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Increasing the heat transfer efficiency of sectional radiators in building heating systems

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Abstract. In heating systems of residential and public buildings, the sectional radiators are widely used as heating devices, where its heat transfer efficiency critically decreases, when the heat-carrying agent's temperature lowered. At the same time, in order to increase the heat transfer efficiency of heat-exchange equipment, the positive experience of using the pulse flows is known. The heat supply method proposed in the process of the work performing, which consists in periodic supply of hot and cold heat-carrying agent through the sectional radiators. Thermal tests of 12 sectional radiators Rifar BASE 500 type at the temperatures from 42 °C to 67 °C and pulsation frequencies of the heat-carrying agent from 0.52 Hz to 0.62 Hz, showed an increase in their efficiency at the nominal flow rate of 1.8–2.2. With an increase in the flow rate and temperature of the heat-carrying agent, the SR efficiency decreases in a pulsating mode. The study of the SR efficiency from the parameters of the heating system and their switching circuit was carried out on a mathematical model in the form of energy chain that takes into account the mass and storage capacity of the heat-carrying agent. For a parallel connection up to 10 SR, the optimal circular frequency of the heat-carrying agent pulsations was 3 rad/s, and for a serial connection it was 4.2 rad/s, which is consistent with the results of thermal tests at the level of 7 %.

1. Introduction

Modern global trends in the development of heat supply systems are aimed for reducing irrational costs and heat-carrying agent losses, while improving the quality of maintaining the temperature regime in buildings. Such trends are observed almost in all programs related to the integrated development of the cities. With the development of the heat supply systems in Russia the priority is given to the district heat supply systems from combined sources of electric and thermal energy. Experience in developing of promising urban heat supply schemes shows that the quality, efficiency and reliability of the operation of heat supply systems is associated with the new technologies and tools, which are used to create individual heating plants (IHP) at the inputs to the buildings. The mass introduction of IHP instead of the traditional heating units will not only improve the temperature regime in buildings but also it will solve the problem of ensuring a given pressure at the inputs to the buildings, while increasing the degree of centralization of heat supply systems from combined sources. However, the IHP is successfully implemented only in areas of new development, where in heating systems the panel radiators are mainly used and they are connected independently to the heating networks. At the same time, in the areas of old building development the building heating systems (heating and ventilation) are still connected to the heating networks in a dependent way through the elevator and sectional radiators (SR) are mainly used as the heating devices. As for the last ones the effectiveness of the SR (the ratio of actually achieved thermal capacity to the design one) with a decrease in the heat-carrying agent temperature of 50 °C decreases to 30 %. It has been repeatedly proved as the result of numerous energy inspections of buildings. According to the fact, that with the new construction they have recently switched to the plate radiators of the PURMO type [1]. That is why the hydraulic mode of heating networks in cities is built taking into account the transformation of thermal energy, and each heating unit has the throttling device at the input [2]. At each heating unit appeared the energy losses, for instance, in Moscow there are more than 9500 of them only in the system of OJSC

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"MOEK". The total value of these losses is equivalent to hundreds MW of electric energy which is necessary for the city economy. Nowadays, they are trying to solve the problem of ensuring the given thermal regime of the building with optimization of the hydraulic regime of the heating network by using a mixing pump in the heating units at the inputs of the buildings, which almost increases the speed of the heat-carrying agent through the heating devices in two times, but the achieved SR efficiency has not reached the design capacity. From the 7 academic buildings of National Research Ogarev Mordovia State University in which this method was implemented, the achieved effectiveness of the SR in 2018 was at the level of 60 % of the design capacity. It did not give the expected effect, as far as an increase in the speed of the heat-carrying agent through the heating devices changes the mixing coefficient of the hot and return heat-carrying agent, therefore it reduces the power of the heating device. In addition to that, the installation of mixing pumps increased the consumption of an electric energy in academic buildings for 6 %. This situation has appeared due to the lack of reliable and inexpensive technologies for supplying the heat-carrying agent, which should be based on the research and best practices in the field of new heat supply strategies, taking into account the characteristics of hydrodynamics and heat transfer of specific heating devices.

In the world practice the attention has been focused on the intermittent heating of buildings [3] strategy, which is aimed to reduce the heat energy consumption during working hours by predicting the rational power of heating equipment, depending on the type of buildings. By mixing the period of heating and cooling, there we can see the economy for 20 % of the heat energy, due to its limitation in non-working hours. The usage of such strategy increases the power of heating equipment by 1.1–1.3 times and requires the additional costs. Among the continuous heating strategies the technologies with pulsating (pulsed) heat-carrying agent circulation and the features for their creation deserves attention, which are described in details in publications [4,5]. In these works the positive experience of oscillating flows in heat exchange equipment extends to the heat supply systems with independent connection to the heating networks, without the heating devices. Recommendations are given for the construction of such schemes; however, the quantitative estimates of the achieved efficiency of such heat supply systems are not given. The influence of the pulse flow for the energy consumption of panel radiators was studied in the works [6–8], which are contain the quantitative estimates of the increasing efficiency about 20 % with fluctuations in the pulse flow in the frequency range from 0.027 m/s to 0.051 m/s and the frequency of 0.0523 rad/s to 0.209 rad/s is obtained by modeling methods of two panel emitters while maintaining the temperature on the surface of the radiator 50 °C. It is unclear, how the panel emitters efficiency changes, while changing the amplitude consumption of the heat-carrying agent. In the work [9], which is devoted to increasing the capacity of a heating system by replacing a constant flow of a supplied heat-carrying agent with a pulsed one, using the Simulink/Matlab software, a mathematical model of the recreation room with one radiator was implemented. The pulse flow with amplitude from 0.024 kg/s to 0.048 kg/s and a frequency from 0.0017 rad/s to 0.017 Hz allows saving 22 % of thermal energy due to more uniform temperature distribution in the recreation room. The model takes into account the flow hydrodynamics, the heat transfer does not take into account the features of the channels. More detailed studies of hydrodynamics and heat transfer were performed on heat exchange equipment to specific heat transfer surfaces at the higher frequencies. In the work [10], the heat transfer enhancement for finned tube heat exchangers was studied using a pulsating air flow. The research was conducted on an experimental installation at the frequencies from 10 Hz to 50 Hz with a change in the amplitude of the air flow from 13.33 % to 15.35 %, while an increase in the heat transfer coefficient was noted within 12.3 %. For the liquid medium the heat transfer is also enhanced at the lower frequencies. The work [11] presents the results of experimental studies for a horizontally located coil for heating cold water in a reservoir. The average temperature of the heated water was maintained at 60 °C; the flow was interrupted both at the input and output of the coil with a frequency from 0 to 20 Hz at Reynolds numbers from 6220 to 16300, the average heat transfer coefficient was increased to 26 % mainly due to the fluctuations in the coil.

