Methodology for determining the flow rate and temperature of generated hot water when calculating the thermal diagram of a hot water boiler room

V P Gorshenin¹, A N Kachanov¹, VA Chernyshov¹, D A Korenkov¹, V V Maksimov²
¹ Oryol State University, 95 Komsomolskaya Street, Orel, Russia
² Kazan State Tekhnicheskiy University, 51 Krasnoselskaya Street, Kazan, Russia

Abstract: The consumption and temperature of hot water produced by boiler units are calculated using such a quantity as the consumption of the consumed network water. The formulas represent functional dependencies connecting the obtained values not only with the consumption of heating water, but also with the consumption of hot water supplied for recirculation, for own needs and for the needs of the fuel economy. They take into account the losses of network and hot water. The formulas are obtained as a result of the joint solution of the equation for the total consumption of hot water and the equation for its partial costs.

1. Introduction. At present, one of the main tasks facing enterprises of the housing and communal complex, is energy saving - increasing the efficiency of the use of fuel and energy resources. The goals of calculating the heating scheme of a boiler house [1]: determination of its total heat load, including external loads and heat consumption for auxiliary needs; calculation of heat fluxes and flow rates of heat carriers through all types of auxiliary equipment, which ensures its selection and determination of the diameters of pipelines and fittings; determination of the initial data for further technical and economic calculations. The calculation of the heating scheme of the boiler house is carried out for the typical modes of its operation [1, 2]. The calculation results make it possible to correctly substantiate the number and performance of auxiliary equipment.

The basic thermal diagram of a boiler house with hot water boilers is shown in the figure 1.

The boiler room operates on a closed heating network. The pipelines, depicted in the form of dotted lines, ensure the inclusion of heaters of the original 2 and chemically treated 5 water in the heating circuit of the boiler house according to various options. In the presented thermal diagram, heaters 2 and 5 for heating (hot) water are connected in series.

2. Materials and methods
At the outlet of the boiler units, hot water is divided into four streams: into the heating network, for recirculation, for the auxiliary needs of the boiler house and into the fuel economy:

\[
G_{HW\text{(prod)}}^{bh} = G_{HW\text{(prod)}}^{hn} + G_{HW\text{(prod)}}^{on} + G_{HW\text{(prod)}}^{bh} + G_{HW\text{(prod)}}^{fu},
\]

(1)

where \(G_{HW\text{(prod)}}^{bh}\) – total consumption of hot water produced by the boiler house; \(G_{HW\text{(prod)}}^{bh}\) – consumption of hot water generated to meet the household needs of residential buildings (for supply to the heating network); \(G_{HW\text{(prod)}}^{on}\) – consumption of hot water generated for its recirculation from the outlet to the inlet of the boiler units; \(G_{HW\text{(prod)}}^{fu}\) – consumption of hot water generated to meet the boiler

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
Figure 1. Basic thermal diagram of a heating boiler house with hot water boiler units operating on a closed heating network:

1 - initial (raw) water pump; 2 and 5 - heaters of raw and chemically treated water; 3 - chemical water treatment area; 4 - pump of chemically treated water; 6 - vapor cooler; 7 - vacuum deaerator; 8 - make-up (deaerated) water tank; 9 - make-up water pump; 10 - network water pump; 11 - hot water boiler unit; 12 - recirculation pump; 13 and 14 - control valves; 15 - water jet ejector; 16 - working water tank; 17 - working water pump; 18 - gate valve; 19 and 20 - supply and return heat pipelines of the heating network; 21 and 22 - supply and return heat pipelines of the fuel oil facility.

...room's own needs (for supply to deaerator 7 and heat exchangers 2 and 5); \( G_{\text{HW\ prod}} \) – consumption of hot water generated to meet the needs of the fuel economy.

Hot water generated by boiler units, when moving to consumers, is partially lost in the boiler room and in external heat pipelines. In this regard, the flow rate \( G_{\text{HW\ prod}} \) of hot water is represented as follows:

\[
G_{\text{HW\ prod}} = G_{\text{prod}}^L + G_{\text{prod}}^C + G_{\text{prod}}^h = k_{\text{HW}} \cdot G_{\text{HW\ prod}}^h = k_{\text{HW}} \cdot \alpha_{\text{HW\ prod}} \cdot G_D,
\]

where \( G_{\text{prod}}^L \), \( G_{\text{prod}}^C \) – the consumption of hot water lost in the supply heat pipelines, respectively, of the boiler house and heating network; \( G_{\text{prod}}^h \) – consumption of hot water consumed to meet the household needs of residential buildings; \( k_{\text{HW}} \) – coefficient taking into account the loss of hot water in the supply heat pipes of the boiler house and heating network; \( \alpha_{\text{HW\ prod}} \) – the share of hot water consumption in the network water consumption; \( G_D \) – current consumption of the consumed network water.

