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# Dynamic method of the heating devices efficiency measurement

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**Abstract**

To study the energy efficiency of heating devices a mathematical model was used. It is a non-linear differential equation of the heating device heat balance. The heating device cooling mode analysis enabled to find a simple analytical expression for its heat transfer coefficient. Experimental studies of two devices were conducted: the cast-iron and aluminum radiator. The experimental results match the theoretical calculations. The developed method allows the heat transfer coefficient of the heating device to be found with its individual characteristics taken into account.



*Keywords:* heating device; heat transfer coefficient; thermal power; efficiency; heat-transfer fluid

## 1. Introduction

The efficiency of heating devices is characterized by the heat transfer coefficient which is named G, the essence of which follows from the equation for the thermal power or $P_{th}$ produced by the device:

$$P_{th} = G \cdot (T_h - T_a) \tag{1}$$

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There is a great deal of articles and patents dedicated to the research of heating devices efficiency [1–3]. All these studies rely on the usage of Eq. (1). It measures supplied thermal power and temperatures. Similar technology is used in the study of heat exchangers [4]. So [1] provides a comparative analysis of different methods of the heating devices efficiency measurement, both in Russia and abroad. The main conclusion that can be outlined from this work is that the efficiency indicators depend heavily on the operating conditions and the large number of parameters. These parameters include the heat-transfer fluid supply rate, operational temperatures range, heating system circuit (single or double pipe based), the system pressure, etc.

In order to minimize these uncertainties special isothermal measuring chambers were developed. These chambers are complex, cumbersome and expensive devices which require well-trained personnel. Nevertheless, these chambers do not provide a full uncertain measurements elimination. As the heating systems in Russia and Europe differ significantly, it is not always possible to compare their effectiveness. Another uncertainty factor lies within the fact that the heat transfer processes contain radiative and convective components [5, 6]. Since the convective heat transfer efficiency is characterized by the non-linear dependence on the temperature difference ($T_h$–$T_a$), then it is necessary to characterize either the effectiveness of a function, or some characteristic of this function. The present-day techniques usually use the efficiency values at a single point.

Paper [2] presents the experimental research results of heat transfer coefficient in a special unit operating in a steady mode. In accordance with Eq. (1) the input heating power and temperature drop were being measured. Dependencies of heat transfer coefficient on the heating device temperature, air temperature and the heat-transfer fluid supply rate were obtained. However, the number of experimental points is poor, and accuracy characteristics (the measurement errors) are not discussed.

**Nomenclature**

| | |
|---|---|
| $G$ | heat transfer coefficient |
| $P_{th}$ | thermal power |
| $P_{in}$ | input power |
| $T_h$ | average heating device surface temperature |
| $T_a$ | average room temperature |
| $C_h$ | heating device heat capacity |
| $t$ | current time |
| $C_1$ | heat-transfer fluid (water) heat capacity in the heating device |
| $V_h$ | volume of water in the heating device |
| $C_2$ | heating device material heat capacity (metal) |
| $P_2$ | weight of the metal |

## 2. Model formulation

We consider another possibility of investigating and measuring the heat transfer coefficient in the dynamic mode when the thermal power as well as the heating device surface temperature is changing [7–9]. In order to do this the heating device non-stationary heat balance equation should be examined:

$$C_h \cdot \frac{dT_h}{dt} = P_{in} - G \cdot (T_h - T_a) \tag{2}$$

In this equation the heat gain is obtained due to the thermal power supplied to the heating device $P_{in}$ and the heat consumption occurs due to the radiator heating transfer into the air $G \cdot (T_h - T_a)$. As an assumptions, it is considered that the coefficients G and $C_h$ in the first in the approximation are constants, although in practice they can be the functions of the temperature $T_h$.

It is necessary to simulate the heating device cooling mode. In this case, heat-transfer fluid supply stops and $P_{in}$ = 0 W at the initial time moment (t = 0 s.).