The intensification of heat transfer depends on the time of interruption of the heat-carrying agent flow. When the flow interruption time is reduced to a few milliseconds, the pulsating mode becomes pulsed (impulse), which is accompanied by a hydraulic shock, which energy can be successfully used, for example, for the drive of a membrane pump [5]. The experimental study of the heat exchange with a pulsating flow in a plate heat exchanger at the frequency about 1 Hz is presented in [12]. The increase in heat transfer is fixed at 25 %. A significant increase in the heat transfer in the pulsed mode at the level of 40 % has been experimentally proved by cooling powerful semiconductor converters at the frequency about 1 Hz [13].

More in-depth studies on the heat transfer enhancement using a pulsating mode for a laminar flow of the heat-carrying agent in specific channels were carried out at the Moscow Power Engineering Institute. In the works [14–16], the influence of the thermal conductivity of a liquid along the axis of the channel, the thermal resistance of the wall for a pulsating laminar flow of the heat-carrying agent was studied. A significant increase in heat transfer from heat transfer surfaces of heat exchangers is associated with flow turbulence, which is especially important for creating new designs of microchannel heat exchangers.

It is applicable for heating devices which are operate in transient conditions with Reynolds numbers from 2000 to 6000, an increase in their efficiency is also observed with pulsating and pulsed heat-carrying agent flow, depending on the frequency and amplitude. A significant increase in the efficiency of SR heating at the level of 40 % was obtained using the membrane pumps at the frequency of 0.5 Hz to 1 Hz on the IHP experimental installation are explained by a more uniform temperature distribution on the surface. It should be noted that the calculated efficiency parameters were not achieved due to the limitations of the experimental installation of the IHP [17–19].

In this regard, the aim of this work was to increase the efficiency of heat transfer of SR in building heating systems, based on pulsating supply and mixing of the heat-carrying agent due to the inclusion of a double-flow membrane pump in the IHP scheme. For realization this goal, the following tasks were solved: the choice of a method for increasing the heat transfer efficiency of SR heating based on pulsating supply and mixing of the heat-carrying agent; development of a IHP design of a building with a double-flow membrane pump and the implementation of its experimental sample; conducting hydrodynamic and thermal tests of the experimental model of IHP; simulation of the effectiveness of the SR from the parameters of the heating system and their inclusion on a mathematical model.

2. Methods

The research of the efficiency of heat transfer of SR in the heating building systems from the parameters of the heat-carrying agent, the mixing coefficient of a hot and cold flow, the amount of SR and the scheme of their inclusion, as well as the parameters of the device that creates the pulsating mode was performed using the methods:

- a complex analysis when analyzing a problem and searching for optimal design solutions for finding a method of pulsating supply and mixing of the heat-carrying agent;
- physical modeling of hydrodynamics and heat transfer in the SR at the different frequencies and amplitudes of the flow pulsations, the mixing coefficient of the heat-carrying agents in the experimental IHP installation with pulsating flow and mixing of the heat-carrying agent and automated data collection;
- the method of mathematical modeling of the heat transfer efficiency of the SR at the different frequencies of flow pulsations, mixing coefficients of the heat-carrying agents, the number of the SR and their switching schemes based on the energy chain that allow studying the processes of the different physical nature based on their analogy (heat, mechanics, electricity, hydraulics) in the frequency area;
- Mathematical statistics for processing arrays of experimental data and establishing dependencies.

The starting point for conducting the complex analysis of technologies and features for implementing pulsating supply and mixing of the heat-carrying agent was the early experimental studies of heat transfer and hydrodynamics of SR heating, carried out at the Chair of heat and power engineering at the National Research Ogarev Mordovia State University which revealed the potential for increasing their effectiveness. Studies of the effectiveness of SR were carried out using various schemes for switching the membrane pumps. According to that, it was possible only partially to realize the potential for increasing the efficiency of the SR due to the limitations of the experimental IHP installation [17–19]. In a point of a fact, the fluctuations in the flow rate of the heat-carrying agent in the early studies were not purely harmonic and there was a constant component in the total flow rate of the heat-carrying agent. In addition, there were difficulties with mixing hot and cold heat-carrying agent flows in the SR and electric energy was partially used for the drive of the membrane pump.

In this work, the realization of the potential of heat transfer efficiency of SR heating was realized through the use of a double-flow membrane pump with a pulsed heat-carrying agent flow distributor in the design of the IHP experimental installation, which generates a hydraulic shock and additionally uses it for the drive of the membrane pump [20]. Figure 1 shows a diagram of an experimental individual heating plant with a membrane pump. The scheme allows you to create the two independent circuits.

IHP with double-flow membrane pump (Figure 1) consists of feeding and return pipeline and with the left and right section of membrane pump. Both sections of the membrane pump are controlled from a pulsed flow distributor 5, connected with an electric motor drive 6. A feed pipe 1 is connected to the input of the pulsed flow distributor 5, and its outputs are connected to the chambers 3 and 4. The left section of the membrane pump 3 and the right section of the membrane pump 4 are rigidly connected to the link rod 7. The switching mechanism of the shock valves 8 is connected to the one side of a link rod 9 and on the other side to the left 10 and right 11 shock valves. Radiant space heater of the right section is connected in parallel with the hot-water calorifier 13. The left section is connected in the same way, but it has not been used in this installation.

