tag{16}
$$

- the relative drop in the power unit power

$$
\dot{Q}_{proc} = \frac{100\dot{Q}_{t}}{\dot{Q}},
\tag{17}
$$

- drop in power during the night off-peak hours

$$
S_{M} = 100 - \dot{Q}_{proc}.
\tag{18}
$$

The energy balance equation for the example the control region for the boiler is given by

$$
\dot{m}_{fuel}\,H_{LV}\,\eta_{b} + \dot{m}_{fw}\,h_{fw} + \dot{m}_{reh}\,h_{RH1}^{inlet} = \dot{m}_{s}\,h_{SH5}^{outlet} + \dot{m}_{reh}\,h_{RH2}^{outlet} + \dot{m}_{br}\,h_{br}.
\tag{19}
$$

The drop in the boiler output and in the power unit power in the night off-peak hours during the filling of the tank is shown Tab. 2.

The use of hot water accumulators increases the average efficiency of the power plant. The increase in efficiency occurs during the off-peak night hours when demand for electricity is low. The steam taken from the turbine bleed to heat water in hot water tanks does the work, on the section from the turbine inlet to the steam bleed. In this way, the steam taken in the bleed passes the main source of heat loss which is the turbine condenser. Such a method of improving the efficiency of Rankine cycle is also used in power plants through the use of regenerative heating of feed water or in combined heat and power plants for water heating in district heating

Table 2: List of results – the drop in the boiler output and in the power unit power in the night off-peak hours during the filling of the tank (power capacity 206 MW).

Item	Number of tanks	Time of filling the tanks during the night off-peak hours, h	Water mass flow to tanks, t/h	Boiler output during the filling of tanks, t/h	Relative drop in power, %
1		3	108.46	607.38	2.29
2	2	4	81.34	610.51	1.79
3		5	65.07	612.51	1.46
4		6	54.23	613.89	1.24
5		3	216.91	596.99	3.96
6	4	4	162.67	601.80	3.19
7		5	130.15	605.05	2.66
8		6	108.46	607.38	2.29
9		3	433.83	583.03	6.21
10	8	4	325.37	589.13	5.22
11		5	260.30	593.60	4.51
12		6	216.91	596.99	3.96
13		3	650.75	574.21	7.63
14	12	4	488.06	580.46	6.62
15		5	390.45	585.30	5.84
16		6	325.37	589.13	5.22

network. In the period of peak demand for electricity, the steam unit works with the efficiency typical for condensing regime. Low-pressure steam bleeds are closed to increase the power of the block. However, the hot water with temperature typical for normal block operation flows from storage tanks the degasser. The time-averaged efficiency of the block with hot water storage tanks is greater than the efficiency of the unit without hot water accumulators. Preliminary analysis of the economic viability of the use of the pressure accumulation of hot water has been presented in [5]. In year 2016 in Poland eight tanks of hot water (Tab. 2) were profitable if the price of 1 MWh of electrical energy in peak will be higher than 240 PLN/h [5]. The experience of Western Europe power plant users shows that the cost of installing accumulators of hot water for increasing the power plant flexibility return in the period from one to two years. The thermodynamic and economic analysis of the power plant of the pressurized hot water storage tanks carried out in the paper is preliminary. The real

benefits of using the accumulators can thoroughly be estimated after the construction of a pilot plant.

4   Summary

The results of the analysis of the 200 MW power unit thermal system and of the thermal calculations lead to the following conclusions:

- The power unit maximum power capacity of 206 MW may be raised during the period of peak demand for electricity by 7.32% (0.0732 × 206 MW = 15 MW)

- The period of the power unit operation with the raised maximum power capacity may last:

- 30 min at two tanks with the total capacity of 360.5 m^3

- 60 min at four tanks with the total capacity of 721 m^3

- 120 min at eight tanks with the total capacity of 1442 m^3

- 180 min at twelve tanks with the total capacity of 2163 m^3

- The maximum reduction in the power unit power capacity (which is 135 MW before the activation of the heat storage tanks) during the night off-peak hours is 16.27% (0.1627 × 135 MW = 21.96 MW) at eight tanks with the total capacity of 1442 m^3. The period in which the tanks are charged, and consequently the time of the power unit operation under a reduced load, is 3 h.

- If eight water tanks with the total capacity of 1442 m^3 are charged for 6 h, the reduction in the power unit power capacity is 8.15% (0.0815 × 135 MW = 11 MW). If the water pressure tanks are discharged during 2 h period of peak demand for electricity, the increment in the power unit power capacity totals 7.32% (15 MW). This solution, which anticipates installation of 8 tanks charged for 6 h during the night off-peak period and discharged for 2 h in the peak period, is recommended to be used in practice.

- The tanks may be made as vertical structures with stratification of cold and hot water and operating in a parallel system. The hot water

tanks may also be horizontal. In this case, they operate as a series-parallel system.

- Hot water pressure tanks may also be used in power units participating in the automatic system of frequency and power control to ensure a sudden increase in the power unit power at any time of the day.

In order to shorten the start-up from the cold state, the boiler evaporator may be flooded with hot water from one of the pressure water tanks.

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