The simulation results are shown in Fig. 1, where the heating device $C_h$ heat capacity value is the parameter. In the simulation, it was assumed that $C_h$ = 78.273 kJ/°C, G = 20 W/°C.

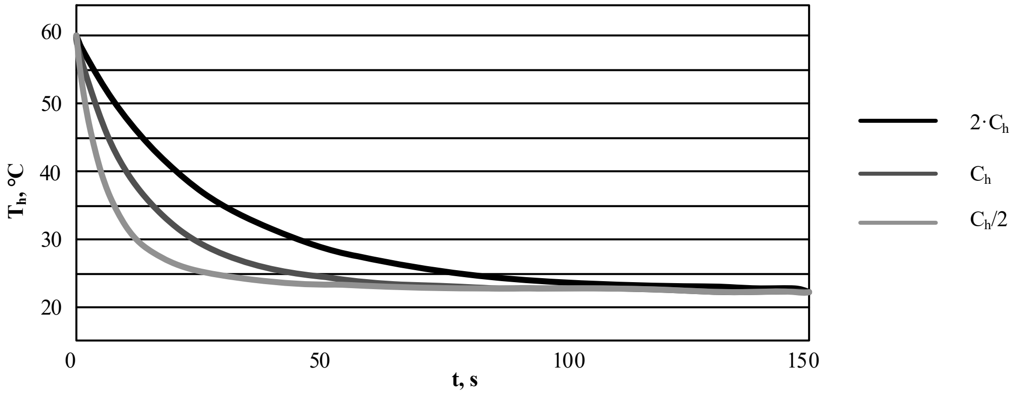



Fig. 1. The radiator temperature cooling under different $C_h$.

Analysis of the results leads to the obvious conclusion: the temperature reduction is exponential, where the exponential time constant (rate of decay) depends on G and $C_h$.

If the heat-transfer fluid supply stops ($P_{in}$ = 0 W), then the heat transfer coefficient can be obtained from the Eq. (2):

$$G = \frac{C_h \cdot \frac{dT_h}{dt}}{T_h^c - T_a^c} \text{ , W/°C} \tag{3}$$

The measurement procedure is the following:

- Finding the cooling heating device temperature as a function of time $T_h$ = f(t);
- The air temperature measurement, which is a constant within the observation interval;
- Finding the heating device temperature changing rate at a given point in time $\frac{dT_h}{dt}$, and then calculating the heat transfer coefficient (3) at a known heating device capacity. In the first approximation, the heat capacity value is the sum of the heat-transfer fluid capacities and the metal body. Later, this value can be specified.

In this case, the heat transfer coefficient is measured for each heating device with its individual characteristics taken into account. Another advantage of this heat transfer coefficient measurement method is that it takes the heat transfer coefficient dependency on the heating device temperature into account. This follows from the differential Eq. (2) pattern. When the inverse problem (finding G) is solved, the non-linearity will be taken into account.

It is necessary to estimate the inaccuracy of the proposed method. Only the value of the systematic inaccuracy will be taken into account, as the random inaccuracy component is excluded while processing of the experimental results by applying the averaging and smoothing operations.

The heating device heat transfer coefficient measurement inaccuracy can be found as the sum of inaccuracies in determining the individual quantities included in the Eq. (3): $C_h$, $\frac{dT_h}{dt}$ and $\Delta T = (T_h - T_a)$.

The relative inaccuracy in determining the total heat capacity of the water heating device is the following:

$$\delta_{C_h} = \delta_{C_1} + \delta_{V_1} + \delta_{C_2} + \delta_{P_2} \approx 1\% \tag{4}$$

We assume that the inaccuracy value $\delta_{Ch}$ in Eq. (4) does not exceed 1 % in view of this characteristics stability.

