ENHANCEMENT OF POWER UNIT FLEXIBILITY USING PRESSURE ACCUMULATION OF HOT WATER

Authors: Jan Taler, Marcin Trojan, Dawid Taler, Piotr Dzierwa, Karol Kaczmarski, Marcin Liszka

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Key words: flexibility of thermal power units, power output increasing, lowering of minimum load, pressure accumulation of hot water

Summary. 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 night off-peak hours, water is heated to the nominal temperature in the feed water tank and then directed to water pressure tanks. The water accumulated during the night is used to feed the boiler in 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 (in Polish: ARCM), 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 the night off-peak 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.

1. INTRODUCTION

A 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 (within 8 hours from decay)
- Start-up from the hot state (within 8 to 50 hours of downtime due to a failure)
- Start-up from the cold state (after more than 50 hours of downtime)

This article 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 night off-peak 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 power capacity may be raised. Low-pressure regenerative bleedings are then shut off, which involves a rise in the power unit electric power 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 (ARMC) to ensure a sudden increase in the power unit electric power. Shutting off low-pressure regenerative bleedings 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.

2. ANALYSIS OF THE POSSIBILITY OF USING WATER TANKS TO FILL THE EVAPORATOR WITH HOT WATER DURING A START-UP FROM THE COLD STATE

Fig.1. 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 figure.
Fig. 1. History of changes in power, fuel mass flow and the boiler efficiency in a tree-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: 10.06.15 (06:45 ÷ 08:15)
b – power unit operation under a nominal load during the day 14.25 h: 10.06.15 (08:15 ÷ 22:30)
c – decrease in power from the maximum to the minimum value 1.5 h: 10.06.15 (22:30) ÷ 11.06.15 (00:00)
d – power unit operation under the minimum load during the night 6 h: 11.06.15 (00:00 ÷ 06:00)

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 Figure 2.

Pressure tanks may be used to flood the boiler evaporator with hot water during the power unit start-up from the cold state (Fig. 2a). Filling the evaporator and then the drum with the initial temperature T0 with hot water with temperature T0+ΔTcz (Fig. 3), 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 Standard PN-EN 12952-3, stresses on the edge of the hole in the drum-downcomer tube interface do not exceed permissible values. If the boiler evaporator is heated at rates determined according to Standard PN-EN 12952-3, permissible stress values are exceeded on a part of the hole perimeter [1-3]. 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 mazout fired in the boiler in the start-up first phase due to the fact that the temperature of the medium is raised to the nominal temperature of about 315°C from 100°C already and not from 20°C.
Fig. 2. 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 - medium 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.
2.1. Calculations of the water tank capacity

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

- absolute pressure: \( p = 0.7 \) MPa
- saturation temperature: \( T = 164.9 ^\circ C \)
- density: \( \rho_w = 902.56 \) kg/m\(^3\)
- power unit power: 200 MW
- boiler output: \( m_w = 650 \) t/h
- the inner diameter of a single tank: \( d_w = 3 \) m.

It should be mentioned that the power unit generating capacity is 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 Table 1.

Equations (1-2) were used to calculations of water required volume \( V_w \) and height of tanks \( H_{zasob} \) at the

\( n \) - the number of tanks.

\[
V_w = \frac{m}{\rho_w} \cdot t_{szez} \quad (1)
\]

\[
H_{zasob} = \frac{V_w}{n \cdot \frac{\pi d_w^2}{4}} \quad (2)
\]
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.

![Fig. 4. Vertical, parallel configuration of tanks](image)

**2.2. Method of the power unit power capacity determination**

Determination of the power unit power capacity in the night off-peak

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

\[
Q_{wp} = m_{wp} \left( i_{up}^{wil} - i_i \right) + (m_{wp} - m_i)(i_i - i_i)
\]  

(3)

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

\[
Q_{sp} = m_{sp}(i_{sp} - i_{III}) + (m_{sp} - m_{III})(i_{III} - i_{IV}) + (m_{sp} - m_{III} - m_{IV})(i_{IV} - i_{V})
\]  

(4)

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

\[
Q_{lp} = m_{lp}(i_{lp} - i_{VII}) + (m_{lp} - m_{VII})(i_{VII} - i_{lp})
\]  

(5)

- the total internal power of the turbine set

\[
Q = Q_{wp} + Q_{sp} + Q_{lp}
\]  

