Using full-flow cogeneration turbine condensate to heat various heat transfer agents

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Abstract. The article gives an overview of the possibilities to upgrade power plant cogeneration turbines efficiency by using low grade heat transfer agents to heat water in cogeneration systems and to increase electricity production in the heat-end mode operations. It brings up technologies based on using turbine full-flow condensate to heat initial water found in additional heaters implemented in the cogeneration turbine recovery system. Introduction of these technologies leads to an increase in steam consumption and to a decrease in enthalpy of regenerative turbine stage steam to heat the condensate, which consequently increases combined heat and power electricity production. An experimental research of cogeneration turbine recovery systems is carried out to find out the minimum and maximum initial water flow through the surface heaters implemented in the turbine recovery system and graphs are built to show the correlation between the initial heated water flow and full-flow turbine condensate temperature.

1. Introduction
The combined generation of electricity and heat during one technological cycle at a power plant has undeniable thermodynamic advantages when compared to separate generation of these two energy types [1]. Most Russian urban areas have significant cogeneration and district heating systems based on heat and power plants of various capacities. Unfortunately, today we face a decrease in the combined heat and power plant (CHPP) efficiency caused by several reasons: wearing and deterioration of installed equipment, lack of renovation and repair funds, existing energy market conditions, usage of outdated technologies and other factors [2]. At this point, considering present wholesale energy market dynamics, there is much concern about enhancing the efficiency of Russian combined heat and power plants. So, the heat and power plant efficiency could be upgraded together with a significant improvement in their profitability either by introducing costly gas turbine units, or by using internal reserve energy sources, for example, low-potential and secondary heat agents, available at a wide range of the power plant systems.

The operation of industrial combined heat and power stations that deliver technological steam to machinery or petrochemical production plants is associated with substantial extra expenses on supplying makeup feed water to boilers as the production process does not implicate recapturing the condensate. Organizing a budget-friendly way of heating the makeup feed water at the heat and power stations of similar type will have a significant influence on their energy efficiency.

The quality and the energy efficiency of the makeup feed water treatment process mostly depend on thermal deaeration temperature conditions.
Water degassing in vacuum deaeration plants significantly increases water treatment efficiency by using vacuum deaeration equipment with low temperature settings and low temperature cogeneration turbine steam draw-off. However, water treatment heating schemes on various combined heat and power plants were found to have a nonoptimal design.

2. Applying recovery turbine steam draw-off to heat transfer agents
The main disadvantage of a typical makeup feed water treatment scheme is using production condensate at a temperature of 55-60°C as a heating medium; such a low temperature does not guarantee effective vacuum deaeration of the makeup feed water. Moreover, the amount of condensate returning from production rarely reaches design values, so most combined heat and power plants use high temperature draw-off steam as a main heating medium.

Using high temperature draw-off steam as a main heating medium creates a significant decrease in heat efficiency of a combined heat and power plant due to displacement of low temperature recovery turbine steam draw-off when heating the makeup feed water in a low-pressure heater. Thereby a typical makeup feed water deaeration scheme does not ensure a failure-safe and efficient performance of water treatment equipment on combined heat and power plants. What is more, it does not allow using low temperature heat sources for vacuum deaeration to the full extent.

To improve the performance of low and medium capacity water treatment equipment (100 – 500 m³ per hour) the authors have designed energy-saving technologies [3] based on application of low temperature cogeneration turbine steam draw-off to set the required temperature at a water treatment system of a combined heat and power station.

These technologies imply heating the makeup feed water in the surface heater by means of full-flow condensate before it goes to the water softener and vacuum deaerator. To control efficiency the full-flow condensate draw-off may be made upstream the first, second or third low-pressure heater, located downstream the condensate flow. The Figure 1 contains the scheme showing the stages of heating the makeup feed water by full-flow turbine condensate drawn off before the first low-pressure heater.

**Figure 1.** Heating the makeup feed water by full-flow turbine condensate (scheme): 1 – feed water deaerator; 2 – low-pressure regenerative heater; 3 – condenser; 4 – full-flow condensate pipeline; 5 – initial water heater; 6 – water softener; 7 – vacuum deaerator; 8 – makeup feed water pipeline; 9 – cogeneration turbine T-100/120-130.
All engineering solutions aimed at energy efficient heating of boiler makeup feed water are based on maximum usage of low temperature cogeneration turbine steam draw-off, helping to improve the combined heat and power plant energy efficiency by increasing electricity production in internal heat consumption.