In the calculation of the derivative determination inaccuracy $\frac{dT_h}{dt}$ the fact that the temperature measurement inaccuracy includes additive and multiplicative components will be taken into account. As the temperature difference is calculated using a single temperature sensor, the effect of the additive component is close to zero. The error multiplicative component will also be small, because the same error is inherent in the measurement of the temperature difference ΔT. When performing a division operation, according to Eq. (3), these errors cancel each other. The estimates show that the inaccuracy of the temperature gradient calculation is less than 1 %.

Thus, the main contribution to the coefficient *G* finding inaccuracy is the inaccuracy additive component in the temperature difference ΔT determination. With the precise temperature measurement of 0.2 °C and the value of ΔT = 20 °C, the maximum accuracy of the temperature difference determination is 2 %, and the total inaccuracy of the heat transfer determination coefficient does not exceed 3 %–4 %.

## 3. Results and Discussion

The verification of the proposed method was carried out in the experimental installation. Its block diagram is presented in Fig. 2.

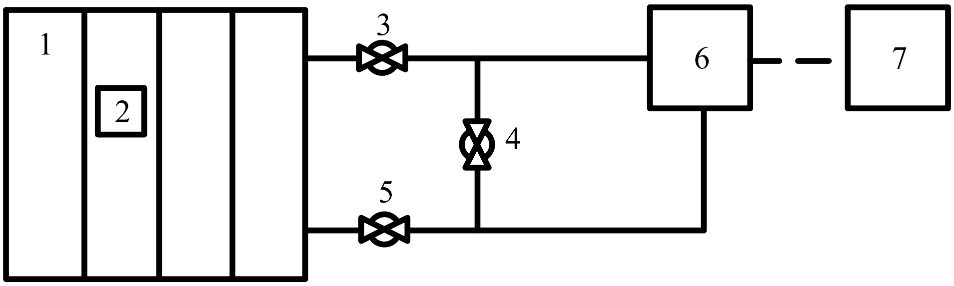
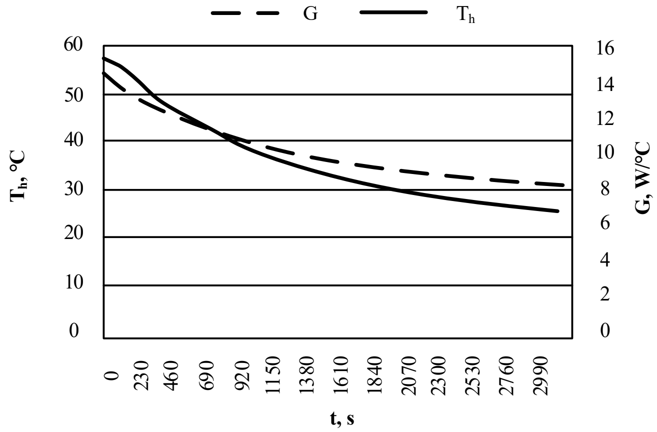


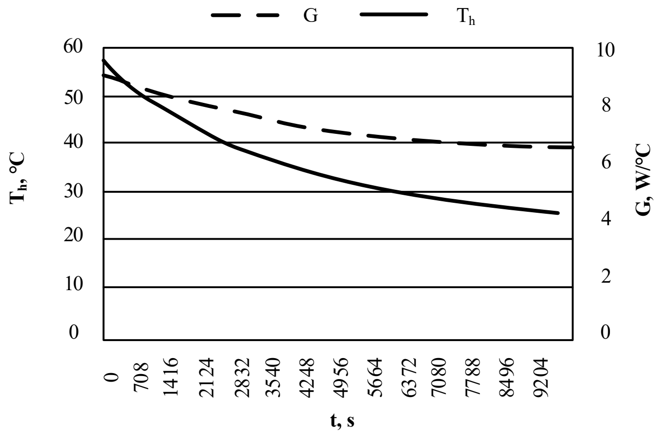

Fig. 2. The block diagram of the experimental installation: 1 – the observed heating device; 2 – thermal sensor; 3, 4, 5 – the lock valves; 6 – water heater; 7 – electric meter.