The value \( \alpha_{\text{HW\ prod}} \) is determined within the framework of the requirements for the law of temperature change \( \tau^*\) of direct supply water. The change in this temperature during the heating period is carried out in accordance with the temperature schedule of the heating network. In this case, within the framework of the heating season, two ranges of outdoor temperature values are distinguished:

\( \tau_{\text{ob}} \ldots \tau_{\text{obp}} \), \( \tau_{\text{obp}} \ldots \tau_{\text{dea}} \) where \( \tau_{\text{ob}} \) – outdoor temperature corresponding to the beginning (end) of the heating period,°C; \( \tau_{\text{obp}} \) – outside air temperature corresponding to the break point of the temperature graph,°C; \( \tau_{\text{dea}} \) – design outside air temperature (for heating design), °C.
To provide at each moment of time the required temperature value \( \tau^*_1 \) of direct heating water, chilled water is added to the hot water. The flow rates of hot water and chilled water mixed with it are determined by jointly solving the equations of material and heat balances written for the mixing points a (see figure). Solving these equations gives:

\[
G_{HW (mix)}^{Dn} = G_{HW (S)}^{Dn} = \alpha_{HW (D)} \cdot G_{D(S)}^D; \\
G_{RW (mix)}^{Dn} = G_{D(S)}^D - G_{HW (S)}^{Dn} = \alpha_{RW (D)} \cdot G_{D(S)}^D,
\]

where \( G_{HW (mix)}^{Dn} \) – consumption of hot water coming from boiler units to the mixing points A and then entering as part of the network water into the supply line of the heating network; \( G_{RW (mix)}^{Dn} \) – flow rate of the recovered (replenished) return water flowing through the bridges from the boiler units inlet to the outlet pipelines (at the mixing point A); \( G_{D(S)}^D \) – consumption of network water supplied to the supply line of the heating network; \( \alpha_{HW (D)}, \alpha_{RW (D)} \) – the share of the consumption of hot and recovered return water, respectively, in the flow of heating water \( (\alpha_{HW (D)} + \alpha_{RW (D)} = 1) \).

The quantities \( \alpha_{HW (D)} \) and \( \alpha_{RW (D)} \) are equal:

\[
\alpha_{HW (D)} = \frac{\tau^*_1 - \tau_{RW}}{\tau_{2(HW)} - \tau_{RW}}; \\
\alpha_{RW (D)} = \frac{\tau_{2(HW)} - \tau^*_1}{\tau_{2(HW)} - \tau_{RW}},
\]

where \( \tau^*_1 \) – temperature of the direct supply water at the entrance to the supply line of the heating network [3]; \( \tau_{RW} \) – temperature of the recovered hot water return at the outlet of the network pumps, °C; \( \tau_{2(HW)} \) – temperature of hot water produced by boiler units, °C.

The \( \tau_{RW} \) temperature of the recovered return water at the outlet of the network pumps is found as a weighted average:

\[
\tau_{RW} = \frac{\alpha_{DW(WVR)} \cdot \tau_{DW} + \alpha_{HW(WVR)} \cdot \tau_{2(HW)} + \alpha_{CH(WVR)} \cdot \tau_{CH} + 1 \cdot \tau^*_2}{\alpha_{DW(WVR)} + \alpha_{HW(WVR)} + \alpha_{CH(WVR)} + 1},
\]

where \( \alpha_{DW(WVR)}, \alpha_{HW(WVR)}, \alpha_{CH(WVR)} \) – the share of the consumption of deaerated and cooled heating water entering the return line (to the input of the network pumps), respectively, from the deaerator, heaters of chemically treated and source water, fuel facilities; \( \tau_{DW} \) – temperature of deaerated water, at the inlet to the return line, °C; \( \tau_{2(HW)} \) – temperature of the cooled heating water entering the return line from the heaters of chemically treated and initial water, the fuel economy, respectively, °C; \( \tau^*_2, \tau^*_2 \) – temperature of the heating system return water returning to the boiler room at the inlet of the network pumps [3].