When you turn on the electric motor drive 6 and establish the required pulsation frequency of the pulsed flow distributor 5, the heat-carrying agent is alternately supplied from the supply pipe 1 to the internal (working) parts of sections 3 and 4, where it performs the work. In the final positions of the link rod 9 the shock valves 10 and 11 are switched with the help of the mechanism of switching the shock valves 8 and the external (pumping) sections intake the heat-carrying agent through SR 12 and the hot-water calorifier 13. At the next cycle the cooled heat-carrying agent goes repeatedly through the SR 12 and hot-water calorifier 13 and pushed into the return pipeline 2. Cooled water regulating temperature is conducted by the changing the load of the hot-water calorifier. Through this process, we can see that for the one period of double-flow membrane pump work the hot or cooled heat-carrying agent goes through the SR.

There is an experimental model of IHP with a double-flow membrane pump with a capacity of 3000 l/h was implemented at the Chair of heat and power engineering of Federal State Budgetary Institution of Higher Education Ogarev Mordovia State University. The main components of the plant is shown in Figure 2, 3.

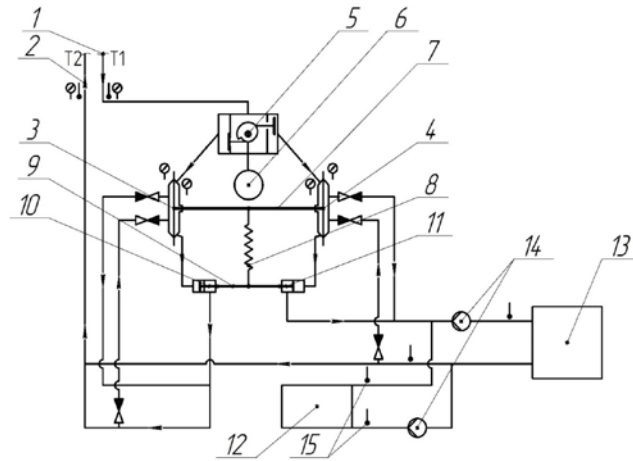


Figure 1. Scheme of experimental plant (installation) of Individual Heating Plant on the basis of double-flow membrane pump: 1 – feeding pipe line; 2 – return pipe line; 3 – the left section of membrane pump; 4 – the right section of membrane pump; 5 – pulsed flow distributor; 6 – electric motor drive; 7 – link rod; 8 – switching shock valves mechanism; 9 – link rod; 10 – the left shock valve; 11 – the right shock valve; 12 – heating device; 13 – hot-water calorifier; 14 – flow nozzle; 15 – temperature sensor.

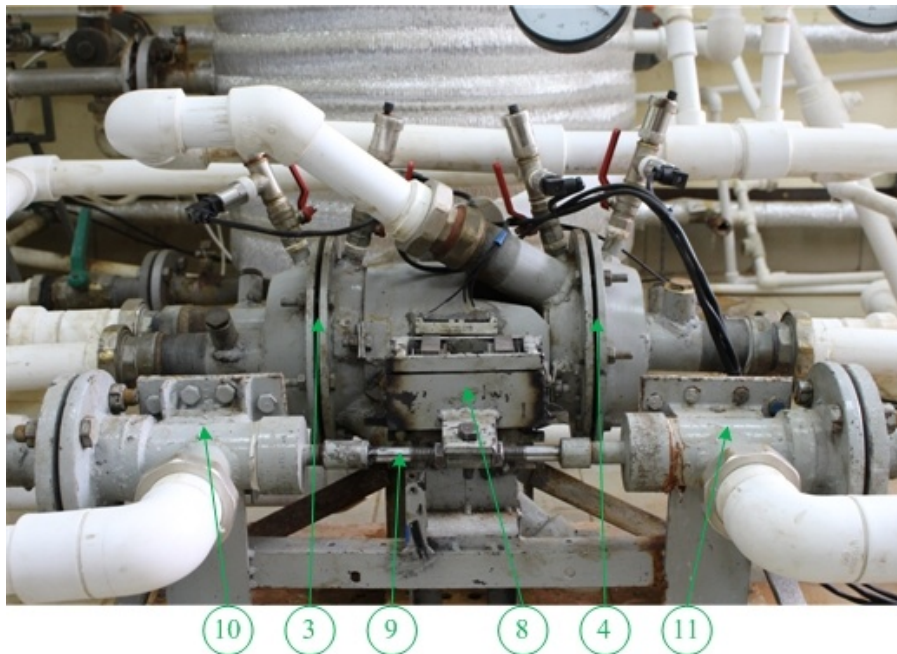


Figure 2. Physical form of experimental unit of IHP on the basis of double-flow membrane pump: 3 – Membrane pump left section; 4 – Membrane pump right section; 8 – Switching shock valves mechanism; 9 – Link rod; 10 – Left shock valve; 11 – Right shock valve.



Figure 3. Pulsed flow distributor.

