Simulation of heat transfer processes in cooling systems with heat recovery

Anton Sinitsyn\textsuperscript{1*}, Vyacheslav Rakov\textsuperscript{1}, A P Eperin\textsuperscript{2}, Yu A Rundygin\textsuperscript{2}, R V Rusinov\textsuperscript{2}, R A Izmailov\textsuperscript{2}, A M Simonov\textsuperscript{2}, V K Yun\textsuperscript{2}, Anton Mihin\textsuperscript{2} and Irina Akhmetova\textsuperscript{3}

\textsuperscript{1}Vologda State University, Heat Gas Supply and Ventilation, 160000 Lenin st., 15, Russia
\textsuperscript{2}Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation
\textsuperscript{3}Kazan State Power Engineering University, Kazan, Russian Federation

* Corresponding author: sinitsyn.science@mail.ru

Abstract. The article considers modeling of modern heat exchange systems which use thermal energy for its beneficial use. The proposed mathematical model makes it possible to investigate systems with utilization of thermal energy. The article presents the results of simulation of heat exchange processes using heat energy recovery for internal combustion engines.

1. Relevance of the investigation

Today, energy conservation is a worldwide strategic task of national importance. Meanwhile, many enterprises have significant energy losses due to insufficient use of heat generated in technological processes. In particular, the heat of gas heated during the process of any production is either not used efficiently or not used at all and the heated gas is released into the atmosphere. This leads to enormous energy losses in the volume of the enterprise, country, world, and also determines various environmental problems [1-6]. This is especially typical for high-temperature productions with coolant temperatures from 1000 °C and more, where energy losses are the greatest, as well as when using gases containing a large amount of impurities and aggressive substances.

In the metallurgical industry, increasing the energy efficiency of heat exchange systems is a very urgent task. In ferrous and non-ferrous metallurgy, as well as in the metalworking process, a great amount of heat is expended, much of which is discharged into the environment. In such systems, reducing heat energy losses is most relevant, for example, through the use of heat energy recuperators. A typical heat exchanger is a surface-type heat exchanger which uses waste gas heat, in which heat exchange between the heating and heated medium is carried out through a separation wall. Typical designs of recuperators of metallurgical furnaces are ceramic, metal loop, block, etc. Such devices allow using a part of waste heat to improve the process, or for other needs, such as heating. The authors are working on development and implementation of gas-liquid heat exchangers in production, transport, metallurgy and other industries. Several experimental samples were made, original ways of increasing the efficiency were found, described in [7-9].

2. Description of the mathematical model
Evaluation of efficiency of heat recovery device introduction into heat exchange system at the design stage is associated with problems of modeling the heat exchange system. The authors propose to use mathematical modeling to compare operation of the heat exchange system before and after installation of heat energy recuperator.

To simulate the heat exchange process, a block model was used, consisting of 3 main blocks: heating unit (HU), recuperator of thermal energy (RTE) and a cooling circuit (CC).

The system carries out the process of receiving thermal energy from HU $Q_{HU}$ and from RTE $Q_{RTE}^{out}$ during heating. Thermal energy $Q_{HU}$ and $Q_{RTE}^{out}$ depend primarily on the mode of operation of the HU.

The use of heat in the system is carried out through the cooling circuit $Q_{rem}^{out}$, the exhaust system $Q_{EG}^{out}$, the radiation of thermal energy into the environment through the heated surfaces of the heating unit $Q_{rem}^{HU}$.

In RTE, heat transfer occurs, which is characterized by supply of a portion of thermal energy $Q_{RTE}^{in}$ from exhaust gases and removal of the utilized thermal energy into the coolant $Q_{RTE}^{out}$ (J).

In the cooling unit, the process of removal of thermal energy from the coolant for the needs of the process is carried out. The intensity of heat transfer in the cooling unit depends on the ambient temperature, the speed of coolant in the heat exchanger, coolant temperature in the heat exchanger and the speed of its circulation. All blocks are connected by a single circulation circuit.

The output parameter in this case is time to reach the required temperature of liquid coolant in the cooling unit.

The ratio between temperature changes will be as follows:

$$M_1^i c_{p1} (T_{out}^{1} - T_{in}^{1}) - M_2^i c_{p2} (T_{out}^{2} - T_{in}^{2}) = 0$$

where $M_1^i, M_2^i$ is mass flow of gas and liquid coolant (kg/s); $c_{p1}, c_{p2}$ is average specific heat capacity of coolant at constant pressure for the given temperature ranges (J/(kg·K)); $T_{out}^{1}, T_{in}^{1}$ is gas and liquid temperature at the output of heat exchanger; $T_{out}^{2}, T_{in}^{2}$ is gas and liquid temperature at the input of heat exchanger (°C).

$$C_1 \Delta T_1 - C_2 \Delta T_2 = 0 \text{ or } Q_1^i - Q_2^i = 0$$

where $C_1, C_2$ is the product of specific heat capacity and the mass flows, $Q_1^i, Q_2^i$ are heat fluxes (W).

