Investigation of the relationship of structural characteristics and operating regime of regenerative heat exchangers

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Abstract. The paper presents the results of a computational study of the operating modes and design factors of a regenerative heat exchanger. The calculations were based on a mathematical model of regenerative heat transfer. It is shown that the most rational mode of heating/cooling the checkerwork is the regular mode. The regular mode is characterized by a constant local temperature head over the height of the checkerwork, and as a result, a linear distribution of the temperature of the checkerwork along the height. It is shown that it is during the implementation of the usual mode that the maximum heating temperature of the coolant and the maximum heat utilization coefficient are provided. The calculations were carried out for a hot-blast stove. In these heat exchangers, the flow rate of the cold heat-transfer agent (blast-furnace air), the temperatures of the hot and cold heat-transfer agent at the inlet to the checkerwork are constant. The range of variation of the heating/cooling time of the checkerwork for such devices is determined to ensure regular mode. It is shown that, within the framework of the regular regime, a decrease in the duration of the cooling period is accompanied by an increase in the temperature of heating the blast-furnace air, a decrease in the temperature of the flue gases, and an increase in the heat utilization coefficient. Also shown are the values of the design parameters of the checkerwork (equivalent diameter of the checkerwork channel, specific heating surface) at which the heat exchanger will operate regular regime. The calculations showed a range in which it makes sense to increase the heat-transfer coefficient of the checkerwork for a specified range of flow rates of the coolants and the time of the periods of heating and cooling. It is shown in the work that increasing the specific surface of the checkerwork heating and increasing the heat-transfer coefficient will allow one to obtain a tangible effect only in combination with a corresponding change in the operating parameters of the heat exchangers.

1. Introduction

Regenerative heat exchangers have long been successfully implemented in various areas of industrial production. Their use in low-grade heat recovery systems is promising. The heat exchange in the regenerative heat exchangers between heat-transfer agents occurs through an intermediate heat-transfer agents, which call a checkerwork. During the working cycle, the checkerwork is sequentially heated and cooled by gaseous or liquid coolants, while the temperature changes both in time and in the volume of the checkerwork. Despite the general principle of operation, the designs of these heat exchangers are different. The operation of various types of regenerative heat exchangers is well studied theoretically and experimentally.
The main objective of any heat exchanger is to provide heating or cooling of the working medium to the required temperature. At the same time, the heat exchanger must operate with the highest possible available heat factor, have the lowest possible geometric dimensions and use relatively inexpensive structural materials. The fulfillment of the above requirements is possible only due to the intensification of heat transfer. In particular, for regenerative heat exchangers, it is important to create new effective checkerwork that can increase the heat transfer coefficient \( \alpha \) and the relative heat transfer surface \( F_{m2/m3} \), by 3 ... 3.5 times in comparison with traditionally used checkers. On the other hand, the efficiency of regenerative heat exchangers is also determined by the operating parameters: the ratio of the flow of coolants, the choice of the duration of the periods of heating and cooling. With the obvious mutual influence of the operating and structural parameters on the operation of the regenerators, at present no attempts are made to take these parameters into account in a complex.

The purpose of this work is to study the mutual influence of structural characteristics and operational parameters of regenerative heat exchangers. The results obtained will allow us to determine the optimal parameters and sizes of the checkerwork, as well as determine the rational modes of operation of the heat exchanger.

2. Mathematical model of heat transfer in a regenerative heat exchanger

A regenerative heat exchanger with counterflow of heat carriers is shown in figure 1.

Through a checkerwork, which in some types of regenerative heat exchangers can be multilayer, hot and cold heat-transfer agent pass alternately. The hot heat-transfer agent moves from top to bottom, and the cold, respectively, from bottom to top. In most types of regenerative heat exchangers, the temperature of heat transfer agents at the entrance of checkerwork are almost constant: \( t_{21} = \text{const} \) and \( t_{11} = \text{const} \). Also, as a rule, the flow rate of the cold transfer agent is constant, i.e. \( Q_1 = \text{const} \).