3. Results and Discussion

Hydraulic tests of IHP with a double-flow membrane pump with a capacity of 3000 l/h showed that the flow rate of a double-flow membrane pump depends on the frequency of interruption of the heat-carrying agent flow. It was found that when the frequency of interruption of the heat-carrying agent flow changes from 0.5 Hz to 0.8 Hz, the flow rate (consumption) of the heat-carrying agent changes from 2000 l/h to 3000 l/h. In this case the pressure at the pump input varied within 0.536 kPa to 0.635 kPa with the same available head between the supply and return pipelines (dependencies 2–5 Figure 4). The calculated dependence of the flow rate of a double-flow membrane pump on the frequency of interruption of the heat-carrying agent flow is somewhat higher and differs from the experimental average within the limits of 4 %. The calculated dependence of the flow rate of a double-flow membrane pump on the frequency of interruption of the heat-carrying agent flow is calculated in the plugflow mode. By the least square method we obtained a regression equation for the dependence of the flow rate of a double-flow membrane pump on the frequency of interruption of the heat-carrying agent flow:

$$G = 177.46 + 3541.99 f. \quad (1)$$

Later on, the thermal tests were carried out according to the results of which the effectiveness of the SR was evaluated in various modes. During thermal tests of IHP with a double-flow membrane pump with a capacity of 3000 l/h, temperature parameters 15 and flow rate 14 of the heat-carrying agent at the input and output of 12 SR Rifar BASE 500 type were recorded. Hereinafter, by the temperature differences at the input and output of the SR, its efficiency was calculated depending on the flow rate of the heat-carrying agent at the certain frequency. The results of calculating the efficiency of SR at four averaged temperatures of the heat-carrying agent (42 °C, 50 °C, 58 °C, and 67 °C) are presented in the form of graphs (Figure 5). In this case the heat-carrying agent's flow through the SR varied from 60 l/h to 360 l/h. Nominal heat-carrying agent flow through the SR is 120 l/h. With an averaged temperature of the heat-carrying agent of 42 °C and nominal flow rate (Figure 5, a), the highest SR efficiency is 0.54 at the heat-carrying agent pulsation frequency of 0.62 Hz. With an increase in the flow rate of the heat-carrying agent through the SR, the efficiency decreases and at the flow rate of 300 l/h it becomes equal to the stationary mode. In a stationary mode the efficiency with increasing flow rate also increases from 0.25 to 0.32. At the averaged heat-carrying agent/s temperature of 50 °C (Figure 5, b), the SR efficiency is 0.52 at the nominal flow rate and frequency of 0.57 Hz. In the stationary mode the efficiency with increasing flow rate also increases from 0.28 to 0.42. At the averaged heat-carrying agent's temperature of 58 °C (Figure 5, c), the highest SR efficiency is 1.03 at the frequency of 0.62 Hz, which decreases with increasing heat-carrying agent's flow rate, and at the flow rate of 240 l/h it becomes equal to the stationary mode. In the stationary mode the efficiency with increasing flow rate also increases from 0.53 to 0.67. With the averaged temperature of the heat-carrying agent at the inlet to the SR equal to 67 °C (Figure 5, d), the greatest efficiency of the SR is 1.28 at the frequency of 0.57 Hz, which decreases with increasing flow rate and with the rate of 180 l / h is approaches to the stationary mode. In the stationary mode the efficiency with increasing flow rate also increases from 0.72 to 0.85. Thus, the SR efficiency at the nominal flow rate of the heat-carrying agent in a pulsating mode, depending on the temperature at the inlet and the pulsations frequency increases by 1.8 – 2.2 times. Moreover, with increasing temperature at the inlet to the SR, the relative value of the efficiency decreases. The frequency of pulsations of the heat-carrying agent has a significant impact on achieving maximum SR efficiency and is determined by its design capacities. With an increase in the heat-carrying agent's flow rate, the efficiency of the SR in the pulsating mode decreases intensively with the high average temperature of the heat-carrying agent.

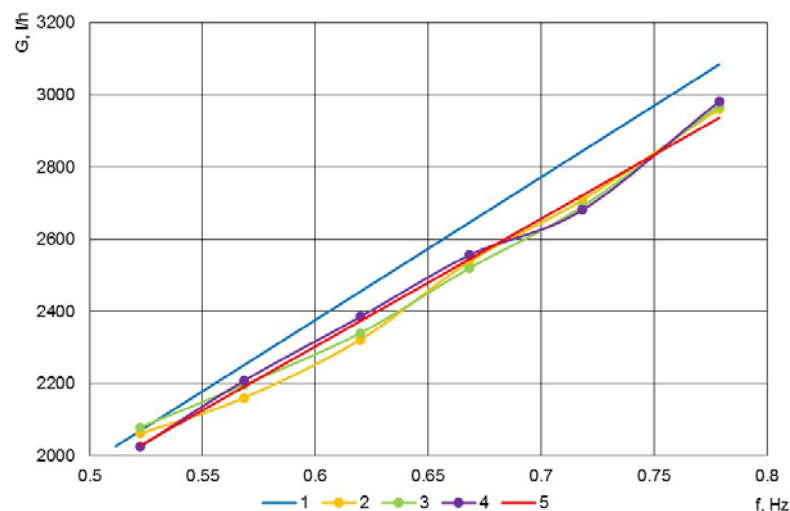


Figure 4. Hydraulic characteristics of IHP on the basis of double-flow membrane pump with different pressure at the input of pump chambers: 1 – calculated; 2 – $P_3=568$ kPa; 3 – $P_2=536$ kPa; 4 – $P_1=635$ kPa; 5 – according to the least square method.

The efficiency of the SR depends on both parameters of the heat-carrying agent and the thermophysical properties of the device itself. The last we can include the mass of the heat-carrying agent, thermal and capacitive resistance. For obtaining the equations describing the movement of heat flows, it is convenient to represent them in the form of an energy chain of SR with a section of the heating network (Figure 6) [21].

Special feature for IHP with double-flow membrane pump is the pulsating regime i.e. flow enthalpy h , J/kg and the mass rate (consumption) g , kg/s, which is periodically changes in time.

The energy chain of the SR with the participation of heat engineering devices includes three links: the first is thermal – it takes into account the decrease in enthalpy due to the mass m , kg and the heat-carrying agent; the second link-is transformative, it is converts an enthalpy h , J/kg, in temperature t , °C, and the mass flow rate g , kg/s, to the specific heat flow rate q , W/°C, through the heat capacity c ; the third link is heat, which takes into account the SR temperature drop with the help of thermal true resistances R_1, R_2, R_3 , °C²/W, corresponding from the heat-carrying agent to the area of heating surface, thermal conductivity of the wall and from the wall to the air and also with accumulating ability of water with ductility l_1 , W/s, and accumulating ability of the wall ductility l_2 , W/s.

