Methodology for calculating previously unaccounted for heat losses of internal hot water supply systems

Roman Hurgin and Evgeniy Nosorev
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: hurgin@mail.ru, znosorev@yandex.ru

Abstract. For a long time, design engineers calculated heat losses according to the method proposed in SNiP 2.04.01-85*, i.e by multiplying the specific value of heat losses per unit length of the pipeline. While this methodology is good enough for simple calculations, it lacks in preciseness, which in turn can lead to an overengineering of the hot water system. In 2017, SP 30.13330.2016 was introduced, in which the calculation of heat loss by pipelines of the hot water system from SNiP was changed to include previously unaccounted for heat losses that were not calculated. Now this methodology almost fully reflects the physical processes of heat transfer, considers the corresponding design parameters, and delivers more precise calculations, than SNiP methodology, which in turn allows to account for precise numbers of heat loss in hot water system. Detailed analysis of formulas and their components will provide better understanding of processes which affect heat losses in hot water systems.

1. SP technique

The methodology provided in SNiP 2.04.01-85* [1], and then supplemented in the Designer Handbook. Internal sanitary facilities. Part 2. Plumbing and sewerage [2] have been used for many years to calculate heat losses in pipelines of the hot water supply system.

Those methodologies are good enough for quick calculations, but are not fully accurate, which is one of their main disadvantages.

The essence of the methodology from the Designer’s Handbook is to simply multiply the total heat losses of pipelines per 1 m of length by the length of these same pipelines:

\[ Q_{ht} = \sum Q_i \cdot l_i; \]

(1)

Where: \( Q_{ht} \) is losses of supply pipelines, W;
\( Q_i \) is heat losses of 1 m of the pipeline of a given diameter, W/m;
\( l_i \) is length of the pipeline section with a given diameter, m;

Data on heat losses per 1 m of the pipeline are presented in Table 10.4 of the Designer Handbook [2] and were obtained empirically during the operation of real-life objects. They give a rather good general idea of the approximate heat losses that are occurring in the hot water supply system at its known length.

In addition, this methodology allows one to calculate with only two parameters in mind: length and certain heat losses per 1 m of the pipeline. This allows for significant time savings, but really lacks in precision of calculation.
But this is also can be disadvantageous for relatively large supply systems, an enlarged calculation can give too high figures of heat losses, which will not correlate with a real figures of heat losses at all. This, in turn, will lead to a potential overengineering of hot water supply system and excess heat consumption for heating hot water, and such heat waste will lead to an increase in the capital construction costs, operating costs and increased wear of the hot water supply system components due to significant irregularities in the usage of hot water supply.

The lack of connection with any physicochemical properties of water as a heat carrier does not allow to accurately assess the heat losses of pipelines in this case, which also negatively affects the system energy efficiency.

The updated methodology in SP 30.13330.2016 [3] provides a new approach to the calculation of heat loss in the hot water supply system. It now includes previously unused coefficients and considers water physicochemical properties. When using the aforementioned methodology for their calculations the authors should define the following parameters:

- linear heat transfer coefficient;
- thermal insulation thickness;
- average water temperature in the pipelines.

These parameters allow for a much deeper and more accurate assessment of the heat losses of the supply pipelines in the hot water supply system, considering water physicochemical properties as well. With this methodology, it is possible to calculate the heat losses for two fundamentally different cases, with and without thermal insulation on the pipe. Using this methodology makes it possible to evaluate heat losses without resorting to average values, which allows for a whole lot more precise calculation of heat losses.

This methodology is much more suitable for careful and precise calculations in large systems, where the issue of energy efficiency plays an important role, and even more important role do the capital construction costs and system operation costs play.

However, it is a very time-consuming methodology, and it requires a careful study of the relevant technical and regulatory literature to understand the very essence of the calculation.

The analysis of the proposed methodology implies a deep study of the relevant technical literature and the analysis of a calculation algorithm.

In SNiP 2.04.01-85* [1], the calculation of heat loss is provided as follows:

\[ Q_{t(hr)}^h = 1.16 \cdot q_{t(hr)}^h \cdot (t_r - t_x) \cdot Q^{ht}; \]  

(2)

Where: \( q_{t(hr)}^h \) is average hourly or maximum hourly liquid flow rate, m³/h;
\( t_h \) is hot water temperature, taken according to clause 5.1.2 [3], °C;
\( t_c \) is cold water temperature at the inlet to the water heater;
\( Q^{ht} \) are unaccounted losses in pipelines are taken equal to 25%.  
1.16 is a conversion coefficient to W;

One can easily see that the heat losses according to this formula is considered as a percentage of the whole heat losses in the form of \( Q^{ht} \).