There are some similar solutions used at combined heat and power plants for heating system feed water treatment. They relate to using low temperature heat transfer agents by means of direct heat exchange; thus, the full-flow turbine condensate is cooled in a surface water radiator by initial makeup feed water, which is sent to water treatment system or directly to vacuum deaerator of makeup water [4, 5].

3. Experimental investigation of cogeneration turbine recovery systems

To evaluate the industrial applicability of the engineering solutions [3-5], connected with using turbine full-flow condensate for heating the initial water in surface heater, a passive complex experiment was held on turbine plants including turbines Т-100/120-130 and PT-80-130/13 on the premises of the Ulyanovsk CHPP-1 which is a part of public company “T Plus” subsidiary.

The multi-factor experiment allowed obtaining a functional relation of a forecast value from several arguments in the form of regression equations. For example, after processing the experimental records from the turbine Т-100/120-130 during two-stage system water heating, the following regression equations were obtained:

\[
Y_1 = 29.5082 + 0.1699X_1 - 0.18X_2 - 0.00006X_1^2 + 0.00004X_1X_2 + 0.00007X_2^2 ,
\]

\[
Y_2 = 56.3081 - 0.0108X_1 + 0.0694X_2 + 0.0001X_1^2 + 0.00001X_1X_2 - 0.0002X_2^2 ,
\]

\[
Y_3 = 67.5789 + 0.1562X_1 - 0.1267X_2 - 0.0009X_1^2 + 0.00005X_1X_2 + 0.00009X_2^2 ,
\]

\[
Y_4 = 96.9647 + 0.0832X_1 - 0.0028X_2 - 0.0003X_1^2 + 0.000005X_1X_2 + 0.00001X_2^2 ,
\]

\[
Y_5 = 106.8849 + 0.1438X_1 + 0.0035X_2 - 0.0001X_1^2 + 0.0001X_1X_2 - 0.00004X_2^2 ,
\]

where \(Y_1, Y_2, Y_3, Y_4\) stand for full-flow turbine condensate temperature before regenerative low-pressure heaters of the first, second, third and fourth stages, respectively, °C; \(Y_5\) stands for full-flow turbine condensate temperature after the fourth stage regenerative low-pressure heater, °C; \(X_1\) stands for turbine main steam flow, m³ per hour; \(X_2\) stands for steam flow at a lower heat extraction, m³ per hour.

These regression equations help us define the full-flow condensate temperatures after each stage of regenerative heating of the turbines Т-100/120-130, PT-80-130/13 as well as their relation to the amount of primary steam forced to the turbine and the heat extraction steam flow when turbines operate at a one or two-stage system water heating mode [3]. For example, the equations (1)-(5) can help us define the point when the steam flow forced to the turbine has to be increased due to the heat load growth and insufficient full-flow condensate temperature after any of the regenerative heaters.

The calculations using the regression equations (1)-(5) show that at almost any operation mode the full-flow condensate temperature is sufficient for heating the initial makeup water up to the process temperature of 35-40°C before it goes to the water treatment section. However, the equations (1)-(5) do not take into account the initial water amount that can be heated in the surface heater by the full-flow condensate in the heating schemes, used at combined heat and power plants similar to that shown in Figure 2. To estimate the possibilities of utilizing turbine Т-100/120-130 recovery system, calculations of initial makeup water flow \(G_{iw}\) were made based on experimental records using the formula

\[
G_{iw} = G_p (t_{fi} - t_{fi}^*) / (t_{fi}^* - t_{fi}^*_{he}) ,
\]
where \( G_{fc} \) stands for the rate of full-flow condensate passing through the initial water heater in m\(^3\) per hour; \( t'_{fc}, t''_{fc} \) stand for full-flow condensate temperatures before and after it goes through the initial water heater in °C; \( t'_{iw}, t''_{iw} \) stand for the initial water temperatures before and after it goes through the heater in °C; \( \eta_{he} \) stands for the efficiency factor of the heat exchanger.