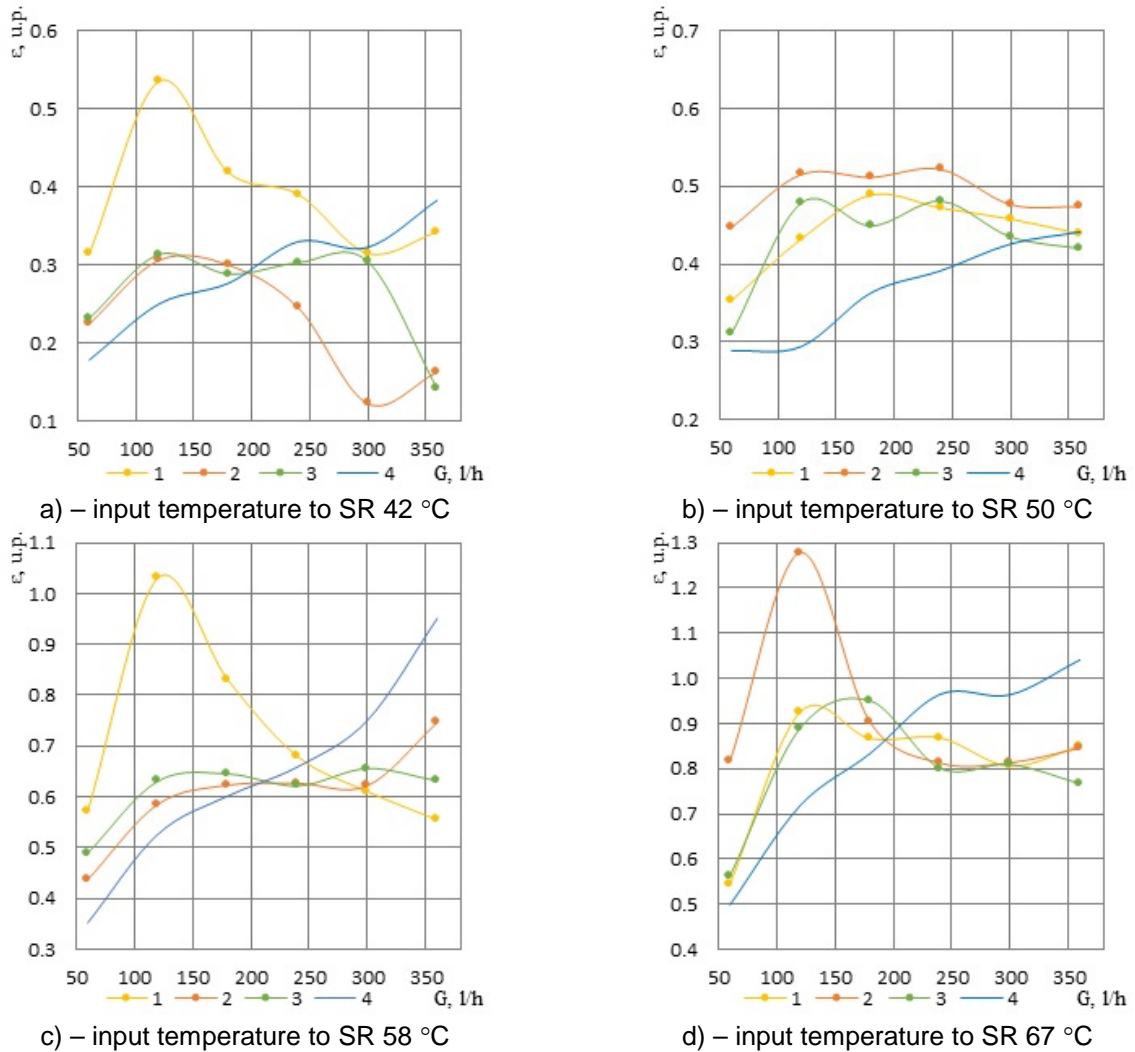


Figure 5. The efficiency of bimetallic sectional radiators which are connected to double-flow membrane pump: 1 – 0.623 Hz; 2 – 0.572 Hz; 3 – 0.523 Hz; 4 – stationary.

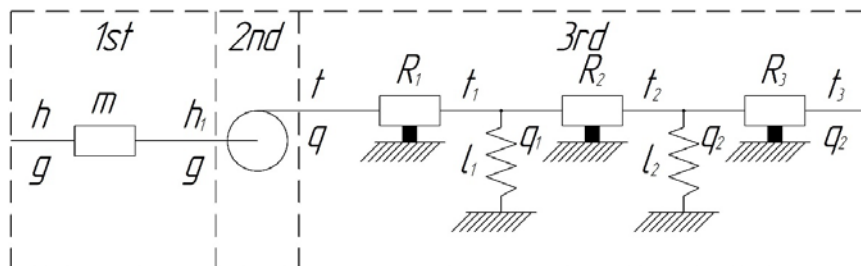


Figure 6. SR's energy chain with the section of heating network.

Chain components equation:

$$\begin{array}{ccc}
 \text{1st} & \text{2nd} & \text{3rd} \\
 \left\{ \begin{array}{l} h = m\dot{g} + h_1, \\ g = q. \end{array} \right. & \left\{ \begin{array}{l} h_1 = ct, \\ g = \frac{q}{c}. \end{array} \right. & \left\{ \begin{array}{l} t = R_1q + R_2q_1 + R_3q_2 + t_3, \\ q = l_1\dot{t}_1 + l_2\dot{t}_2 + q_2. \end{array} \right. \quad (2)
 \end{array}$$

During the modeling process it was necessary to find out how the output of SR temperature will change t_3 , °C, depending of its removal from the source (IHP with double-flow membrane pump), and also what kind of effect has the parallel and compounding connection of SR.