Here, the thermal energy is supplied to the examined heating device from the water heater through the pipe system. With the bridge assistance, the lock valves allow the heating device to be turned off or on to the max load. The electric power consumption measurement is carried out by the electric meter, and temperature measurement is applied by the thermal sensor based on thermocouple or semiconductor devices. Thermal power supplied to the heating device is calculated using the method mentioned in [1]. In order to do this, the water heater and the pipes heating power is subtracted from the total electric power. This installation allows the heat transfer coefficient to be measured using the method of Eq. (1) (when the thermal capacity and temperature drop are known) as well as using the proposed method (Eq. (3)) and then to be compared.

The results are shown in Fig. 3.




(a)




(b)

Fig. 3. The results of experimental studies of various types of radiators: (a) aluminum radiators; (b) cast iron radiators.

Fig. 3 shows the experimentally obtained dependencies of the two cooling heating devices: four sections cast iron radiator and the eight sections aluminum radiator. In order to eliminate accidental releases the smoothing operation was applied.

As it can be observed from the graphs, the cooling process occurs according to the law, close to exponential, with aluminum radiator cools down at a faster rate than the cast iron one. The cooling time to the temperature of 25 °C for the cast iron device was 153 min, for the aluminum one it was 52 minutes.

The determination of coefficient *G* was held by the Eq. (3). At the same time the device heat capacity is the sum of the heat-transfer fluid (water) heat capacities and a metal body (cast iron or aluminum). For the cast iron radiator $C_h$ = 36054 J/°C for aluminum one $C_h$ = 17700 J/°C.

The calculation results are shown in Fig. 3(a) and Fig. 3(b). The experimental values were taken every 10 seconds. As can be seen on Fig. 3(a, b), the heat transfer coefficient is not a constant, for iron radiator it varies in the range from 6.5 to 9 W/°C at the heating device temperatures from 25 °C to 57 °C (25 % relative to the average value); for the aluminum radiator it varies from 8 W/°C to 14 W/°C (37 % relative to the average value). As well as that, the values of heat transfer coefficients were experimentally found, calculated according to Eq. (1) according to the classical method for the temperature $T_h$ = 57 °C. For the cast iron radiators G = 8.32 W/°C and for the aluminum one G = 14.59 W/°C.

The heat transfer coefficient is an individual characteristic of the heating device depending on the operating conditions. One of these conditions is the location of the heating device. For aluminum radiator the studies on the effect of heating device location on the heat transfer coefficient were conducted. The effect of such objects as walls, floor and furniture were determined.

For this purpose, the obtained heat transfer coefficients were compared to the standard value at $T_h$ = 57 °C. The research results are listed in Table 1.

Table 1. The impact of the aluminum radiator location on the heat transfer coefficient.

| Influencing factor | The deviation from the reference value |
|---|---|
| Flooring | 6 % |
| Wall | 9 % |
| Furniture | 12.5 % |

## 4. Conclusions

The obtained experimental results can be concluded:

- The aluminum radiator cools down quicker, because it has lower heat capacity and higher heat transfer coefficient;
- The dependence of the heat transfer coefficient on the temperature drop contains both a constant and a variable component. The constant component characterizes the radiative heat exchange. The variable component is responsible for the convective heat transfer and infrared radiation;
- The proposed method of heat transfer coefficient determination allows the effectiveness of the heating devices to be verified depending on their individual characteristics (type of device, its location, the influence of painting, etc.) and the conditions of heat exchange (heat transfer, convection, etc.);
- Determining the heat capacity and thermal energy, the convective heat transfer, that is, the heat transfer coefficient dependence on temperature difference of the radiator surface of the air must be taken into account. This is especially important for the heating devices with a complex configuration;
- The comparison of experimental results obtained by the proposed method (according to the Eq. (3)) and classical methods (1) gives a positive result and indicates the adequacy of the proposed mathematical model and the method itself.

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