This allows us to understand the overall figures of heat losses in the hot water supply system, but those figures are most likely to be way higher than the real ones. This will lead us to the fact that the system will most likely be overengineered and will not be as energy efficient as it could be. Even 5-10% of heat overconsumption in a few years will grow into incredibly significant amounts of money both for the heat supply organization and for heat consumers.

However, this methodology is quite good when you are in the need of quick estimation of how much heat is needed for water heating in hot water supply system as this methodology does not require a lot of input parameters.

Heat losses by pipelines of the hot water supply system are calculated in accordance with Appendix C, clause C.2 [1] by the formula:

\[ Q^{ht} = \sum Q_l^{ht} = \sum k \cdot (T_{av} - T_{amb}) \cdot l; \]  

(3)
Where: $Q_i^{ht}$ are heat losses of individual sections of the hot water system, W;
$k$ is the linear heat transfer coefficient, W/(m·°C);
$T_{av}$ is average temperature of water in the pipeline, °C;
$T_{amb}$ is ambient air temperature, according to [3] for the basement $T_{amb} = 5 \div 6$ °C, for the heated towel rail $T_{amb} = 22$ °C, for the channel $T_{amb} = 6 \div 8$ °C, for the shaft $T_{amb} = 28$ °C;
$l$ is the length of the pipeline section, m.

In addition to the length and heat losses of the pipeline sections, new calculation methodology includes a linear heat transfer coefficient $k$, which will be analyzed further into the article, and also takes into account the process of natural convection between the pipeline and the ambient air.

Taking into account the fact that the ambient air temperature strongly affects the heat losses of pipelines, the heat losses data will be much more accurate than simply multiplying the heat loss per 1 m of the pipeline by the length of this pipeline.

Temperature losses in the pipelines of the hot water supply system are calculated in accordance with Appendix C, clause C.2 [3] by the formula:

$$T_2 = \frac{3,6 \cdot Q_{sec} \cdot (T_1 - Q_i^{ht}/(1/1163))}{3,6 \cdot Q_{sec}},$$

(4)

Where: $Q_{sec}$ is the estimated liquid flow rate of the pipeline section, l/s;
$Q_i^{ht}$ are heat losses of the pipeline section with thermal insulation, W;
$T_1$ is initial temperature, °C;
$(1/1163)$ is the conversion factor, 1 W = 1,163 Mcal.

The calculation of the linear heat transfer coefficient should be made for 2 cases according to [4], i.e. for pipes with and without thermal insulation:

For a single-layer cylindrical wall (pipes without thermal insulation):

$$k = 1 \cdot \left(\frac{1}{\alpha_1 d_1} + \frac{1}{2 \lambda_1} \ln \frac{d_2}{d_1} + \frac{1}{\alpha_2 d_2}\right)^{-1}.$$  

(5)

For a two-layer cylindrical wall (pipes with thermal insulation):

$$k = 1 \cdot \left(\frac{1}{\alpha_1 d_1} + \frac{1}{2 \lambda_1} \ln \frac{d_2}{d_1} + \frac{1}{2 \lambda_2} \ln \frac{d_3}{d_2} + \frac{1}{\alpha_2 d_3}\right)^{-1}.$$  

(6)

Where: $\alpha_1$ is heat transfer coefficient from hot water to the pipe wall;
$\alpha_2$ is heat transfer coefficient from the pipe wall to air;
$\lambda_1$ is thermal conductivity coefficient of a steel pipe, $\lambda_1 = 46,7$ W/(m·K);
$\lambda_2$ is thermal conductivity coefficient of thermal insulation, it depends on the average temperature of the thermal insulation layer according to [5], W/(m·K);
$d_1$ is pipe inner diameter, m;
$d_2$ is outer diameter of the pipe (inner diameter of the insulation), m;
$d_3$ is outer diameter of the insulation, m, is determined by [5].

This calculation allows to conduct a much more accurate assessment of the heat losses in the areas with and without thermal insulation. This accurate calculation can significantly change total heat losses for a system with a large number of risers. However, the benefits of this calculations may not be so significant for systems with a small number of risers.

This calculation methodology also allows to use different pipes with slightly or not-so-slightly different heat transfer coefficients, which can potentially allow one to reduce the thickness of a thermal insulation layer.

2. Heat loss calculation
It is necessary to dive into more detail for what the heat transfer coefficients $\alpha$ really are, since this allows for better understanding of how this new calculation methodology includes the physical
properties of water and how the hydrodynamic regime and fluid dynamics as a whole affect the heat losses.

This study will make it possible to get a significantly better understanding of the heat losses in the pipelines of hot water supply systems at different regimes of water movement in the pipes, because each regime has a different effect on heat losses in pipelines of hot water supply systems, and hence on a total heat losses of hot water supply systems.