Let's imagine the SR output temperature $t_3 = t_{30} + \bar{t}_3$ and specific heat flow rate $q_2 = q_{20} + \bar{q}_2$ in the form of a constant component and deviation.

q , W/°C equation:

$$\begin{aligned}
 q &= l_1R_2l_2R_3\ddot{\bar{q}}_2 + l_1R_2l_2\ddot{\bar{t}}_3 + (l_1R_2 + l_1R_3 + l_2R_3)\dot{\bar{q}}_2 + (l_1 + l_2)\dot{\bar{t}}_3 + \bar{q}_2 + q_{20} = \\
 &= a_1\ddot{\bar{q}}_2 + a_2\dot{\bar{q}}_2 + \bar{q}_2 + q_{20} + b_1\ddot{\bar{t}}_3 + b_2\dot{\bar{t}}_3. \quad (3)
 \end{aligned}$$

There are expressions for coefficients:

$$a_1 = l_1R_2l_2R_3; \quad a_2 = l_1R_2 + l_1R_3 + l_2R_3; \quad b_1 = l_1R_2l_2; \quad b_2 = l_1 + l_2.$$

t , °C equation:

$$\begin{aligned}
 t &= R_1a_1\ddot{\bar{q}}_2 + R_1a_2\dot{\bar{q}}_2 + R_1\bar{q}_2 + R_1q_{20} + R_1b_1\ddot{\bar{t}}_3 + R_1b_2\dot{\bar{t}}_3 + \\
 &+ R_2l_2R_3\dot{\bar{q}}_2 + R_2l_2\dot{\bar{t}}_3 + R_2q_{20} + R_2\bar{q}_2 + R_3q_{20} + R_3\bar{q}_2 + t_{30} + \bar{t}_3 = \\
 &= a_3\ddot{\bar{q}}_2 + a_4\dot{\bar{q}}_2 + a_5\bar{q}_2 + a_6q_{20} + b_3\ddot{\bar{t}}_3 + b_4\dot{\bar{t}}_3 + \bar{t}_3 + t_{30}. \quad (4)
 \end{aligned}$$

There are expressions for coefficients:

$$a_3 = R_1a_1; \quad a_4 = R_1a_2 + R_2l_2R_3; \quad a_5 = R_1 + R_2 + R_3; \quad a_6 = R_1 + R_2; \quad b_3 = R_1b_1; \quad b_4 = R_1b_2 + R_2l_2.$$

h , J/kg equation:

$$\begin{aligned}
 h &= \frac{ma_1}{c}\ddot{\bar{q}}_2 + \left(\frac{ma_2}{c} + a_3c\right)\dot{\bar{q}}_2 + \left(\frac{m}{c} + a_4c\right)\bar{q}_2 + a_5c\bar{q}_2 + \\
 &+ a_6cq_{20} + \frac{mb_1}{c}\ddot{\bar{t}}_3 + b_3c\dot{\bar{t}}_3 + \left(\frac{mb_2}{c} + b_4c\right)\bar{t}_3 + c\bar{t}_3 + ct_{30} = \\
 &= a_7\ddot{\bar{q}}_2 + a_8\dot{\bar{q}}_2 + a_9\bar{q}_2 + a_{10}\bar{q}_2 + a_{11}q_{20} + b_5\ddot{\bar{t}}_3 + b_6\dot{\bar{t}}_3 + b_7\bar{t}_3 + c\bar{t}_3 + ct_{30}. \quad (5)
 \end{aligned}$$

There are coefficient values:

$$\begin{aligned}
 a_7 &= \frac{ma_1}{c}; \quad a_8 = \frac{ma_2}{c} + a_3c; \quad a_9 = \frac{m}{c} + a_4c; \quad a_{10} = a_5c; \quad a_{11} = a_6cq_{20}; \\
 b_5 &= \frac{mb_1}{c}; \quad b_6 = b_3c; \quad b_7 = \frac{mb_2}{c} + b_4c; \quad b_8 = c + 1.
 \end{aligned}$$

Image equation:

$$(a_7s^3 + a_8s^2 + a_9s + a_{10} + 1)Q_2(s) = -(b_5s^3 + b_6s^2 + b_7s + c + 1)T_3(s). \quad (6)$$

The complex resistance of the chain output:

$$Z(s) = \frac{T_3(s)}{Q_2(s)} = \frac{a_7s^3 + a_8s^2 + a_9s + a_{10} + 1}{-b_5s^3 - b_6s^2 - b_7s - c - 1}. \quad (7)$$

Chain frequency function:

$$Z(j\Omega) = \frac{a_7 b_5 \Omega^6 + (a_8 b_5 + a_7 b_6) j \Omega^5 + (a_9 b_5 - a_7 b_7 - a_8 b_6) \Omega^4}{(b_6 \Omega^2 - b_8)^2 + (b_5 j \Omega^3 - b_7 j \Omega)^2} + \frac{(a_7 b_8 + a_8 b_7 + a_9 b_6 + a_{11} b_5) j \Omega^3 + (a_8 b_8 + a_9 b_7 + a_{11} b_6) \Omega^2 - (a_9 b_8 + a_{11} b_7) j \Omega - a_1 b_8}{(b_6 \Omega^2 - b_8)^2 + (b_5 j \Omega^3 - b_7 j \Omega)^2}. \quad (8)$$

Real part:

$$\text{Re}(j\Omega) = \frac{a_7 b_5 \Omega^6 + (a_9 b_5 - a_7 b_7 - a_8 b_6) \Omega^4 + (a_8 b_8 + a_9 b_7 + a_{11} b_6) \Omega^2 - a_1 b_8}{(b_6 \Omega^2 - b_8)^2 - (b_7 \Omega - b_5 \Omega^3)^2}. \quad (9)$$

Imaginary part:

$$\text{Im}(j\Omega) = \frac{(a_8 b_5 + a_7 b_6) \Omega^5 + (a_7 b_8 + a_8 b_7 + a_9 b_6 + a_{11} b_5) \Omega^3 - (a_9 b_8 + a_{11} b_7) \Omega}{(b_6 \Omega^2 - b_8)^2 - (b_7 \Omega - b_5 \Omega^3)^2} j. \quad (10)$$

Amplitude-frequency characteristics:

$$A(j\Omega) = \sqrt{\text{Re}(j\Omega)^2 + \text{Im}(j\Omega)^2}. \quad (11)$$

The efficiency of sectional radiators, according to this model, was estimated by the value of the temperature drop at the output of the device t_3 , °C, with the single input exposure q_2 , W/°C. It is specified that the temperature t_3 , °C, will go up less, so the efficiency will be higher, comparing with the basic operation.