Taking into account that heat exchanger is not ideal, some of heat energy will be spent on hydrodynamic losses, heat transfer to the atmosphere through the outer walls.

During heating, the heat energy of the coolant will also be spent on heating the walls of RTE, reducing its efficiency [10].

Further we consider an example of a heat exchange system with an air-heating unit, the temperature of the liquid coolant in which is equal to $T^0$, energy $Q$ at this time moment is equal to zero. After starting the heating unit, at each moment of time a certain amount of thermal energy $Q_i$ enters the system, it depends on the amount of combustible fuel and is equal to:

$$\int_{t_{i-1}}^{t_i} Q_i \, dt = q_i \times \rho \times H_U \times 0.3/3600 = 3 \times 0.7 \times 43500 \times 0.3/3600 = 7.61$$

where $q$ is hourly heat consumption, l/h;
$\rho$ is fuel density, kg/m$^3$;
$H_U$ is specific heat of combustion, kJ/kg.

The intensity of the system heating, depending on the incoming additional thermal energy, is determined experimentally and is described by a logarithmic or polynomial law. And its confidence level can be estimated by the trend determination coefficient $R^2$

$$T = A \ln(t) - B, \text{ for } R^2=0.986,$$
$$T = At^2 + Bt + C, \text{ for } R^2=0.998,$$

where $A, B, C, D$ are coefficients taking into account environmental parameters and uneven heating of the heat source.

Received thermal energy in the heating unit will be equal to:

$$Q_{HU} = \int_{t_{i-1}}^{t_i} Q_i \, dt + Q_{HU}^{HI} - Q_{rem}^{HU} - Q_{rem}^{out}$$

$$Q_{rem}^{HU}$$

$$Q_{rem}^{out}$$

(3)
where $Q_{\text{acc}}$ is accumulated heat energy; $Q_{\text{HUE}}$ is heat energy obtained from fuel combustion; $Q_{\text{out}}$ is heat energy removed to the atmosphere (in this case it is unknown); $Q_{\text{CC}}$ is heat energy removed to the cooling circuit.

The energy removed by the cooling circuit per unit time is equal to the difference between input $Q_{\text{in}}$ and output $Q_{\text{out}}$ heat energy for the given time period:

$$Q_{\text{rem}} = \int_{t_{l-1}}^{t_l} (Q_{\text{in}} - Q_{\text{out}}) \, dt$$

(4)

The heat balance of the entire system can be expressed by a general integral equation:

$$Q_{\text{sys}} = \int_0^t (Q_{\text{out}} + Q_{\text{RTE}} - Q_{\text{CC}}) \, dt$$

(5)

The temperature of liquid coolant in the system will depend on balance of receipt of thermal energy and its removal. Based on the presented dependencies, the heating process of HU is modeled by theoretical means, which allows one to estimate the effect of RTE and various factors on the rate of its heating.

Experimental and theoretical studies on efficiency of usage the heat exchanger allow one to a priori estimate the process of the entire system after launch. However, such studies involve a number of complex tasks. The first is the need to find the dependence of the coolant temperature on time $T_C = f(t)$. The second is to find the amount of thermal energy released in the system as a function of time $Q_{\text{HUE}} = f(t)$. The third is to find the amount of thermal energy, removed by the exhaust gas system as a function of time $Q_{\text{EG}} = f(t)$. The fourth is to find CC capacity and the amount of thermal energy removed by it as a function of time $Q_{\text{rem}} = f(t)$. The fifth is to find RTE capacity as a function of the coolant temperature $Q_{\text{RTE}} = f(t)$. The sixth is to find HU thermal characteristics.

3. Description of mathematical methods

When modeling the heat exchange system, the methods of mathematical analysis and statistical calculations described in [11, 12] were used.

3.1 Change of temperature of the heat carrier of the heating unit.

Figure 1 shows theoretical and experimental dependences of the heating. Immediately after switching on HU, the coolant temperature is equal to the ambient temperature $-27 \, ^\circ C$, after which the temperature rises rapidly, then the temperature rise decreases and at 22 minutes the cooling circuit opens and the temperature stabilizes at $93 \, ^\circ C$.