The values \( \alpha_{DW(WVR)}, \alpha_{HW(WVR)}, \alpha_{CH(WVR)} \) in formula (7) at this stage of calculating the boiler room scheme are not known and therefore are preset. In order to avoid low-temperature corrosion, the design temperature \( \tau_{SL(HW)} \) of water at the inlet to steel water-heating boiler units, depending on the type of fuel, should be at least 70 ... 110 °C [4 - 6]. Maintaining the required value of this water...
temperature is ensured by arranging a recirculation line (see figure) and supplying the required flow rate $G_{RW(mix)}$ of hot water through it, while:

$$G_{RW(prod)} = G_{RW(mix)} + G_{RW(L)} = k_{RW} \cdot G_{RW(mix)} = k_{RW} \cdot \alpha_{RW(HW)} \cdot G_{HW(prod)}^h,$$

where $G_{RW(prod)}$, $G_{HW(prod)}^h$ — the same as in equation (1); $G_{RW(mix)}$ — consumption of hot water supplied (recirculated) from boiler units to their inlet; $G_{RW(L)}$ — consumption of recirculating hot water lost during its movement from boiler units to their inlet; $k_{RW}$ — recirculating water loss factor; $\alpha_{RW(HW)}$ — the proportion of the recirculating hot water consumption in the hot water consumption generated by the boiler units.

The flow rate $G_{RW(mix)}$ of recirculating hot water is found as a result of the joint solution of the equations of material and heat balances written for the mixing points B (see figure). Taking into account the equation of the material balance of boiler units:

$$G_{B} = G_{BU} = G_{HW(prod)}^h,$$

this solution gives:

$$G_{RW(mix)} = \alpha_{RW(HW)} \cdot G_{HW(prod)}^h,$$

where $G_{B} = G_{BU}$ — the consumption of improved (heated) water entering the boiler unit inlet; $\alpha_{RW(HW)}$ — the same as in formula (8):

$$\alpha_{RW(HW)} = \frac{\tau_{1S(HW)} - \tau_{RW}}{\tau_{2(HW)} - \tau_{RW}},$$

where $\tau_{RW}$, $\tau_{2(HW)}$ — the same as in equation (5); $\tau_{1S(HW)}$ — design temperature of water entering boiler units, °C.

Initially, it is not possible to calculate the flow rates $G_{HW(prod)}^{on}$ and $G_{HW(prod)}^{fu}$ of hot water. We preset them using empirical expressions of the form:

$$G_{HW(prod)}^{i} = \alpha_{HW(i)} \cdot G_{HW(prod)}^h,$$

where the index $i = on$, $fu$; $\alpha_{HW(i)}^{on}$, $\alpha_{HW(i)}^{fu}$ — the share of hot water consumption, generated, respectively, to meet the own needs of the boiler house and the needs of the fuel economy, in the total consumption of hot water generated.

Solving equation (1) together with equations (2), (8) and (12), the flow rate $G_{HW(prod)}^{h}$ of hot water produced by boiler units is found:

$$G_{HW(prod)}^{h} = \frac{k_{HW} \cdot \alpha_{HW(D)}^{on} + k_{HW} \cdot \alpha_{HW(D)}^{fu} - k_{RW} \cdot \alpha_{RW(HW)}}{1 - \alpha_{HW(HW)}^{on} - \alpha_{HW(HW)}^{fu} - k_{HW} \cdot \alpha_{RW(HW)}} \cdot G_{d}.$$

Hot water boiler units operate reliably in all modes if the flow rate of heated water circulating through them is constant [7 -10]. In this case, the thermal power of the boiler units (boiler room) in the range of outdoor temperature values $\tau_{obp} \ldots \tau_{dah}$ changes as a result of a change in the temperature $\tau_{2(HW)}$ of the hot water supplied by them. During this period of the year, all units installed in the boiler room work.

In the range of outdoor temperature values $\tau_{ob} \ldots \tau_{obp}$ and in the non-heating period of the year ($\tau_{o} > \tau_{ob}$), the temperature $\tau_{2(HW)}$ of hot water produced by boiler units does not change and is taken equal
to its value at the break point of the temperature graph: \( \tau_{2e(HW)} = \tau_{2e(HW)} = \tau_{2e(HW)} \), where \( \tau_{2e(HW)} \) is the temperature of hot water supplied by boiler units at the break point of the temperature graph: (at \( \tau_{a} = \tau_{ob} \), °C).

