

# Estimation of energy efficiency of water heating systems in terms of electricity consumption

Sergey Usikov\*

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

**Abstract.** The article considers the creation of a regulatory framework in the field of rationing the energy efficiency of water heating systems, and gives recommendations for its creation. In heating systems, there are two main types of energy consumption: electrical and thermal. Electric consumption primarily depends on the correct choice of the pump in the system, its efficiency, as well as the design and operation characteristics of the heating system. Existing methods for assessing energy efficiency, used for ventilation systems, are not applicable for heating systems, since certain conditions must be met for high-quality exploitation. In particular, such conditions include the removal of air from the system and the provision of proportional regulation of the heat transfer of the heating devices. The article gives an example of determining the energy efficiency of a heating system depending on these conditions, and the proposed methodology and methodology applicable for ventilation systems are compared. The considered technique can be applied at carrying out of examination of the design documentation of section "Heating and ventilation".

## 1 Introduction

Along with the development of energy-efficient technologies and equipment of engineering systems, there is a need to develop standardization. When designing projects for heating and ventilation systems, the designer is often guided by his own experience and similar projects. As a consequence, the project includes a standard series of equipment that was present in the example projects, but does not contribute to energy efficiency, in vain complicating the system. Even at the design stage, it is necessary to assess the need for particular equipment, as well as its operating mode and its preliminary settings.

On the territory of the Russian Federation, the most widespread was the water heating system. But, like any other heating system, it is not devoid of shortcomings. Provide exactly necessary heat supply to heated rooms throughout the heating season, while not spending "excess" energy, it is impossible. The task of normalizing the energy consumption of water heating systems is to reduce these "excess" energy losses, which can be caused by the irrational design of the system.

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\* Corresponding author: [usikov-work@ya.ru](mailto:usikov-work@ya.ru)

During exploitation of the water heating system consumes thermal and electrical energy. Thermal energy is used to compensate for the thermal losses of the building, as well as to the additional design costs of the system: the loss of heat from pipes laid in unheated rooms, additional heat losses of the external wall behind the heating device, the production list of heat transfer from heating appliances, and the accuracy of automatic regulators.

Electric energy is spent to ensure the operation of circulating, mixing and make-up pumps, as well as the operation of automatic control devices at the heat center. In this publication, the necessity of developing the normalization of the second component of costs, that is, the cost of electrical energy will be discussed in detail.

The costs of electrical energy are inherent in any water heating system, with the exception of systems with natural circulation. In the water pumping heating system, the electrical energy is expended for transporting the coolant by a circulating and mixing-circulating pump, increasing the pressure at the mixing point by the mixing pump, ensuring the operation of the automatic control system and the make-up unit. Additional mixing pumps can also be used to change the system temperature graph (for example, for panel-radiant heating such as "warm floor").

Electricity consumption by additional mixing pumps to change the temperature graph in a separate part of the system is difficult to take into account, since the operating mode of such parts of the system is, as a rule, variable and unpredictable. In the case of continuous use of such mixing units throughout the heating season, the calculation of energy costs in determining the efficiency is carried out similarly to mixing pumps for a centralized heating system.

The energy costs for the automatic control system are approximately the same for different thermal centers, and practically do not depend on the type and brand of regulators, therefore, in determining the energy efficiency, this value should not be taken into account. The make-up unit also consumes electrical energy, but since the probability of the make-up pump operation (which may not be) depends on random factors, this consumption value should not be taken into account in determining the energy efficiency.

For heating systems connected by an independent scheme to heat networks, as well as systems with local heat supply (individual boilers), electric energy is used up by the circulation pumps - to transfer the coolant in the system. The pressure created by the circulation pump is used to overcome the hydraulic resistance in the system.

The hydraulic resistance in the system, in turn, depends on the design of the heating system, including from the tracing of heat pipes, the diameters of heat pipes, the presence of shut-off and control valves. The higher the hydraulic resistance of the heating system, the greater the power consumption of the circulation pump.

The choice of mixing and mixing-circulating pumps with the dependent connection of the heating system to the heating networks also depends on the pressure loss in the heating system circuit, and, consequently, on the consumption of electrical energy.

Thus, the most economical option from the point of view of operation is the design of the system, in which the least loss of pressure. This can be achieved by selecting large pipe diameters, as well as fittings with the lowest hydraulic resistance.

