Improving urban district heating systems and assessing the efficiency of the energy usage therein

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Abstract. The report describes issues in connection with improving urban district heating systems from combined heat power plants (CHPs), to propose the ways for improving the reliability and the efficiency of the energy usage (often referred to as “energy efficiency”) in such systems. The main direction of such urban district heating systems improvement suggests transition to combined heating systems that include structural elements of both centralized and decentralized systems. Such systems provide the basic part of thermal power via highly efficient methods for extracting thermal power plants turbines steam, while peak loads are covered by decentralized peak thermal power sources to be mounted at consumers’ locations, with the peak sources being also reserve thermal power sources. The methodology was developed for assessing energy efficiency of the combined district heating systems, implemented as a computer software product capable of comparatively calculating saving on reference fuel for the system.

1. Introduction
In accordance with the latest assessment, more than 105 million people in Russia, that is 74% of the population, live in large cities. Urban consumers are provided with thermal and electric power via large thermal power systems, designed by national professionals back in the middle of the XX century. During recent decades, reliability and performance of the urban heating systems became worse, having not been substantially upgraded since mid-80s, and the operation level for both thermal power networks and for thermal power consumers deteriorates. The majority of existing heating systems, being unable to react to ever-changing weather and climate conditions, failed to adjust thermal load and to supply thermal power to consumers properly, therefore, losing to competitors, such as decentralized heating systems without combined production of both electric and thermal power.

Nonetheless, thermodynamic advantages of district heating systems based on combined electrical and thermal power production on CHPs are a no-doubt. Full implementation thereof today needs reconsidering approaches to covering thermal loads from consumers and modifying urban heating systems structure modification [1].

2. Combined urban district heating systems
Improving reliability and energy efficiency of urban heating systems required the Research Laboratory of Heat-and-Power Systems and Units to develop technologies for combined thermal power supplies accounting for using structural elements of both centralized and decentralized systems [2, 3]. The combined thermal power systems cover the basic part of the thermal load of the system by highly
efficient thermal power plants turbines steam extraction methods, while peak loads are covered by decentralized peak thermal power sources installed at consumers’ sites (Figure 1). Decentralized peak thermal power sources capable of being used as reserve power sources may be gas and electric boilers, heaters etc.

The technologies have advantage of making each particular consumer capable of selecting the moment of enabling the peak thermal power source as appropriate, with no reference to others, and of the amount of heat to be transferred to water therein, thus improving the thermal power supplies quality and making conditions more comfortable for every consumer on individual basis. In addition, emergency situations at thermal power plants resulting in thermal power supplies interruptions would not cause thermal power supplies failures, as the standalone peak thermal power sources would continue operating anyway, substituting the centralized thermal power supplies for the time being, therefore, protecting the heating systems from freezing and improving overall reliability. Even during maintenance downtime, consumers with decentralized peak thermal power sources have hot water all the time.

![Figure 1. Flowchart of the Combined urban district heating system: 1 – thermal power plant’s turbine with heating extractions of steam; 2 – network heaters; 3 – thermal power distribution networks; 4 – network pumps; 5 – local consumer heating system; 6, 7 – supplying and reversed pipelines of the local system; 8 – decentralized peak thermal power source; 9 – circulation pump; 10 – controller; 11 – air temperature sensors.](image)

The combined urban heating system operation mode differs from the one of a traditional system. Thermal power plant load is modified via centralized qualitative regulation due to changing heating water temperature within the 60-88°C range (Figure 2) with the heating water constantly flowing through the heaters $G_{nw}$. Modifying peak thermal load is made by means of local quantitative regulation at every consumer via changing the heating water flow rate through the decentralized peak thermal power sources (gas boilers) and local systems of the consumers. Therewith, the heating water temperature after decentralized peak thermal power sources does not exceed the temperature after the network heaters. This reduces the reversed heating water temperature down to $r_2' = 49°C$, resulting in increased thermal power production at CHP and reduced losses in pipelines transferring thermal power.
Figure 2. Diagrams for changing temperatures of heat carriers in centralized ($\tau_1$, $\tau_2$, $\tau_{nh}$) and in combined ($\tau_1'$, $\tau_2'$) district heating systems.