(6)

- the relative drop in the power unit power

\[
Q_{proc} = \frac{100Q_{proc}}{Q}
\]  

(7)
- drop in power during the night off-peak hours

\[ S_{uf} = 100 - Q_{proc} \]  

\[ m_{sp}W_d\eta_d + m_{wt}\eta_w + m_{wt}^{wyl}RH_1 = m_{sp}^{wyl}SH_5 \]  

\[ + m_{wt}^{wyl}RH_2 + m_{wat}^{wyl} \]  

Table 1. Results for diameter \( d_w = 3 \) m

<table>
<thead>
<tr>
<th>Tank dimensions</th>
<th>Time of peak-demand operation</th>
<th>Water volume</th>
<th>Number of tanks</th>
</tr>
</thead>
<tbody>
<tr>
<td>diameter</td>
<td>height</td>
<td>capacity</td>
<td>minutes</td>
</tr>
<tr>
<td>m</td>
<td>m</td>
<td>m³</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>25.5</td>
<td>180.25</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>240</td>
</tr>
</tbody>
</table>

Fig. 5. 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

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 Table 2.
3. FINANCIAL AND ECONOMIC PROFITABILITY ANALYSIS OF THE USE OF HEAT ACCUMULATORS

The works comprised a financial and economic analysis of the costs and benefits resulting from the use of a battery of heat accumulators for a power unit with the nominal electric power capacity of about 200 MWe.

The method used in the economic model is based on the investment discounted cash flow (DCF) analysis. The following definitions of the economic assessment basic indices are assumed [5]:

- net present value (NPV):
  \[ NPV = \sum_{t=0}^{N} \frac{NCF_t}{(1+r)^t} \]  

- the internal rate of return (IRR):
  \[ \sum_{t=0}^{N} \frac{NCF_t}{(1+IRR)^t} = 0 \]  

- discounted payback period (DPB):
  \[ \sum_{t=0}^{DPB} \frac{NCF_t}{(1+r)^t} = 0 \]  

- net present value rate (NPVR):
  \[ NPVR = \frac{NPV}{PVI} = \frac{\sum_{t=0}^{N} \frac{NCF_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{I_{ukl}}{(1+r)^t}} \]  

The economic assessment indices are calculated in variants reflecting two ways of the investment financial analysis:

- using the measure of free cash flow to equity (FCFE) [5] – the markings are then as follows: NPV\(^E\), IRR\(^E\), DPB\(^E\), NPVR\(^E\) (“company owner's perspective”),
- using the measure of free cash flow to firm (FCFF) [5]) – the markings are then: NPV\(^F\), IRR\(^F\), DPB\(^F\), NPVR\(^F\) (“classical” method taking account of the perspective of all parties financing the venture).
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)

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

Assuming an incremental method of economic calculation, it is possible to reduce the uncertainty in the determination of trends and basic levels of pricing paths to the changes in prices of electricity generated in peak-demand periods and during the night off-peak hours only. Taking account of the interest of the entity making the investment, a database of quotations of electricity prices on the hour-based market in the years 2012÷2014 was created to determine the periods of charging and discharging the tanks (the lowest night off-peak tariffs and the highest day peak tariffs). The data are taken from sources such as trade portals [6, 7], and they take account of quotations in the single-price system I and in the single-price system II, continuous trading and total quotations.

Fig. 6. Averaged hourly prices of electricity from the years 2012÷2014
Fig. 6 presents averaged hourly prices of electricity in the single-price system I (due to the substantially higher volume).

Based on the analysis of historical data (including both hourly-averaged data and data characteristic of the day or night period) and using the information from Polish and European hour-based current quotations from the period of the last several months, the following parameters are assumed for further analysis:

– averaged a selling price of night off-peak electricity in year zero at the level of 110 PLN/MWh,
– averaged a selling price of sub-peak electricity in year zero at the level of 180 PLN/MWh,
– averaged a selling price of peak electricity in year zero at the level of 300 PLN/MWh,
– time of commencement of the heat storage tanks charging – 24:00,
– time of commencement of the heat storage tanks discharging – 5 p.m.

The assumed distribution of averaged prices is presented in Fig. 7. Hours of charging the tanks is marked in red; green colour marks the hours when the heat accumulators are discharged.