Consider the one-dimensional heat transfer problem between the checkerwork and the heat transfer agent for the \( dx \) layer. To combine heat, transfer by convection and thermal conductivity in the checkerwork, we represent the checker layer in the form of a conditionally thermally thin body. The relationship between the average layer temperature \( t_m(x, t) \) and the actual distribution of the checkerwork temperature in the layer is determined by the mass coefficient \( m = f(Bi) \). Under the condition of a steady temperature distribution in the layer characteristic of the regenerative regime, the massive coefficient...
\[ m = \frac{t_f(x, \tau) - t_m(x, \tau)}{t_f(x, \tau) - t_w(x, \tau)} = 1 + \frac{Bi}{3}. \]  

Then the system of equations describing regenerative heat exchange can be represented as [1]

\[
\begin{align*}
\frac{\partial t}{\partial \tau} + \frac{Q^*}{Q_f} \frac{\partial t}{\partial x} &= \frac{\alpha_f f_0}{Cm} \mathcal{G}(x, \tau); \\
\frac{\partial t_i}{\partial x} + \frac{1}{Q_f} \frac{\partial t_i}{\partial \tau} &= \frac{\alpha_f f_0 \rho^*}{mC_f Q_f} \mathcal{G}(x, \tau); \\
\mathcal{G}(x, \tau) &= t_f(x, \tau) - t_m(x, \tau); \\
m &= t_f(x, \tau) - t_m(x, \tau) - t_w(x, \tau).
\end{align*}
\]  

The single-valuedness condition:
- for the cooling period at \( \tau = 0, t_H = t_{21}, \) at \( \tau = \tau_1, t_H = t_{12}; \)
- for the heating period at \( \tau = 0, t_{H-0} = t_{11}, \) at \( \tau = \tau_2, t_{H-0} = t_{22}; \)
- the initial distribution of the checkerwork temperature is described by the function \( t = \varphi(x), \) the thermophysical properties of the checkerwork are determined in accordance with its temperature, the reduced heat carrier flow rate \( Q_f^* \) (per 1 m² of the checker) and the heat transfer coefficient \( \alpha \) are constant throughout the entire period.

3. The study of the operating mode of regenerative heat exchangers

At each moment of time, the heat exchange intensity between the checker and heat carriers is determined by the average heat transfer coefficient \( \bar{\alpha} \) over the entire height of the checkerwork and the average temperature head \( \bar{\mathcal{G}}. \) All other things being equal, the maximum average temperature head exists in the case of a local temperature head that is constant over the entire height of the checkerwork, i.e. \( \nu = \text{const}. \) In turn, the fulfillment of this condition is possible only in the case of a linear distribution over the height and temperature of the checkerwork and the temperature of the heat carrier.

Thus, the heating (cooling) regime of the checker at \( \nu = \text{const} \) is characterized only by the time dependence of the temperature of both the checker and the heat-transfer agent, and the linear temperature distribution along the checker height is preserved.

In this case, regular temperature conditions are established [2].

The sequential numerical solution of systems (1) and (2) when substituting the corresponding distributions of the checkerwork temperature at the end of each period into the initial conditions of the subsequent period allows calculating the regular operation of the regenerative heat exchangers, in which there is a linear distribution of the checkerwork temperature after each period. A linear temperature distribution over the height of the checkerwork during normal operation can be obtained, for example, by choosing the ratio of the reduced heat-transfer agent flow rates to the time of the heating and cooling periods.

In most cases, the flow rate of one of the heat-transfer agents passing through the regenerative heat exchangers is known and almost unchanged. For example, for hot-blast stove, the flow rate of hot-blast stove is strictly predetermined. Also, the flow rate of combustion air is set in a rotary regenerative air heater. Therefore, when solving the system of equations (1) and (2) with different ratios of flow rates, it is possible to determine the flow rate of the heating fluid with a linear distribution of the checkerwork temperature along the height. Using the same principle, it is possible to determine the optimal duration of the periods of heating and cooling of the checkerwork. On the other hand, the optimal ratio of flow
rate of heat-transfer agent to the duration of the heating/cooling periods will be different for different checkerwork.

To determine the mutual influence of the structural characteristics and operational parameters of the regenerative heat exchangers, a series of calculations was performed according to the regime 1 (1) – (2) for a hot-blast stove.