2.1. Calculation of heat losses for hot water supply system pipelines without thermal insulation

According to [6], the heat transfer coefficient for inner walls $\alpha_1$ is calculated by the formula:

$$\alpha_1 = \frac{Nu_1 \lambda_1}{d_1};$$

(7)

Where: $\lambda_1$ is thermal conductivity coefficient of the liquid, W/(m·K);

$d_1$ is pipe inner diameter, m;

$Nu_1$ is the Nusselt number characterizing the similarity of heat transfer processes at the boundary between the wall and the fluid flow; it is calculated depending on the flow regime under forced convection.

We need to review and compare three different hydrodynamic regimes of fluid motion in order to understand how strongly the motion regime actually affects heat transfer.

For a laminar flow regime, where $Re \leq 2320$:

$$Nu = 0,15Re^{0,33} \cdot Pr^{0,43} \cdot Gr^{0,1} \cdot \left(\frac{Pr}{Pr_w}\right)^{0,25};$$

(8)

Where: $Re$ is the Reynolds number, which characterizes the hydrodynamic flow regime; it is calculated by the formula:

$$Re = \frac{\omega d_1}{v};$$

(9)

Where: $\omega$ is fluid velocity, m/s;

$d_1$ is equivalent diameter, equal to the diameter of the pipeline, since the pipeline operates with a full section, m;

$v$ is kinematic viscosity of the liquid, m$^2$/s, calculated by the formula:

$$v = \frac{\mu_1}{\rho};$$

(10)

Where: $\mu_1$ is dynamic viscosity of the liquid, Pa·s;

$\rho$ is density of the liquid, kg/m$^3$;

$Pr$ is the Prandtl number characterizing the physicochemical properties of the heat transferring liquid. It establishes a relationship between thermal conductivity and fluid movement, calculated by the formula:

$$Pr = \frac{c \mu_1}{\lambda_1};$$

(11)

Where: $c$ is specific heat capacity of the liquid, J/(kg·°C);

$Pr_w$ is the Prandtl number for a pipe wall, equal to $Pr$, since it’s safe to assume that the pipe wall temperature is equal to the water temperature in it, as the thermal conductivity of water and a steel pipe is several times higher than the air thermal conductivity, and the wall thickness is insignificant, thus allowing us to use this assumption in the calculations;

$Gr$ is the Grashof number, which characterizes the action of the hydrostatic lifting force and the liquid viscosity force under natural convection, calculated by the formula:

$$Gr = \frac{\frac{g l^3 \beta \Delta t}{\mu_1^2}}{\mu_2};$$

(12)
Where: g is gravity acceleration, \( g = 9.81 \text{ m/s}^2 \);
l_i is a characteristic size, for horizontal sections \( l_i = d_i \), for vertical sections \( l_i = l_{sec} \), m;
\( \beta \) is the thermal expansion coefficient, equal to \( \beta = 1/(t + 273) \), K^{-1};
\( \Delta t \) is temperature difference between the pipe wall and air temperature, K;
\( \mu_a \) is air dynamic viscosity, Pa·s;
For a transient regime of fluid movement, where \( 2320 \leq \text{Re} \leq 10000 \):
\[
\text{Nu} = C \cdot \text{Pr}^{0.43} \cdot \left( \frac{\text{Pr}}{\text{Pr}_{ct}} \right)^{0.25};
\]
(13)

Where: C is the coefficient taken according to tables in [9], depending on the value of the Reynolds number;
For a turbulent regime of fluid movement, where \( \text{Re} \geq 10000 \):
\[
\text{Nu} = 0.021 \text{Re}^{0.8} \cdot \text{Pr}^{0.43} \cdot \left( \frac{\text{Pr}}{\text{Pr}_{ct}} \right)^{0.25};
\]
(14)

According to [6], the heat transfer coefficient for outer walls \( \alpha_2 \) is calculated by the formula:
\[
\alpha_2 = \frac{\text{Nu}_2 \lambda_i}{d_2};
\]
(15)

Where: \( d_2 \) is the pipe outer diameter, m;
\( \text{Nu}_2 \) is the Nusselt number, calculated by the formula for natural convection:
\[
\text{Nu} = C \cdot (\text{Gr} \cdot \text{Pr})^{0.4} \cdot \left( \frac{\text{Pr}}{\text{Pr}_{ct}} \right)^{0.25};
\]
(16)

Where the coefficient C and the exponent n depend on the hydrodynamic regime of fluid movement and they can be found in the tables of [6].

2.2. Calculation of heat losses for hot water supply system pipelines with thermal insulation

When obtaining heat losses of the heat-insulated sections of hot water supply system pipelines, it is necessary to calculate the insulation thickness according to [5].