Figures 8÷10 present results of the sensitivity analysis concerning the impact of changes in the investment outlay (Fig. 8), the selling price of peak electricity (Fig. 9) and the operation time (Fig. 10) on the main indices of economic profitability of the upgrade project.
Fig. 8. Sensitivity to changes in the investment outlay

Fig. 9. Sensitivity to changes in the selling price of peak electricity

Fig. 10. Sensitivity to changes in the power unit annual time of operation
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:

1. The power unit maximum power capacity of 206 MW may be raised in the period of peak demand for electricity by 7.32% \((0.0732\times206 = 15 \text{ MW})\)

2. The period of the power unit operation with the raised maximum power capacity may last:
   - 30 minutes at two tanks with the total capacity of 360.5 \(\text{m}^3\)
   - 60 minutes at four tanks with the total capacity of 721 \(\text{m}^3\)
   - 120 minutes at eight tanks with the total capacity of 1442 \(\text{m}^3\)
   - 180 minutes at twelve tanks with the total capacity of 2163 \(\text{m}^3\)

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% \((0.1627\times135=21.96 \text{ MW})\) at eight tanks with the total capacity of 1442 \(\text{m}^3\). The period in which the tanks are charged, and consequently the time of the power unit operation under a reduced load, is 3 hours.

4. If eight water tanks with the total capacity of 1442 \(\text{m}^3\) are charged for 6 hours, the reduction in the power unit power capacity is 8.15% \((0.0815\times135=11 \text{ MW})\). If the water pressure tanks are discharged during 2 hours he period of peak demand for electricity, the increment in the power unit power capacity totals 7.32% \((15 \text{ MW})\). This solution, which anticipates installation of 8 tanks charged for 6 hours during the night off-peak period and discharged for 2 hours in the peak period, is recommended to be used in practice.

5. 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.

6. The results of the economic calculations indicate that for the adopted assumptions concerning among others the power unit operation and the averaged hourly selling prices of peak and night off-peak electricity, the profitability of the proposed investment project is high, compared to similar projects undertaken in this category of facilities. Nevertheless, attention should be drawn to the fact that the project economic performance is heavily dependent on the relations of the selling price of electricity generated in the peak and night off-peak periods. According to the sensitivity analysis results, if the differences between the selling price of peak and off-peak electricity are slight, the investment may become
unprofitable. The break-even point expressed in terms of the selling price of electricity is 240 PLN/MWh.

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

8. 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.

**NOMENCLATURE**

- $d$: diameter, m
- $G$: generator,
- $H$: height, m
- $i$: working fluid enthalpy, kJ/kg
- $i_I$: enthalpy of bleed I steam, kJ/kg
- $i_{II}$: enthalpy of bleed II steam, kJ/kg
- $i_{III}$: enthalpy of bleed III steam, kJ/kg
- $i_{IV}$: enthalpy of bleed IV steam, kJ/kg
- $i_V$: enthalpy of bleed V steam, kJ/kg
- $i_{VI}$: enthalpy of bleed VI steam, kJ/kg
- $i_{w_1}^{\text{ref}}$: steam enthalpy upstream the steam reheater stage I, kJ/kg
- $i_{w_2}^{\text{ref}}$: steam enthalpy downstream the steam reheater stage II, kJ/kg
- $i_{ods}$: enthalpy of desalted matter, kJ/kg
- $I_{aki}$: investment expenditures per system, PLN
- $i_{sbi}$: enthalpy of the boiler live steam, kJ/kg
- $i_{wz}$: enthalpy of feed water, kJ/kg
- $i_{znp}$: enthalpy of the steam flows from the turbine low-pressure part, kJ/kg
- $n$: number of tanks,
- $N$: time horizon of the analysis (total length of the investment and operation phases), years
- $NCF_t$: net cash flows calculated as of the end of year $t$, PLN
- $NP$: turbine low-pressure part,
- $PK$: condensate pump,
- $PVI$: present value of investment, PLN
- $PZ$: feed water pump,
\( Q_{\text{hp}} \) the power of the turbine high-pressure part, MW
\( Q_{\text{ip}} \) the power of the turbine intermediate pressure part, MW
\( Q_{\text{lp}} \) the power of the turbine low-pressure part, MW
\( Q_t \) turbine power (operation with the heat storage tank), MW
\( Q_{\text{proc}} \) the increment in the turbine power, %
\( Q \) turbine power (operation without the heat storage tank), MW
\( S_M \) reduction in power during the night off-peak hours, %
\( r \) discount rate,
RH steam reheater,
SH live steam superheater,
SP turbine intermediate-pressure part,
\( t \) number of the subsequent year of the analysis,
\( t_{\text{szcz}} \) time, s
\( W_d \) fuel calorific value, kJ/kg
WP turbine high-pressure part,
\( V_W \) capacity, m³
XN low-pressure regenerative heaters,
XW high-pressure regenerative heaters,
ZWZ feed water tank,
\( \eta_b \) boiler efficiency,
\( m \) fluid mass flows rate, kg/s
\( m_I \) steam mass flows from bleed I, kg/s
\( m_{II} \) steam mass flows from bleed II, kg/s
\( m_{III} \) steam mass flows from bleed III, kg/s
\( m_{IV} \) steam mass flows from bleed IV, kg/s
\( m_V \) steam mass flows from bleed V, kg/s
\( m_{VI} \) steam mass flow from bleed VI, kg/s
\( m_{VII} \) steam mass flows from bleed VII, kg/s
\( m_{\text{ods}} \) desalted matter mass flow, kg/s
\( m_{\text{pal}} \) fuel mass flow, kg/s
\( m_{ps} \) boiler output (live steam mass flow at the boiler outlet), kg/s
\( m_{wt} \) reheated steam mass flow at the boiler inlet, kg/s
\( m_{wz} \) boiler feed water mass flow, kg/s
REFERENCES