Hot-blast stove is designed to heat blast-furnace air to a temperature of 1100 ... 1250 °C due to the heat of combustion products of blast furnace gas. The temperature of the combustion products at the inlet to the checkerwork is kept constant (1300 ... 1500 °C). The temperature of the cold blast-furnace air is also constant (70...100 °C). The height of the ceramic checker of the apparatus is 30...40 m, the checkerwork is made of blocks with channels of various shapes. Gas flows are passed through the checkerwork alternately. The relative flow rate of the blast-furnace air is always known and amounts to 2...2.5 m³/(m²·s).

In one block are from three to five hot-blast furnaces. To check the mathematical regime 1 (1) – (2), a calculation was performed for a standard air-heater for functioning a blast-furnace air with a volume of 3200 m³ and a checkerwork height of 40 m, and the checkerwork is made of blocks BCP-12-2. Four hot-blast stoves are installed in the blast furnace unit.

The temperature of the flue gases at the inlet to the checkerwork is \( t_{21} = 1350 \) °C, the temperature of the cold blast-furnace air \( t_{11} = 80 \) °C. The reduced blast-furnace air flow rate \( Q_1^* \) is 2.14 m³/(m²·s), the reduced flue gas rate \( Q_2^* \) is 0.85 m³/(m²·s); average heat transfer coefficients \( \alpha_1 = 60 \text{ W/(m}^2\text{°K}), \alpha_2 = 20 \text{ W/(m}^2\text{°K}) \). The duration of the cooling period is 60 minutes; the heating period is 180 minutes. The average temperature of heating the blast-furnace air obtained as a result of calculations is 1226 °C, the temperature of the flue gases at the outlet of the apparatus at the end of the heating period is \( t_{22} = 400 \) °C. The results obtained are in good agreement with the actual data on the operation of air heaters.

Calculations by regime 1 (1) – (2) made it possible to determine the duration of the checkerwork cooling period (blast heating), at which it is possible to provide a quasi-stationary distribution of the checkerwork temperature over the apparatus height: \( \tau_1 = 30...50 \) min. The durations of the cooling and heating periods for the blast-furnace heater block are rigidly interconnected, therefore, knowing \( \tau_1 \), we can determine \( \tau_2 = 70...130 \) min. The calculated temperature distribution over the height of the checkerwork is shown in figure 2.

An increase in the time of heating and cooling the checker leads to a distortion of the linear distribution of the temperature of the checkerwork, overheating of the upper and supercooling of the lower layers of the checkerwork. In figure 3 shows the distribution of the checkerwork temperature at a cooling time of 120 min (heating 340 min) obtained by solving the system of equations (1) - (2).

**Figure 2.** Temperature distribution over the checkerwork height for regular regime: 1 - at the end of the blast period, 2 - at the end of the heating period.

**Figure 3.** The temperature distribution of the checkerwork \((\tau_1=120 \text{ min})\): 1 - at the end of the blast period, 2 - at the end of the heating period.
Obviously, the upper part of the checkerwork (approximately 8 m in height) is heated up to the temperature of the flue gases at the entrance to the checkerwork. During cooling, the same layer in the lower part of the checkerwork is supercooled to the temperature of a cold blast-furnace air. In this case, the average temperature of the blast-furnace air is down to 1200 °C (the minimum temperature at the end of the blast period is 1032 °C), and the temperature of the flue gases at the of the blast furnace at the end of the heating period reaches 480 °C.

The regular regime can be implemented for any values of blast and heating times outlet provided that the dome temperature increases linearly during the heating period and linearly decreases to the minimum cold blast temperature during the cooling period. At constant temperatures of flue gases and cold blast at the inlet to the checkerwork, with an increase in the duration of the period, a transition to an irregular regime occurs.