## 2 Existing methods for determining the energy efficiency of ventilation systems

In the foreign practice of rationing of energy consumption in ventilation systems, the use of the value of «specific fan power» [1]:

$$P_{SFP} = \frac{P}{q_v} = \frac{\Delta p}{\eta_{tot}} \cdot \frac{W}{m^3/s}, \quad (2.1)$$

$P_{SFP}$  – specific fan power, W/(m<sup>3</sup>/s);  
 $P$  – input power of the motor for the fan, W;  
 $q_v$  – design airflow through the fan, m<sup>3</sup>/s;  
 $\Delta p$  – total pressure difference across the fan, Pa;  
 $\eta_{tot}$  – overall efficiency of the fan.

The obtained value is compared with the normative values and the system is assigned an energy efficiency class.

However, as in ventilation systems and in heating systems, this ratio gives a very rough estimate of the system, without going into the architectural features of the serviced building and the design of the system. The introduction of such an indicator into the practice of standardizing the energy saving of central heating systems might solve the problem with the election of irrationally powerful and expensive pumps "with a margin" [2], but would not be suitable for assessing the whole variety of heating system designs.

It is proposed in [3] to classify spent electric energy by a fan as "useful" and "lost". Useful costs include the power expended on the preparation of air in the supply unit (normalized) and the aerodynamic power of the flow leaving all air distribution devices. The remaining costs are "lost".

In systems of water heating, we can also identify "useful" and "lost" costs, which will be referred to here as redundant.

### 3 Features of exploitation of water heating systems wagging on energy efficiency

Electric power of the pump  $N_{pump}$ , W, depends directly on the flow of water that it pumps, the pressure it creates  $\Delta p_{pump}$ , Pa, and its design, that is, the full efficiency of the pump [4]:

$$N_{pump} = \frac{Q_{pump} \Delta p_{pump}}{\eta_{tot.p}}, \quad (3.1)$$

$Q_{pump}$  – water flow rate provided by the pump, m<sup>3</sup>/s;  
 $\Delta p_{pump}$  – pressure created by the pump, kPa;  
 $\eta_{tot.p}$  – overall efficiency of the pump.

For a building in which a heating system is provided, the coolant flow will not depend on the design of the system, since the amount of heat exactly necessary (determined by calculation of heat losses) must be supplied to each heated room. Accordingly, in order to reduce the consumption of electrical energy, it is necessary to use pumps with the maximum efficiency in the operating mode, and by reducing the hydraulic resistance of the heating system. However, the hydraulic resistance is limited by the features of the exploitation of the heating system, so it can only be reduced to certain limits.

From the point of view of ensuring air removal and exploitation regulation of the heat transfer of the heaters, there is a certain limit on the choice of pipe diameters and the cross-section of the control valves.

According p. 6.3.10 [5] the maximum velocity of the coolant in the pipes of heating systems is limited. But the minimum velocity of the coolant in the pipes is limited by the speed of air bubbles. Thus, the minimum velocity of the coolant must be at least [6]:

- a) 0,2 m/s in vertical pipes;
- b) 0,1 m/s in horizontal pipes, with a slope of at least 0.002 from the air outlet point.

Permitted velocity reduction in the liner to the radiators if the slope is formed in the direction of the point of venting a value not less than 0.005.

Unfortunately, this limitation is not enough to select the diameter of the pipes and the caliber of the equipment. The difficulty lies in the need to achieve the most convenient and effective regulation of the heat output of heaters.

In the practice of exploitation heating systems, qualitative, quantitative and qualitative-quantitative regulation is applied. It is impossible to achieve precisely the necessary heat transfer of heaters under changing conditions of the external climate and internal thermal conditions throughout the entire heating season only at the expense of qualitative regulation. This is due to the fact that in each separate building of civil buildings there is its unique heat balance, which depends on many unpredictable or poorly predicted facts [7]. Therefore, for more precise regulation, the node and individual quantitative control [8].

Quantitative regulation has its own characteristics. In the works [8, 9] the nonlinearity of the heat output of the heater is shown, depending on the degree of closure of the control valve. To achieve linearity of regulation allows a special design of regulators with its own special characteristic of regulation.

According to [9], to ensure proportional control of the heat transfer of heaters by individual regulators, it is necessary to ensure a certain amount of pressure loss on the regulating device. That is, for systems where only individual regulators are installed in heating appliances, the authority of the regulator should be not less than:

- a) when using a linear characteristic controller – 0,6;
- b) when using a regulator with a logarithmic (equal percentage) and parabolic characteristic – 0,5;
- c) when a regulator with a log-linear characteristic – 0,3.

Thus, the necessary loss of pressure on the individual regulator  $\Delta p_{i.reg}$ , Pa, can be determined by formula:

$$\Delta p_{i.reg} = \frac{a}{1-a} \Delta p_{reg.sect}, \quad (3.2)$$

$a$  – authority of the regulator;

$\Delta P_{reg.sect}$  – loss of pressure on the regulated sector, Pa.