3. Methodology for calculating energy efficiency of the combined district heating systems
Let us calculate the energy efficiency of a combined district heating system in accordance with the figure 1 during thermal power plant typical operation and in accordance with the methodology presented in [4, 5]. The financial efficiency of the proposed technology shall be assessed based on annual saving of reference fuel $\Delta B_{sum}$, kg/year, on transferring from traditional centralized heating system to the combined one from thermal power plants and with decentralized peak thermal power sources

$$\Delta B_{sum} = \Delta B_1 + \Delta B_2 + \Delta B_3 + \Delta B_4 + \Delta B_5$$

$\Delta B_1$ is the decrease in spending reference fuel by means of increasing thermal power production in a turbine unit at transition from the centralized system to the combined one, kg/year; $\Delta B_2$ is the decrease in spending the reference fuel at transferring the heat load from the thermal power plants peak boilers towards decentralized peak thermal power sources, kg/year; $\Delta B_3$ is the change in spending reference fuel on producing electricity for thermal power plants network pumps and those installed locally, kg/year; $\Delta B_4$ is the fuel saved by reducing heat losses by the network pipelines, kg; $\Delta B_5$ is the change in spending reference fuel at boilers in the heating systems, kg/year.

Calculation needs the information about the city’s climate conditions at the heating system location, the thermal power load equal for both systems, designed heating coefficient, temperature schedule for both centralized and local heating systems, pressures and efficiency factors for network and local pumps, external heat transfer system parameters, basic parameters of the decentralized peak thermal power sources.

Saving reference fuel, $\Delta B_1$, kg/year, by means of increasing turbine’s power resulting from transition from the centralized heating system to the combined one is defined by the expression

$$\Delta B_1 = G_{in}c_m k\eta_{em} \Delta h \sum_{j=1}^n \left[ \frac{(\tau'_j - \tau'_{2,j})(h_o - h'_o)}{h'_o - h'_j} - \frac{(\tau_{nhj} - \tau_{2,j})(h_o - h_{nj})}{h_{nj} - h_{kj}} \right] e_j \cdot 10^{-3}$$
$G_{nw}$ is the heating water rate, kg/s; $c_{nw}$ is the heating water specific heat capacity, kJ/(kg·°C); $k_2$ is the coefficient, accounting for regenerative heating of turbine steam extraction condensate; $\eta_{em}$ is the electromechanical efficiency factor of a turbine generator; $\Delta h_2$ is the difference of rates for the reference fuel for producing power in accordance with condensing and thermal power production cycles, g/(kW h); $\tau_{ij}$, $\tau_{2j}$, $\tau_{nhj}$ are, correspondingly, water temperatures in feeding, reversed pipelines and after network heaters for the centralized thermal power supplies system in $j$th mode; °C, $\tau'_{ij}$, $\tau'_{2j}$ are water temperatures in feeding and reversed pipelines for the combined thermal power supplying system in the $j$th mode; °C; $h_j$ is the acute steam enthalpy, kJ/kg; $h_{nj}$, $h'_{nj}$ are average enthalpies of steam of heating extractions before reference network heaters in centralized and combined heating systems in the $j$th mode, kJ/kg; $h_{kj}$, $h'_{kj}$ are the average condensate enthalpies after reference network heater in centralized and combined heating systems in the $j$th mode, kJ/kg; $z_j$ is the duration of the system operation in the $j$th mode, hours/year; $j = 1, \ldots, m$ is the number of the system operation modes during the peak period.

Changing in fuel rate at producing additional steam in boilers are defined by the expression

$$\Delta B_2 = \frac{3600G_{nw}c_{nw}(h_0 - h_{fw})}{Q'_{i} \eta_\nu} \sum_{j=1}^{m} \left[ \frac{\tau'_{ij} - \tau'_{2j}}{h'_{nj} - h'_{kj}} - \frac{\tau_{nhj} - \tau_{2j}}{h_{nj} - h_{kj}} \right] z_j$$

(3)

$Q'_{i}$ is the lowest calorific value of reference fuel, kJ/kg; $h_{fw}$ is the boiler feeding water enthalpy, kJ/kg; $\eta_\nu$ is the boiler efficiency factor.