At outside air temperatures \( \tau_{a} > \tau_{ob} \), the heat output of the boiler room is controlled by changing the number of operating boiler units - by starting or stopping a part of the boiler units. At the same time, through each operating unit, the estimated consumption of heated water is provided. Initially, at the design temperature \( \tau_{HO} \) of the outside air, we find the flow rate \( G_{HW(\text{prod})}^{ob} \) of hot water produced by the boiler units at \( \tau_{a} = \tau_{ob} \): \( \tau_{2S(HW)} = \tau_{1S}^{*} \) and \( \alpha_{HW(i)}^{f} = 1 \).

The resulting value of the flow rate of the generated hot water is calculated and is taken over the entire range of outdoor temperature values \( \tau_{ob} \ldots \tau_{daa} \). Knowing the flow rate of the generated hot water, we calculate its temperature \( \tau_{2e(HW)} \) at the required values of the outdoor air temperature, including when \( \tau_{a} = \tau_{ob} \). In the range of outdoor air temperature values \( \tau_{ob} \ldots \tau_{o} \), and in the non-heating period of the year, the flow rate \( G_{HW(\text{prod})}^{BH} \) of the generated hot water is found by the value of its temperature \( \tau_{2a(HW)} \).

3. Investigation results

Solving equation (1) together with expressions (2), (8) and (12), and also taking into account relations (5) and (11), we determine the temperature of hot water produced by boiler units at \( \tau_{a} = \tau_{ob} \ldots \tau_{daa} \):

\[
\tau_{2e(HW)} = \tau_{RW} + \frac{k_{HW} \cdot G_{D} \cdot (\tau_{1}^{*} - \tau_{RW}) + k_{HW} \cdot G_{HW(\text{prod})}^{bh} \cdot (\tau_{1e(HW)}^{*} - \tau_{RW})}{(1 - \alpha_{ho}^{m} - \alpha_{HW(i)}^{f}) \cdot G_{HW(\text{prod})}^{bh}}.
\] (14)

The flow rate \( G_{IW}^{BH} \) of the initial (raw) water and the flow rate \( G_{XOB(TCT)}^{D} \) of chemically treated water entering the deaerator are interconnected as follows:

\[
G_{IW}^{BH} = G_{IW(L)} + G_{CTW(L)} + G_{CTW(E)}^{D} = k_{IW} \cdot G_{CTW(E)}^{D}.
\] (15)

where \( G_{IW}^{BH} \) is the flow rate of the source water entering the chemical water treatment area (CWTA); \( G_{IW(L)} \) – the consumption of the source water lost as a result of its costs for the auxiliary needs of the chemical water treatment site and in the form of leaks; \( G_{CTW(L)} \) – consumption of chemically treated water lost in the form of leaks during its movement to the deaerator; \( G_{CTW(E)}^{D} \) – consumption of chemically treated water entering the deaerator; \( k_{IW} \cdot \cdot k_{HB} \) is a coefficient that takes into account the loss of initial and purified water.

Consumption \( G_{CTW(E)}^{D} \) of chemically treated water entering the deaerator and consumption \( G_{HW(C)}^{D} \) of hot water consumed by the deaerator as heating coolant, we find as a result of the joint solution of the equations of material and heat balances of the deaerator. This solution gives:

\[
G_{CTW(E)}^{D} = D_{\text{LEAV}} + G_{MW(S)};
\] (16)

\[
G_{HW(C)}^{D} = G_{MW(S)} \cdot \frac{(i_{1}^{s} - i_{CTW}^{d}) + d \cdot (i_{1}^{s} - i_{CTW}^{d})}{(i_{2}^{s} - i_{1}^{s}) - d \cdot (i_{1}^{s} - i_{CTW}^{d})}.
\] (17)

where \( D_{\text{LEAV}} \) – flow rate of the steam-gas mixture (vapor) leaving the deaerator; \( G_{MW(S)} \) – consumption of make-up water supplied by the deaerator to the heating network; \( d \) – specific consumption of vapor;
specific enthalpies of deaerated, chemically purified, hot water and vapor, respectively.

Consumption $G_{MW(S)}$ of make-up water supplied by the deaerator is equal to:

$$G_{MW(S)} = k_{MW} \cdot (G_{d(L)} + G_{HW(L)}^h + G_{RW(L)}^h + G_{HW(L)}^{in})$$  \hspace{1cm} (18)

where $k_{MW}$ - make-up water loss factor; $G_{i(L)}^j$ - consumption of water lost in meeting certain needs:

$$G_{j(L)} = \mu_{j} \cdot G_{j(C)} \left( j = d, HW, RW; i = hn, on, fu \right)$$  \hspace{1cm} (19)

where $\mu_{j}$ - the share of the lost water consumption from the consumption $G_{j(MFR)}$ of the consumed water.