It should be noted that in some cases, additional automatic nodal regulators (regulators of pressure drop, flow and temperature) are also needed for installation [10]. The need for their installation is determined by the ability to exclude noise in individual regulators for heaters. The elimination of noise generation is not their only function, but the remaining tasks they solve are very complex for numerical verification. Since the nodal regulator is an additional local resistance, its installation will lead to additional electrical costs for the transfer of the coolant, as well as the selection of more powerful and expensive pumps.

In addition, in order to eliminate the influence of the natural gravitational circulation force on the floors by two-pipe systems, it is also necessary to create additional pressure losses on the regulators of the heater.

The value of this pressure loss is determined by calculation, from the condition that in the design mode the value of the natural circulation pressure in the small circulation rings should not be more than 10% of the total pressure loss in these rings [11].

Losses of pressure above the necessary (to remove air, provide individual control and eliminate the effect of natural circulation pressure) will be considered excessive.

## 4 Methodology

Thus, in order to assess the energy efficiency of a heating system in terms of electricity consumption, it is proposed to introduce a dimensionless coefficient  $\eta_{el}$ , %:

$$\eta_{el} = 100 \frac{N_{min.n.}}{N_{pump}}, \quad (4.1)$$

$N_{min,n}$  – minimum required energy costs for high-quality exploitation of the heating system, W;

$N_{pump}$  – consumed power by mixing, circulation, or mixing-circulating pump heating system, W (determined according to project documentation).

Since depending on the connection scheme of the heating system to the heat network, the pump has a different purpose and is selected differently, we will consider one of the most used options - connection of the heating system according to an independent scheme.

Necessary electricity costs  $N_{min,n}$ , W, in this case are considered as an idealized consumption of electricity, without taking into account the design features of the pump, that is, its efficiency:

$$N_{min,n} = \eta_{tot} N_{pump}. \quad (4.2)$$

Then, we take as the pressure created by the pump, the minimum necessary resistance of the system and substitute the formula (4.2) in (4.1), we obtain:

$$N_{min,n} = Q_{pump} \Delta P_{min,n}. \quad (4.3)$$

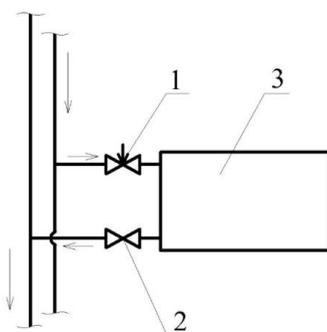
$\Delta p_{min,n}$  – minimum required pressure loss in the heating system to ensure high-quality exploitation, kPa.

It should be noted that according to [2] the pump is selected with a 10 % stock. This stock, as part of the energy efficiency assessment of the system, cannot be attributed to "excessive" costs, since it is established normatively, then formula (4.3) takes the form:

$$N_{min,n} = 1,1 Q_{pump} \Delta P_{min,n}. \quad (4.4)$$

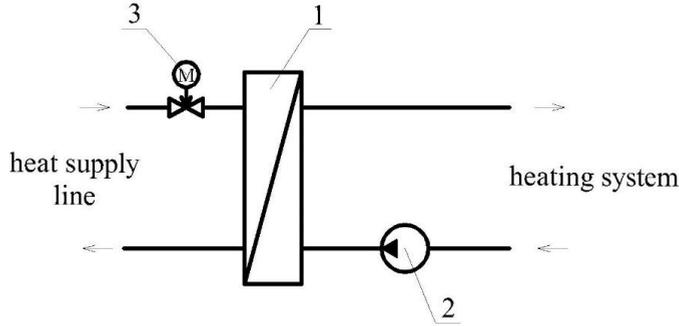
## 5 Example

For an example of determining the minimum required pressure loss in a system, we consider a vertical two-pipe water heating system with a lower wiring, with a passing motion of the coolant. As regulators to the installation, individual regulators are adopted for heaters of the thermostatic valve type with a logarithmic characteristic. The heater connection is shown in Figure 1. The heating system is connected in an independent circuit, the schematic diagram of which is shown in Figure 2. As a circulating pump, a pump with a wet rotor for heating systems with a rated capacity of 0.219 W is installed. The thermal capacity of the system is 162514 W, and the circulating water flow in the system is 6973 kg/h, or 1.94 m<sup>3</sup>/s.