Saving fuel at load transfer from the peak boiler to the individual ones to be used locally as decentralized peak thermal power sources is defined by

$$\Delta B_3 = \frac{3600c_{nw}}{Q'_{i} \eta_\nu} \sum_{j=1}^{m} \left[ G_{nw} (\tau_{ij} - \tau_{nhj}) - \frac{G_{dpsj} (\tau'_{ij} - \tau'_{2j})}{\eta_{dpsj}} \right] z_j$$

(4)

$G_{dpsj}$ is the water flow rate through the standalone peak heat source in the $j$th mode, kg/s; $\eta_{dpsj}$ refer to efficiency factors for the peak boiler and the local decentralized peak thermal power source.

The combined heating systems have temperature mode notably lower than those for the centralized ones; therefore, the former would have lower losses in pipelines, too. Assessing the value of the reference fuel saved at reduced heat losses in the combined heating system is possible with the expression

$$\Delta B_4 = \frac{3600c_{nw}}{Q'_{i} \eta_\nu} \sum_{j=1}^{m} \left[ q_{ap} + q_{nb} \right] - \left[ q'_{ap} + q'_{nb} \right] \beta \cdot L \left[ \sum_{j=1}^{m} q_{ap} + q_{nb} \right]$$

(5)

$\beta$ refers to the thermal power local losses coefficient, accounting for those by enforcing rods, compensators and supports; $L$ is the heating system portion length, m; $q_{ap}$, $q'_{ap}$ are the standard average annual specific thermal power losses in supplying pipelines of the centralized and the combined heating systems, W/m; $q_{nb}$, $q'_{nb}$ are the standard average annual specific thermal power losses in the reversed pipelines of the centralized and the combined heating systems, W/m.

Changing in spending reference fuel on producing power consumed by pumps in the combined heating system is defined by
\[
\Delta B_z = b_c^e g \rho_{nw} \left( \frac{\Delta H_{np} V_{np}}{\eta_{np}} \sum_{j=1}^{m} \zeta_j - \sum_{j=1}^{m} \frac{H_{dpsj} V_{dpsj} z_j}{\eta_{dps}} \right) \cdot 10^{-6} \tag{6}
\]

\(b_c^e\) is the specific reference fuel rate for condensation power production, g/(kW h); \(\Delta H_{np}\) is the difference between network pump pressures, m; \(H_{dpsj}\) is the average local pumps pressure, m; \(V_{np}\), \(V_{dpsj}\) refer to supplies by the network and all local pumps in the \(j^{th}\) mode, m³/s; \(\eta_{np}, \eta_{dps}\) are the average efficiency factors for the network and the local pumps; \(\rho_{nw}\) is the heating water density, kg/m³; \(g\) is the gravity acceleration, m/s².

Substituting the calculation results in accordance with the expressions (2)-(6) into (1), we obtain the combined heating system, for the Ul'yanovsk city, the annual saving of the reference fuel is \(\Delta B_{sum} = 3638\) t/year, or 13.46 million rubles/year with the average cost of the reference fuel 3700 Russian rubles per ton.

Energy efficiency calculation in accordance with the methodology developed shall be quite complicated. Improving calculation accuracy and making it faster with different input required the dedicated software product to be developed and registered as “The combined heating systems energy efficiency calculation accounting for CHPs and standalone peak thermal power sources” [6].

Reference fuel saving diagrams at the figure 3 are built based on software calculation results for different climates and design coefficient of CHP \(\alpha_{CHP}\) for the combined district heating system with the turbine T-100-130, water flow rate 1111 kg/s, operating in reduced temperature mode, compared to traditional scheme operating in design mode 150/70°C.

![Figure 3](image-url)

**Figure 3.** Correlation diagrams between reference fuel saving and design coefficient of CHP for the combined district heating system under various climate conditions in cities: 1 – Moscow; 2 – Ul'yanovsk; 3 – Arkhangel'sk; 4 – Orenburg.

4. **Conclusion**

- Existing urban district heating systems technologies have drawbacks and fail to provide good and reliable thermal power supplies to consumers, therefore, structural modernization and improvements thereof should involve both existing systems and those currently being designed.
- Improving energy efficiency and retaining advantages of thermal power production and delivery to consumers required creating combined heating systems of thermal power distribution covering basic thermal load by means of thermal power plants turbine network
heaters, with peak loads to be covered by decentralized peak thermal power sources installed locally at local consumers’ systems.

- The methodology was developed for assessing energy efficiency of the combined district heating systems with decentralized peak thermal power sources, implemented as a computer software product capable of comparatively calculating saving on reference fuel for the system, with diagrams built for various cities, depending on design coefficient of CHP.

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