Calculations show that for the BCP-12-2 checkerwork with a reduced flow rate \( Q_1^* = 2.14 \text{ m}^3/(\text{m}^2 \cdot \text{s}) \), the regular regime can be implemented with a blast duration of not more than 50 minutes. A decrease in the flow rate of blast-furnace air is accompanied by an increase in the time range for the implementation of the regular regime, for example, with a reduced flow rate of \( 1.4 \text{ m}^3/(\text{m}^2 \cdot \text{s}) \), the regular regime is realized for a duration of 80 minutes. Under the regular regime, a decrease in the duration of the blast period is accompanied by an increase in the temperature of the blast, a decrease in the temperature of the flue gases, and an increase in the heat utilization coefficient.

Obviously, for other regenerative heat exchangers, the boundaries for the implementation of the regular regime will be different, however, general trends remain. Let us analyze how the design characteristics of the checkerwork affect the implementation of the regular regime of operation of the regenerative heat exchanger.

4. Study of the structural characteristics of regenerative heat exchangers

Currently, there are a large number of checkers, the heat transfer coefficient of which varies from 20 to 100 W/(m²·K), ceteris paribus, and the specific surface of the checkerwork varies from 0.025 to 0.2 m²/kg [3, 4]. Based on the calculations according to equations (1) – (2), it is possible to determine the range of variation in the thermotechnical characteristics of the checkerwork blocks, within which a significant increase in the temperature of heating the blast-furnace air is observed. Computational studies were carried out with varying the duration of the cooling period from 30 to 50 minutes. The calculation results for \( \tau_1 = 40 \text{ min} \) are shown in figure 4. The BCP-12-2 checker, when operating in this regime, provides an average blast heating temperature of 1244 °C.

A noticeable increase in the temperature of the blast-furnace air is observed with an increase in \( f_0 \) to 0.1 m³/kg. Further increase in the specific heating surface at the temperature of the blast-furnace air has practically no effect. In this range, a change in the heat transfer coefficient significantly affects the blast-furnace air temperature. According to the calculations (see figure 4), with an increase in the checkerwork surface above 0.1 m²/kg, the influence of the heat transfer coefficient is small and it is not impractical to increase it.

The value of the heat transfer coefficient noticeably affects the temperature of the blast-furnace air only at \( \tau_1 = 30 - 35 \) min. In this case, using effective checkers with \( \alpha_1 = 50 - 60 \text{ W/(m}^2\cdot\text{K}) \), it is possible to increase the temperature of the blast-furnace air to 1266 °C.

Thus, it is advisable to use checkerwork with a specific surface area of 0.025–0.1 m²/kg, providing a heat transfer coefficient of 30–60 W/(m²·K), which will increase the temperature of the blast to 1247 – 1266 °C (depending on the time of the blast period).

The organization of a regular heating/cooling regime makes it possible to reduce the height of the air heater by an average of 7-10 m at a constant blast-furnace air temperature. In this case, checkerwork with heat transfer coefficients \( \alpha_1 = 30–60 \text{ W/(m}^2\cdot\text{K}) \) and a specific heating surface of 0.025–0.1 m²/kg will be optimal in this case (figure 5). A further increase in these parameters at the checkerwork height has practically no effect.
Figure 4. The influence of the thermal characteristics of the checkerwork blocks on the temperature of the blast:
1 – $\alpha_1 = 30 \text{ W/(m}^2\cdot\text{K)}$;
2 – $\alpha_1 = 40 \text{ W/(m}^2\cdot\text{K)}$;
3 – $\alpha_1 = 50 \text{ W/(m}^2\cdot\text{K)}$;
4 – $\alpha_1 = 60 \text{ W/(m}^2\cdot\text{K)}$

Figure 5. The influence of the thermal characteristics of the checkerwork blocks on the temperature of the checkerwork:
1 – $\alpha_1 = 30 \text{ W/(m}^2\cdot\text{K)}$;
2 – $\alpha_1 = 40 \text{ W/(m}^2\cdot\text{K)}$;
3 – $\alpha_1 = 50 \text{ W/(m}^2\cdot\text{K)}$;
4 – $\alpha_1 = 60 \text{ W/(m}^2\cdot\text{K)}$

Currently, checkerwork block with cylindrical channels are most widely used in blast-furnace air heaters. The geometric dimensions of the blocks vary over a wide range: $d_e = 15 – 55 \text{ mm}$, $F = 0.25 – 0.5 \text{ m}^3/\text{m}^2$. The specific surface of block checkerwork can be represented as $f_0 = \frac{4F}{(1-F)d_e\rho^*}$. Based on this, the geometric dimensions of the checkerwork blocks were determined at which the thermal parameters ($\alpha$ and $f_0$) will be optimal, and the operation of these checkerworks was investigated.