Thermal true resistances of the chain R_1 , R_2 , R_3 , °C²/W, were selected based on the temperature drop during the passing of the heat flow. Moreover, the same temperature drop according to the experimental conditions was strictly maintained. The ratio between these resistances was taken in accordance with the distribution of heat transfer coefficients. The value of ductility was chosen based on changes in the volume of the heat-carrying agent and heat capacity depending on the material of the pipe and sectional radiators. The mass of the heat-carrying agent was taken based on the diameter of the pipe and its length. Initial parameters for predicting the switching modes of sectional radiators: basic; parallel and sequential connection (Table 1).

Table 1. Parameters for operation modeling.

№	Operation	E-Chain parameters					Heat-carrying agent parameters		
		m , kg	R_1 , °C ² /W	R_2 , °C ² /W	R_3 , °C ² /W	l_1 , W/s	l_2 , W/s	t_n , °C	g , kg/s
1	basic	6	0.774	0.04	36.13	0.01	0.2	48.6	0.0333
2	parallel	8.4	0.387	0.02	18.37	0.01	0.2	48.6	0.0333
3	sequential	9	1.5	0.08	72	0.01	0.1	48.6	0.0333
4	With increased mass	8	0.774	0.04	36.13	0.01	0.2	48.6	0.0666

Modeling results are given in amplitude-frequency characteristic in three modes of operation (Figure 7).

As we can see from the amplitude-frequency characteristics graphs in the basic operation mode the greatest decrease in temperature at the output of the SR for a single surge in specific heat flow is observed at the circular frequency of 3.6 rad/s and corresponds to 3.6 °C which completely coincides with the experimentally obtained dependences of the SR efficiency at the given circular frequency (curve 2 of Figure 5). When the SR is connected in parallel, the thermal true resistance is reduced due to the better mixing of the heat-carrying agent. the circular frequency, which has the greatest decrease in temperature at the output of the SR is 3 rad/s, it corresponds to 2.23 °C. It follows that in order to provide the improved SR efficiency, it is necessary to switch to the angular frequency of 3 rad/s (0.47 Hz). With sequential SR connection the thermal true resistances are increasing for 3 times. The heat-carrying agent mass increases to 2.4 kg. As for the last SR output temperature, so it increases to 6.7 °C and the circular frequency goes higher and it shows 4.2 rad/s. In this case, the flow rate of the heat-carrying agent is not changing. According to this fact, it is necessary to increase the flow rate of SR in two times with the sequential connection. The last operation mode corresponds to the basic parameters with the increased mass. In this operation mode the circular frequency decreases to 3 rad/s and the minimum temperature at the output of the last SR is 4.33 °C

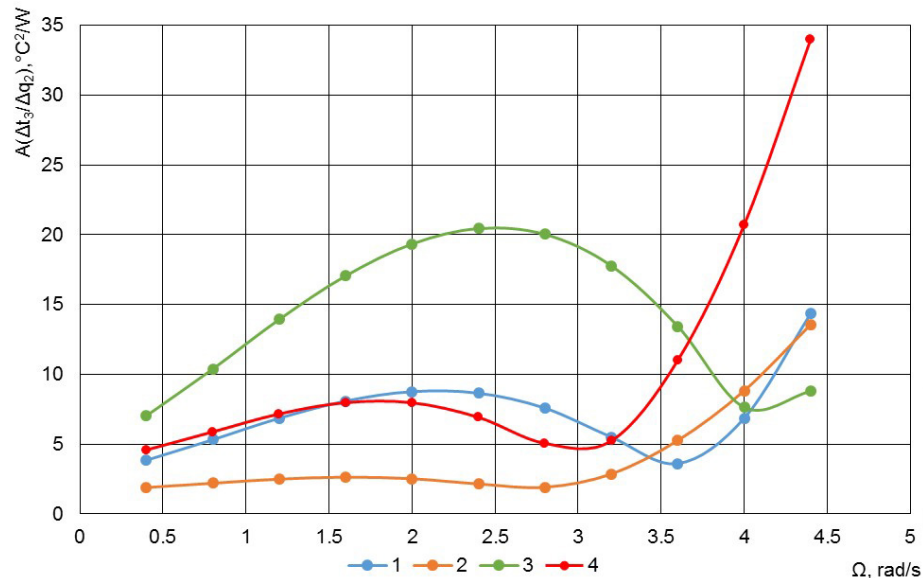


Figure 7. Amplitude-frequency characteristics of energy chain: 1 – basic powering SR; 2 – parallel connection SR; 3 – sequential connection of SR; 4 – with increasing the mass of the heat-carrying agent to the basic operation.

4. Conclusion

1. In heating systems of residential and public buildings, SR are widely used as heating devices due to their compactness. Resistance to pressure drops high corrosion resistance and good aesthetic qualities. However, in practice they showed a low efficiency (power reduction) with a decrease in the heat-carrying agent temperature which is typical for the spring-autumn period of the heating system work. This disadvantage is compensated by installing an additional number of sections in the SR or using the electric energy for heating purposes which is inefficient in the context of the implementation of the energy conservation policy. At the level of implementation of urban energy-saving programs with the introduction of IHP based on traditional technologies, they are trying to solve this problem, however. Nowadays it has been possible to realize the potential for increasing the efficiency of heat supply systems with SR only partially. Among non-traditional technologies and developments in world practice over the past ten years much attention has been focused on the heating systems with pulsating (pulsed) heat-carrying agent circulation. This allows not only increasing the heat transfer efficiency from the surfaces of heating devices up to 40 %, but to reduce the consumption of thermal energy up to 20 % due to equalization of indoor temperature. However, the experience is still insufficient for using these developments in the IHP schemes of buildings with SR. The researches of the heat transfer and hydrodynamics of heat-exchange equipment in most of the works has the one-sided character and were carried out by mathematical modeling methods for one heater at a constant temperature of the heat-carrying agent at the input. According to the fact, increasing the efficiency of heat transfer of SR in building heat supply systems based on pulsating supply and mixing of the heat-carrying agent due to the inclusion of a non-volatile double-flow membrane pump in the IHP scheme has scientific and practical value.