**Fig. 1.** Heater connection:

1 – thermostatic valve; 2 – shut-off valve; 3 – steel panel radiator



**Fig. 2.** Wiring scheme of the heating system:

1 – heat exchanger; 2 – circulation pump; 3 – control valve of the heating system

First, we determine the loss of pressure in the pipes, if their diameter was chosen based on the recommended flow velocity of the coolant for effective air removal.

Diameter of pipe sectors  $d_{a.e}$ , mm, in this case, is chosen according to formula:

$$d_{a.e} = \sqrt{\frac{4G_{sect}}{3600\pi v_{min}\rho}} = 18,81 \sqrt{\frac{G_{sect}}{v_{min}\rho}}, \quad (5.1)$$

$G_{sect}$  – coolant flow in the hydraulic section, kg/h;

$\rho$  – density of water at the design temperature in the section, kg/m<sup>3</sup>;

$v_{min}$  – minimum required speed on the site, to ensure effective air evacuation, m/s.

After determining the value  $d_{a.e}$  from pipes producers' catalogs, the nearest pipe of the smaller diameter is selected. The diameter of the valve was also re-selected, according to the diameter of the pipe sections.

According to the results of the hydraulic calculation for this system with the adopted pipes, according to the possibility of air removal, the loss of pressure in the pipes and the valves of the system was 13 466 Pa.

Since the system does not provide additional regulators, in addition to the individual, the regulated area of the system will be the entire circulation ring from the heat source to the basic design heater. The basic design heater for this system will be a device of the upper floor, the central most loaded riser [11]. Thus, in order to ensure proportional regulation, the pressure loss on the regulator must be, according to formula (3.2), not less than:

$$\Delta p_{i.reg} = \frac{a}{1-a} \Delta p_{reg.sect} = \frac{0,3}{1-0,3} 13466 = 5722 \text{ Pa}. \quad (5.2)$$

Then the total minimum required pressure loss in the system is:

$$\Delta p_{min.n} = \Delta p_{i.reg} + \Delta p_{reg.sect} = 13466 + 5722 = 19188 \text{ Pa}. \quad (5.2)$$

Based on the obtained value, the useful power of the circulation pump will be:

$$N_{min.n} = 1,1 Q_{pump} \Delta p_{min.n} = 1,1 \cdot 1,94 \cdot 19,188 = 41 \text{ W}. \quad (5.3)$$

The coefficient  $\eta_{el}$  for the heating system provided in the building will be:

$$\eta_{el} = 100 \frac{N_{min.n}}{N_{pump}} = 100 \frac{41}{122} = 33,6 \%. \quad (5.4)$$

In this case, if the efficiency of the system is determined by the parameter  $P_{SFP}$  according to [1], then its value is:

$$P_{SFP} = \frac{P}{q_v} = \frac{122}{1,94} = 63 \frac{W}{m^3/s}.$$

## 6 Results and discussions

The principal difference in the determination of energy efficiency by the  $P_{SFP}$  parameter and by the  $\eta_{el}$  factor is that in order to reduce the  $P_{SFP}$  value it is sufficient simply to increase the pipe diameters and use a control valve with a minimum resistance. This can lead to problems in exploitation and a disproportionate automatic individual control, which will cause thermal discomfort in the heated rooms. The coefficient  $\eta_{el}$  takes into account the design and operational features of the system, and if its value exceeds 100%, this will signal a wrong calculation and selection of equipment in the design of the system.

In turn, the coefficient  $\eta_{el}$  can serve as an indicator of the energy efficiency of the system, and its required values can be fixed normatively. But to develop such a standard, it is necessary to conduct a sufficiently large amount of research work, the basis of which will be this study.

In addition, the article does not consider the whole variety of water heating systems, but shows the basic principles of determining energy efficiency, based on which you can obtain dependencies for all types of systems.

According to the results of the study, we can draw conclusions:

1. As the prices for electricity increase, and for the purposes of the country's environmental security, it is necessary to develop regulatory documents assessing the energy efficiency of heating systems.

2. The energy efficiency of heating systems should be assessed in terms of consumption of thermal and electrical energy.

3. The consumption of electrical energy by the heating system directly depends on the architecture of the building, the structural and operational characteristics of the heating system.

4. Estimation of the energy efficiency of the heating system according to the index  $P_{SFP}$  does not reflect operational features of the heating system.

5. The loss of pressure in the heating system has a certain lower limit associated with the operational characteristics of the system, so it is necessary to separate the necessary amount of pressure loss from the useless (excess) loss.

6. The proposed methodology will allow expert organizations at a higher level to monitor and evaluate technical solutions, even at the design stage of heating systems.

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