![Figure 1](image)

**Figure 1.** The intensity of temperature change of the coolant system without RTE.

3.2 The amount of heat energy released into the system.

It is known that part of the energy of combustion of the air-fuel mixture is discharged into the heat exchange circuit [8]. Thus, knowing the amount of combustible fuel, the amount of thermal energy...
entering the heat exchange circuit is established. The heat capacity of fuel combustion is \( H_U = 46000 \) kJ/kg. The density of fuel is 0.75 g/cm³. At low coolant temperature (Figure 2), the amount of combustible fuel is greater, while the amount of energy discharged into the heat exchange system decreases and stabilizes after the operating temperature is reached.

\[
Q_{\text{HH}}^C, \text{kJ}
\]

\[
Q_{\text{HH}}^C = -120.16/n(t) + 487.64
\]

\[
R^2 = 0.9951
\]

**Figure 2.** Relationship between the thermal energy removed to CC and time.

After the heating unit is turned on, the heat from exhaust gases is consumed mostly for heating elements of the exhaust system; therefore, during this period gas temperature is not significant. Intensive temperature rise begins after about 40 s, and after 2 min exhaust temperature is already more than 200 °C, which is equivalent to 1.5 kW of heat output. After warming up to the operating temperature, 40% of the thermal energy from the combustible air-fuel mixture is already discharged into the exhaust system.

The results of calculating the characteristics of HU heating in different modes of operation of the cooling circuit (Figure 3) show that when its capacity is increased to 100%, the coolant does not warm above 55 °C, and the maximum thermal energy entering the cooling circuit will not exceed 1 kW, which indicates inefficiency of the cooling unit.

**Figure 3.** Coolant temperature raise intensity for cooling circuit power: 1 – 0%; 2 – 20%; 3 – 40%; 4 – 60%; 5 – 80%; 6 – 100%.
When the cooling circuit is turned off, the coolant warms up to the operating temperature only at the 21st minute. When turning on the cooling circuit: at 0.5 kW, the temperature at the 21st minute will reach 88 °C; when switched on at full capacity, the coolant at the specified time will only warm up to 55 °C. The cooling circuit will receive only 1.4 kW of thermal power. Further, the temperature of the coolant will not rise at all.

The RTE power depends on the exhaust gas temperature. From previous studies, it is known that after starting the heating unit, the heat energy of the exhaust gas is spent mostly on heating the HU parts and the exhaust system. As shown by tests, the efficiency of conversion of heat energy of the exhaust gas during heating of the coolant can reach 50%, and the energy return begins only after the 2nd minute of the heating unit.

The results of theoretical studies show that the use of a device for heat energy recovery makes it possible to reduce the warm-up time to working temperature from 22 to 10 minutes, and when the cooling circuit is turned on, an additional 2.5 kW of heat energy can be obtained already at the 12-minute after switching on, while without using RTE, the heating unit cannot provide this amount of energy for up to 22nd minute.

4. Conclusions

Summing up the research on the creation of a new type of heat exchangers, we can note the following:

1. A method for study of heat exchange systems with a heat recuperator is proposed.
2. The results of the study of the heat exchange system in various modes of operation before and after application of heat recuperator are presented.
3. The adequacy of the adopted mathematical model and calculation program is confirmed by the analysis of laboratory studies and operating experience of heat exchangers.

References

[1] Zlotin V E 2011 Efficient heat recovery heat exchangers Novosti teplosnabzheniya 1
[2] Potekhin V V, Pantyukhov D N and Mikheev D V 2017 Intelligent control algorithms in power industry EAI Endorsed Transactions on Energy Web 17(11)
[3] Grasmanis Dz, Sovetnikov D O and Baranova D V 2017 Energy performance of domestic hot water systems Magazine of Civil Engineering 76(8) pp 140–55
[4] Szkarowski A, Janta-Lipińska S and Gawin R 2016 Reducing emissions of nitrogen oxides from dkvr boilers [Obniżenie emisji tlenków azotu z kotłów dkvr] Rocznik Ochrona Środowiska 18(1) pp 565–78
[5] Zubkova M, Strogonov A, Chusov A and Molodtsov D 2017 Hydrogenous fuel as an energy material for efficient operation of tandem system based on fuel cells Key Engineering Materials 723 pp 616–21
[6] Sebelev A, Kirillov A, Porshnev G, Lapshin K and Laskin A 2018 Thermodynamic analysis of design and part-load operation of a novel waste heat recovery unit MATEC Web of Conferences 245 p 04010
[7] Sinitsyn A 2012 Science, Technology and Higher Education Westwood, Canada
[8] Rakov V A 2012 Using exhaust heat to reduce engine warm-up time and vehicle cabin heating Autotransportnoe predpriyatiye 8
[9] Petukhov B S and Shikov V K 1987 Energoatomizdat 1
[10] Kruglov G A 2010 Thermal Engineering
[11] Migay V K 1987 Simulation of heat exchange energy equipment