The heat transfer coefficient for inner walls \( \alpha_1 \) will remain the same as has been calculated above for the pipelines without thermal insulation.

However, \( \alpha_2 \) will be equal to \( \alpha_{ext} \) – the heat transfer coefficient of the outer surface of the insulation, taken according to table C.2 [5]:

- for horizontal pipeline sections \( \alpha_{ext} = 7 \text{ W/(m}^2\cdot\text{°C)} \);
- for vertical pipeline sections \( \alpha_{ext} = 8 \text{ W/(m}^2\cdot\text{°C)} \);

The analyzed methodology provides a detailed study of the processes of heat exchange of pipelines with the environment by means of natural convection. The main difficulty of the methodology lies in obtaining the heat transfer coefficients \( \alpha \) and thermal conductivity \( \lambda \) of the pipes, which can be manufactured at different manufacturing plants. These coefficients will not vary significantly, but one needs to know them if they want to get accurate data on heat losses. They play a very important role in calculating the linear thermal conductivity coefficient \( k \), which directly affects heat losses.

To use these calculations of heat losses of hot water supply system pipelines in practice, it will be necessary to request those coefficients from the pipeline manufacturers, which is not possible sometimes.

2.3. Calculation of circulating liquid flow rate of hot water supply systems

Heat losses directly affect the circulating liquid flow rate in hot water supply system.

The circulation flow rate is calculated according to appendix C, clause C.1 [3], by formula:
\[
Q_i = \frac{Q_{ht}}{\rho_c(t_1 - t_2)};
\]
(17)
Where: $\rho$ is density of the liquid, kg/m$^3$;
$c$ is specific heat capacity of the liquid, J/(kg · °C);
$t_1$ is water temperature, when it leaves the heat exchanger, °C;
$t_2$ is water temperature, when it reaches the consumer, °C;
$\Delta t$ is water temperature difference, °C;
$J$ is heat transfer rate, W.

As we can see in this formula, there are 2 constants in the denominator: $\rho$, density of the liquid, and $c$, heat capacity of the liquid. Also, the temperature which is regulated by [3]. In the numerator there are only the heat losses, which means that circulating liquid flow rate depends nearly entirely on the amount of heat losses. Thus, it is important that the calculation of heat losses is precise, because the diameters of risers depends on the flow rate. Diameter of the pipe affects the flow speed, i.e. the lower the speed of the liquid is, the lesser the temperature will be, when the liquid reaches the consumer, but as the temperature is stated in [3] and is used in the equation (17), so the low speed is unacceptable. Thus, the diameter, which significantly affects the speed, should be considered with optimal flow speed in mind. In addition to this, circulating liquid flow rate affects the choice of the circulation pump, which in turn affects capital construction costs and system operation costs. This once again leads us to the importance of the precise calculations of hot water supply system heat losses.

3. Conclusions
First of all, new methodology allows to consider heat losses that were previously unaccounted for in the calculations at all, for example, heat losses that are caused by natural convection.

This approach has an extremely positive effect on the calculation accuracy, although it takes quite a lot more time. However, the increased accuracy of calculations allows for better assessment of the system energy efficiency.

Secondly, this new methodology allows to consider the difference in thermophysical characteristics of pipelines from different pipe manufacturers.

For calculations, it is necessary to obtain the heat transfer coefficients and thermal conductivity coefficient for each different pipe directly from the pipe manufacturers. Even though this process may take a big amount of time, it must be done to improve the accuracy of the calculations.

Thirdly, bringing the calculation of heat losses of hot water supply system into a general table after the initial design stage will allow for a better inspection of the general system condition, determining the system weakest points in terms of heat losses, and it will allow for more accurate adjusting of the values of the thermal insulation thickness, by adjusting the diameters and temperature in the heat exchanger.

This method can also allow to gain a lot in terms of the hot water supply system energy efficiency in general, as isolating and re-calculating some specific bottlenecks will have a beneficial effect on the hot water supply system as a whole.

Finally, precise calculation of heat losses of hot water supply system directly affects the circulating liquid flow rate. Circulating liquid flow rate in turn affects the diameter of pipelines, where we can’t afford to have a low flow speed. Also circulating liquid flow rate affects the choice of the circulation pump, which can lead to an increased capital construction costs and system operation costs, both of which are not welcome at all.

However, to fully understand the principles of heat losses of hot water supply system calculation, an in-depth study of the technical literature on the topic of heat transfer and thermal conductivity is necessary, since this will allow one to understand the very essence of the process, and why the new methodology is so closely interconnected with water physicochemical properties and various hydrodynamic regime and fluid dynamics as a whole.

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