The results of calculations carried out for a fixed cycle time ($\tau_1 = 40 \text{ min}$) and blast consumption are presented in figure 6. It is shown that when varying the geometric dimensions of the checkerwork blocks in a wide range, the temperature of heating the blast changes slightly.

For checkerwork blocks with $d_e < 35 \text{ mm}$, an increase of $F$, and hence $f_0$, has practically no effect on the temperature of the blast-furnace air. This is fully explained by the results of previous calculations (see figure 4), since the values of the heat transfer coefficient in this case are close to the maximum optimum value of 60 W/(m$^2$-K). In addition, it is very difficult to choose the design of the checkerwork with high values of $\alpha$ and $F$ at the same time.
The performed calculations show that an increase in the specific heating surface of the checker and an increase in the heat transfer coefficient will allow one to obtain a tangible effect only in combination with a corresponding change in the operating parameters of the heat exchangers. For example, using a checkerwork with high heat transfer coefficients, to obtain the set temperatures, we must reduce the duration of the heating and cooling periods at the same flow rates. Or, under the constant conditions, use checkerworks with a higher density and heat capacity. Otherwise, the checkerwork will overheat at a sufficiently high height, which will make the work of the regenerative heat exchanger irrational and reduce the heat utilization coefficient.

The same must be done when using checkerworks with a larger specific heat transfer surface. Thus, when introducing highly efficient checkerworks, it is necessary to change the design of devices or to intensify the regime of their operation, reducing the time of heating/cooling periods and at the same time increasing fuel consumption.

5. Conclusion
It is shown a regular heating/cooling regime is the most rational for a regenerative heat exchanger. Numerical studies using the example of a hot-blast stove made it possible to establish a relationship between the operating parameters of the heat exchanger and the design characteristics of the checkerwork. It is shown in which range of the cooling/heating period of the checkerwork a regular regime can be ensured. It was found that for a given regime of operation, an increase in the heat transfer coefficient above the level of 60 W/(m²·K) and a specific surface of the checkerwork of more than 0.1 m²/kg is impractical, since a further increase in the thermal characteristics of the checker does not significantly affect the heating temperature of the blast-furnace air and the height of the chamber checkerwork. It was also revealed that an increase in the heat transfer coefficient and the heating surface of the checkerwork makes sense only with a corresponding intensification of the operating regime of the heat exchanger.

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Appendices
List of designations:
\( C \) – heat capacity of checkerwork, J/(kg·K);
\( C_i \) – heat capacity of heat-transfer agent, J/(m³·K);
\( f_0 \) – specific surface area of the checkerwork, m²/kg;
\( H \) – height of the checkerwork, m;
\( m \) – massive coefficient of the checkerwork;
\( Q'_f \) – reduced flow rate of the heat transfer agents, \( \text{m}^3/(\text{m}^2 \cdot \text{s}) \);
\( t_m \) – average temperature of the checkerwork, °C;
\( t_f \) – temperature heat transfer agent at the moment of time, °C;
\( t_{i1} \) – temperature heat transfer agent at the entrance to the checkerwork, °C;
\( t_{i2} \) – temperature heat transfer agent at the exit to the checkerwork, °C;
\( t_w \) – surface temperature of checkerwork, °C;
\( x \) – coordinate of the vertical axis;
\( \alpha_f \) – heat transfer coefficient, \( \text{W}/(\text{m}^2 \cdot \text{K}) \);
\( \rho^* \) – density of checkerwork, \( \text{kg}/\text{m}^3 \);
\( \tau \) – time, s;
\( \theta \) – average temperature drop between the heat transfer agent and the checkerwork, °C.

Indexes:
\( f \) – number of heat transfer agent: \( f=1 \) – cold heat-transfer agent, \( f=2 \) – hot heat-transfer agent.

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