2. A method is proposed for increasing the efficiency of heat supply systems of buildings with SR based on pulsating supply and mixing of a heat carrying agent. The essence of the method consists in periodically passing through SR heating of hot and cooled pulsating heat-carrying agent. The pulsating flow rate and temperature of the heat-carrying agent with the frequency up to 1 Hz makes it possible to increase the efficiency of SR about two times due to a more uniform temperature distribution on the heat transfer surface. For realization, this method in the heating systems of buildings with SR, an IHP scheme was developed and tested on the basis of a non-volatile dual-flow diaphragm pump, using up to 20 meters of the available pressure of the heating network.

3. Hydraulic tests of the IHP on the basis of a non-volatile double-flow membrane pump with a capacity of 3000 l/h showed that the flow rate of a dual-flow diaphragm pump from 2000 l/h to 3000 l/h is regulated by the frequency of pulsations of the heat-carrying agent from 0.5 Hz to 0.8 Hz and has a linear relationship. The calculated dependence of the flow rate of a double-flow membrane pump on the frequency of interruption of the heat-carrying agent flow obtained using the least squares method in the form of a regression equation differs from the experimental average within 4 %. The linear dependence of the flow rate on the frequency of a double-flow membrane pump allows it to accurately keep track according to the number of cycles without the use of expensive heat meters.

4. In the process of thermal tests of 12 SR Rifar BASE 500 type connected to IHP based on a double-flow membrane pump, with the temperatures from 42 °C to 67 °C and pulsation frequencies of the heat-carrying agent from 0.52 Hz to 0.62 Hz, was found its efficiency increase at the nominal flow rate of 1.8 – 2.2.

Moreover, with temperature increase of the heat-carrying agent at the entrance to the SR, the relative value of the efficiency decreases relative to the stationary mode. The frequency of the heat-carrying agent pulsations has a significant impact on achieving maximum SR efficiency and determined by its design features. With an increase in the flow rate of the heat-carrying agent, the SR efficiency in a pulsating mode decreases intensively with the high temperature at the entrance.

5. The prediction of the heat transfer of several SR included in the building heating systems was carried out with the mathematical model in the form of energy chain that takes into account the mass of the heat-carrying agent in the pipelines of the heating network and SR, as well as thermal active and storage resistances. The simulation results are presented in the form amplitude-frequency characteristics (temperature increment at the output of the last SR in the heating system to the heat flow increment). The adequacy of the model was tested in the basic mode for one SR at the circular frequency of 3.6 rad/s, while the decrease in temperature at its output amounted 3.6 °C, which completely coincides with the experimentally obtained dependences of the effectiveness of the SR at this frequency. For a parallel connection up to 10 SR the optimum circular frequency of the pulsations of the heat-carrying agent was 3 rad/s, and for a sequential connection – 4.2 rad/s, which is consistent with the thermal test results at the level of 7 %.

6. The results of this research can be used in the design of IHP with pulsed circulation and mixing of the heat-carrying agent for heat buildings supply with dependent connection to the heating network which will ensure the required temperature conditions in the recreation rooms throughout the heating period at the low heat-carrying agent temperatures, also will reduce the heat energy consumption and simplify the heat carrying agent accounting and eliminates the cost for circulation pumps drive.

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Повышение эффективности теплопередачи секционных радиаторов в системах теплоснабжения зданий

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Ключевые слова: способ теплоснабжения, радиаторы отопления, эффективность теплопередачи, пульсация теплоносителя, мембранный насос, тепловой пункт

Аннотация. В системах теплоснабжения жилых и общественных зданий в качестве отопительных приборов широко используются секционные радиаторы (СР), эффективность теплопередачи которых при понижении температуры теплоносителя снижается до 30 %. На практике низкая эффективность СР компенсируется за счет установки дополнительного числа секций и использования электрической энергии на нужды отопления, что в условиях реализации политики энергосбережения нерационально. В процессе выполнения работы предложен способ теплоснабжения, заключающийся в периодической подаче горячего и холодного теплоносителя через СР, который реализован в схеме лабораторной установки ИТП на базе энергоэффективного двухпоточного мембранного насоса производительностью 3000 л/ч, которая имеет возможность изменять диапазон частот от 0,3 до 1 Гц. В результате гидравлических испытаний двухпоточного мембранного насоса установлена линейная зависимость расхода от частоты пульсаций теплоносителя на частотах до 1 Гц. Тепловые испытания 12 СР типа Rifar BASE 500 в пульсирующем режиме на частотах от 0,5 Гц до 0,8 Гц, при средней температуре теплоносителя 48 °С и среднем расходе 120 л/ч показали, что эффективность теплопередачи СР зависит от частоты пульсаций теплоносителя. Наибольшая эффективность СР зафиксирована на круговой частоте 3,6 рад/с и составила 53 %. Исследование эффективности СР от параметров теплосети и схемы их включения выполнялось на математической модели в виде энергетической цепи, которая учитывает массу теплоносителя в трубопроводах тепловой сети и СР, термические сопротивления теплосети и СР, а также аккумулирующую способность воды в трубопроводах тепловой сети и СР. Для параллельного соединения до 10 СР оптимальная круговая частота пульсаций теплоносителя составила 3 рад/с, а для последовательного – 4,2 рад/с, при которых достигается наибольшая эффективность теплопередачи.

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