The calculations were made with identical initial temperatures \( t'_{iw} = 10^\circ \text{C} \) and different final heated temperatures \( t''_{iw} = 35-50^\circ \text{C} \) for the three schemes of adding the initial water heater in the turbine recovery system, upstream the first, second and third low-pressure heaters. The calculations have found that adding the surface heater upstream the first low-pressure heater (Figure 1) ensures efficient initial water heating at a flow up to 80 m\(^3\) per hour. In case the full-flow condensate is drawn off before the second low-pressure heater, the heated water flow may be increased up to 170 m\(^3\) per hour. If the full-flow condensate is drawn off before the third low-pressure heater, the heated water flow may increase up to 310 m\(^3\) per hour. Based on these calculations, graphs have been built to show the relation between the initial water flow and the full-flow condensate temperature upstream the surface heater. An example of such a graph for the second variant that implies adding the heater upstream the second low-pressure heater is shown in Figure 2.

![Figure 2](image)

**Figure 2.** Graphs showing initial makeup water flow through the heater installed upstream the second low-pressure heater depending on the full-flow condensate temperature before the heater at various heating temperatures 1 – \( t''_{iw} = 35^\circ \text{C} \), 2 – \( t''_{iw} = 40^\circ \text{C} \), 3 – \( t''_{iw} = 45^\circ \text{C} \), 4 – \( t''_{iw} = 50^\circ \text{C} \).

4. Calculations of energy efficiency delivered by new technologies

Calculations were made to estimate the new technology energy efficiency by the value of specific electric energy production at a heat-end mode [6]. The combined heat and power plant analysis in question will include two components. Firstly, the value of specific electric energy production at a heat-end mode with adding the surface heater to warm up the initial makeup water to the full-flow condensate pipeline upstream the first low-pressure heater. Secondly, the value of specific electric energy production at a heat-end mode with adding degassed initial makeup water pipeline to the full-flow condensate pipeline upstream the second low-pressure heater.

Therefore, the value of specific electric energy production \( (v_{hl} \text{ in kWh/m}^3) \) of the solution illustrated in Figure 2 can be calculated by a formula:
second stages of regenerative low-pressure heaters in kJ/kg; 

\[ t_{hw} \text{ stands for feed water enthalpy in kJ/kg}; \]

\[ h_{d} \text{ stands for degassed feed water and full-flow condensate upstream the third low-pressure heater can be defined by the formula:} \]

\[ t_{6}, \ t_{7} \text{ stand for full-flow turbine condensate enthalpy after the first and the second stages of regenerative low-pressure heaters in kJ/kg;} \]

\[ \eta_{em} \text{ stands for heat exchanger efficiency factor; } \]

\[ \eta_{p} \text{ stands for pump efficiency factor.} \]

The value of specific electric energy production (\( v_{h2} \) in kWh/m\(^3\)) in the variant that implies adding the surface heater to the full-flow condensate pipeline upstream the second low-pressure heater and mixing the flows of degassed feed water and full-flow condensate upstream the third low-pressure heater can be defined by the formula:

\[ v_{h2} = \frac{0.278}{\eta_{he}} \left[ \left( \frac{T_{m} - T_{o}}{T_{o} - T_{f}} \right) \left( \frac{T_{e} - T_{o}}{T_{e} - T_{f}} \right) \left( h_{e} - h_{e} \right) \eta_{em} + \frac{(T_{pe} - T_{e}) (h_{e} - h_{e}) \eta_{em}}{(h_{e} + h_{e} - 2T_{pe})} - \frac{AP}{\eta_{p}} \right] + \]

\[ + \left( \frac{T_{m} - T_{o}}{T_{o} - T_{f}} + 1 \right) \left( \frac{T_{e} - T_{o}}{T_{e} - T_{f}} \right) \left( h_{e} - h_{e} \right) \eta_{em} + \frac{(T_{pe} - T_{e}) (h_{e} - h_{e}) \eta_{em}}{(h_{e} + h_{e} - 2T_{pe})} - \frac{AP}{\eta_{p}} \right] \right); (7) \]