Słowa kluczowe: elastyczność bloków energetycznych, podwyższenie mocy elektrycznej bloku, obniżenie minimalnego obciążenia, ciśnieniowe zasobniki gorącej wody.

Streszczenie: Przeprowadzono obliczenia układu cieplnego elektrowni z zainstalowanymi zasobnikami ciśnieniowymi wody. Wyznaczono maksymalne podwyższenie mocy elektrycznej bloku spowodowane zamknięciem podgrzewaczy regeneracyjnych niskoprężnych. Kocioł zasilany jest w tym czasie gorącą wodą z zasobników ciśnieniowych wody. Aby zmniejszyć moc elektryczną bloku energetycznego w czasie tzw. „doliny nocnej” podgrzewana jest woda do temperatury nominalnej w zbiorniku wody zasilającej i kierowana do zasobników ciśnieniowych wody. Zgromadzoną w okresie nocy gorącą wodę wykorzystuje się do zasilania kotła w okresie szczytowego zapotrzebowania na energię elektryczną. Wyznaczono spadki mocy elektrycznej bloku energetycznego przy różnych pojemnościach zasobników i czasach ich ładowania. Wykonano analizę finansową i opłacalności ekonomicznej (kosztów i korzyści) zastosowania zasobników dla bloku o mocy 200MW. Zasobniki mogą znaleźć zastosowanie również do nagłego podwyższenia mocy elektrycznej bloku, pracując w układzie automatycznej regulacji częstotliwości i mocy (ARCM).” Z przeprowadzonych obliczeń i analiz wynika, że zainstalowanie ciśnieniowych zasobników wody jest celowe. Inwestycja jest opłacalna. Zasobniki ciśnieniowe mogą służyć nie tylko do obniżenia mocy elektrycznej bloku w czasie tzw. „doliny nocnej” oraz podwyższenia mocy bloku w okresie obciążenia szczytowego, ale również mogą być wykorzystane do szybkiego podwyższenia mocy w dowolnym czasie oraz mogą być zastosowane do napełniania parownika kotła gorącą wodą w czasie rozruchu bloku ze stanu zimnego.

Jan Taler, Prof. dr hab. inż., Faculty of Mechanical Engineering, Cracow University of Technology email: taler@mech.pk.edu.pl,

Marcin Trojan, dr inż., Faculty of Mechanical Engineering, Cracow University of Technology,

Dawid Taler, dr hab. inż., prof. PK, Faculty of Environmental Engineering, Cracow University of Technology,

Piotr Dzierwa, dr inż., Faculty of Mechanical Engineering, Cracow University of Technology,

Karol Kaczmarski, mgr inż., Faculty of Mechanical Engineering, Cracow University of Technology,

Marcin Liszka, dr inż., Exergon Sp. z o.o.