Thermal calculations of heaters 2 and 5, as well as vapor cooler 6, are carried out using their heat balance equations.

Having calculated the flow rates $G_{HW(prod)}^m$ and $G_{HW(prod)}^{in}$, we check the accuracy of setting the values $\alpha_{MW(HW)}^m$ and $\alpha_{HW(HW)}^{in}$ in expression (12).

Calculating the costs $G_{DW(E)}^H$, $G_{HW(E)}^H$ and $G_{CH(E)}^H$, we check the accuracy of setting the values of the quantities $\alpha_{MW(WR)}^H$, $\alpha_{HW(WR)}^H$, $\alpha_{CH(WR)}^H$ in the formula (7).

The reliability of the performed calculations is estimated by checking the fulfillment of equality (9). Its right-hand side is calculated using expression (1). The calculation of the left side of equality (9) is carried out according to the equation:

$$G_{RW(misc)}^{bh} + G_{RW(misc)}^{BU} = G_{RW(BU)},$$  \hspace{1cm} (20)

where $G_{RW(misc)}^{bh}$ is the consumption of recovered water entering the boiler inlet:

$$G_{RW(misc)}^{bh} = G_{d(E)}^{bh} + G_{DW(E)}^{H} + G_{HW(E)}^{H} + G_{HW(E)}^{fu}.$$  \hspace{1cm} (21)

4. Conclusion

The considered method of calculating the heating scheme of the boiler house was accepted for implementation by the Energy Management and Audit Laboratory of the State Institution "Oryol Regional Energy Saving Center" (State Institution "Orel RCE"). Its approbation took place for the first time in 2016, during an energy survey of a hot-water boiler house located on the territory of the FSBEI HE "OSU named after IS Turgenev". The results obtained using the developed methodology and instrumental examinations confirmed a high level of convergence of technological indicators (error less than 5%). Taking into account the achieved positive effect, this technique is used for energy surveys of water heating boilers in Orel and the Oryol region, carried out by specialists of the State Institution "Orel RCE" with the participation of the developers of the technique. Its use makes it possible to increase the accuracy of the performed heat engineering calculations, and also provides a deeper understanding of the essence of heat engineering processes, and, as a result, simplifies the solution of the problem of optimizing the operating modes of boiler equipment [11, 12].

References

[1] SP 124.13330.2012 "SNiP 41-02-2003 Heating networks"
[2] Badaguev B T 2010 Steam and hot water boilers: operational safety: orders, instructions, magazines, regulations (Moscow: Alfa-Press) p 198
[3] Krol L B, Kelman G N 1970 Intermediate superheating of steam and its regulation in power units (Moscow: "Energy") p 320
[4] Kraush S A 2003 Heat-generating installations of heat supply systems: a textbook for university students (Tomsk: Tomsk State University of Architecture and Civil Engineering) p 161

[5] Gusev Yu L 2011 Basics of designing boiler plants 2nd ed. (Moscow: Stroyizdat) p 248

[6] Rivkin A S 2011 Thermal calculation of the boiler unit: textbook. Manual (Ivanovo: ISEU) p 144

[7] 1983 Boilers of low and medium power and combustion devices: 15-83. Industry catalog (Moscow: NIIENFORMENERGOMASH) p 226

[8] Gubarev A V, Vasilchenko Yu V 2008 Heat generating installations. Part 1: tutorial (Belgorod: publishing house of BSTU im. V.G. Shukhova) p 162

[9] Shumilin E V, Psarov S A 2013 Thermal calculation of the boiler: workshop (Khabarovsk: Publishing house of the Pacific State University) p 78

[10] Danilov O L, Garyaev A B, Klimenko A V et al. 2011 Energy saving in heat power engineering and heat engineering: textbook for universities 2nd ed. (M.: Publishing house MEI) p 424

[11] Kachanov A N, Golenkov V A, Stepanov Yu S, Koroleva T G 2003 Methodology for conducting energy audits of public sector enterprises: a tutorial (Orel: Orel State Technical University) p 156

[12] Kachanov A N, Golenkov V A, Stepanov Yu S, Koroleva T G 2003 Methodology for designing energy surveys of public sector enterprises: Textbook (Orel: Orel State Technical University) p 156