where \( T_{m}, \ T_{o} \) stand for initial makeup water enthalpy before and after it goes through the initial water heater in kJ/kg; \( T_{f}, T_{o} \) – full-flow condensate enthalpy before and after it goes through the initial water heater in kJ/kg; \( T_{6}, T_{7} \) – full-flow turbine condensate enthalpy after the first and the second stages of regenerative low-pressure heaters in kJ/kg; \( h_{d} \) stands for main steam enthalpy in kJ/kg; \( h_{d} \) stands for feed water enthalpy in kJ/kg; \( h_{d} \) stands for degassed makeup feed water in kJ/kg; \( t_{m} \) stands for mixed flow of full-flow condensate and makeup feed water before the low-pressure heater in kJ/kg; \( h_{d}, h_{7} \) stand for the 6th and 7th regenerative extractions steam condensate enthalpy in kJ/kg; \( \eta_{he} \) stands for heat exchanger efficiency factor; \( \eta_{em} \) stands for electromechanical turbine generator efficiency factor; \( AP \) stands for pump pressure to transfer heat agent in MPa; and \( \eta_{p} \) stands for pump efficiency factor.

The value of specific electric energy production (\( v_{h3} \) in kWh/m\(^3\)) in the variant that implies heating the initial makeup feed water before it goes to the water treatment plant in the heat exchanger added to the full-flow condensate pipeline of the turbine T-100/120-130 upstream the third low pressure heater and mixing the flows of degassed feed water and full-flow condensate upstream the second low-pressure heater can be defined by the formula:

\[ v_{h3} = \frac{0.278}{\eta_{he}} \left[ \left( \frac{T_{m} - T_{o}}{T_{o} - T_{f}} \right) \left( \frac{T_{e} - T_{o}}{T_{e} - T_{f}} \right) \left( h_{e} - h_{e} \right) \eta_{em} + \frac{(T_{pe} - T_{e}) (h_{e} - h_{e}) \eta_{em}}{(h_{e} + h_{e} - 2T_{pe})} - \frac{AP}{\eta_{p}} \right] + \]

\[ + \left( \frac{T_{m} - T_{o}}{T_{o} - T_{f}} + 1 \right) \left( \frac{T_{e} - T_{o}}{T_{e} - T_{f}} \right) \left( h_{e} - h_{e} \right) \eta_{em} + \frac{(T_{pe} - T_{e}) (h_{e} - h_{e}) \eta_{em}}{(h_{e} + h_{e} - 2T_{pe})} - \frac{AP}{\eta_{p}} \right] \right); (9) \]

After processing the calculations using formulas (7)-(9) the following values of specific electric energy production at a heat-end mode when heating the water in the surface heater were obtained for...
the turbine T-100/120-130: upstream the first low-pressure heater – 37.58 kWh/m³; upstream the second low-pressure heater – 30.63 kWh/m³; upstream the third low-pressure heater – 31.65 kWh/m³.

We can see that the heat from the full-flow turbine condensate which was stage heated in recovery system heat exchangers by low temperature steam extractions can be successfully used to heat initial makeup feed water before it goes to the water treatment plant and vacuum degasser. This procedure can significantly increase the energy efficiency of the cogeneration turbine and enhance economic performance of the combined heat and power station in general.

5. Conclusion

- The analysis results show that most of Russian steam-turbine combined heat and power plants have massive reserves to increase their energy efficiency by improving the operation of water treatment systems.
- Engineering solutions have been elaborated with the aim of heating the initial makeup feed water for boilers, using a surface heater installed into the full-flow condensate pipeline upstream the first, second or third low pressure heater. This ensures reaching a quality standard of the water under treatment together with high energy efficiency of the water treatment process and the combined heat and power station in general.
- Based on experimental records and calculations it has been defined that depending on the chosen variant of adding the surface heater and the final temperature the flow of the initial makeup feed water may vary greatly in the range from 2 to 310 m³ per hour.
- The performed calculations allowed estimating the new technical solutions energy efficiency by the value of specific electric energy production at a heat-end mode. For a combined heat and power plant with a turbine T-100/120-130 the highest level of the specific electric energy production (37.58 kWh/m³) is found to be reached when the initial makeup feed water surface heater is installed into the full-flow turbine condensate pipeline upstream the first low pressure heater and the flows of the degassed makeup feed water and full-flow condensate are mixed upstream the second low pressure heater.

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