Optimization of the operation mode of regenerative heat exchangers

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Abstract. The paper considers the operation of regenerative heat exchangers with a fixed checkerwork. Such a checkerwork allows for high-temperature heating of gases and is made of refractory materials with a relatively high heat capacity, but low thermal conductivity. The article presents calculations of regenerative heat transfer for devices with block checkerwork. It is shown that a decrease in the equivalent diameter of the channel $d$ leads to an increase in the average air heating temperature over the period. An increase in the relative water section of the checkerwork $f$ also leads to an increase in the air heating temperature, but only to a certain limit. On the one hand, with an increase in the relative water section, the specific heat exchanger surface increases. On the other hand, at a certain value $f$, the accumulating mass of the checkerwork significantly decreases, and as a result, the air heating temperature decreases. For the same reason, for checkerwork with a high value of the relative water section, it is necessary to reduce the duration of the heating/cooling periods of the checkerwork. The paper also examines several types of compact checkerwork, which are very promising, including in heat storage systems. It is noted that the use of such attachments in conventional regenerate heat exchangers is impossible. First, it is necessary to increase the water section of the heat exchanger and significantly reduce its height, otherwise, the pressure loss will increase sharply. Secondly, it is necessary to significantly reduce the duration of the heating/cooling periods, otherwise, due to more intense heat exchange, the air temperature at the outlet of the regenerative heat exchanger changes much more than in the block checkerwork.

1. Introduction
Regenerative heat exchangers are devices in which the heat exchange between the heating (hot) and heated (cold) heat transfer agent is carried out through an intermediate heat transfer agent. In the absolute majority of cases, the role of an intermediate heat transfer agent is played by the checkerwork: the hot heat transfer agent first heats the checkerwork, and then the cold heat transfer agent is passed through the checkerwork.

Even though regenerative heat exchangers are not as widespread as recuperative heat exchangers, they have some advantages over recuperative devices.

First of all, only in regenerative heat exchangers, it is possible to organize high-temperature gas heating up to 1700 K. This contributed to the widespread application of regenerative heat exchangers in metallurgy, for example, for the heating hot-blast stove.
In addition, compared to recuperative heat exchangers, regenerative devices have a larger heat exchange surface per unit volume, lower pressure loss, and can work with contaminated heat transfer agents.

Regenerative heat exchangers are distinguished by a constructive variety. According to the operation principle, regenerators are divided into two types. The first type of regenerative heat exchanger is apparatus with a movable checkerwork. The second type is apparatus with a fixed checkerwork. For low- and medium-temperature heating, devices of the first type are used. Devices of the second type are used for high-temperature heating of heat carriers (more than 800°C).

Obviously, the checkerwork of the first type of regenerators can be made of steel, whose heat capacity is on average two times lower than that of refractories, and the thermal conductivity, on the contrary, is much higher. The checkerwork in the second type of regenerators is made of refractory materials with a relatively high heat capacity and low thermal conductivity.

In regenerative heat exchangers of both the first and second types, the checkerwork operates in a periodic mode. Moreover, the heating and cooling periods may differ significantly in duration, moreover, the costs of hot and cold heat transfer agent carriers may also be different.

2. Optimal operation regime of regenerative heat exchangers

By now, the regenerate heat exchanger is quite well researched. In many publications [1-10], the possibilities of improving their design, as well as operating regimes are considered, a large number of mathematical models are proposed that describe the heat exchange processes in the regenerative heat exchanger. However, it is worthwhile noting that almost all available studies are tied to any one design of regenerative heat exchangers and the authors make no attempt to extend the results obtained to other types of regenerative heat exchangers. Most publications are devoted to improving the efficiency of regenerators, however, completely different parameters serve as the efficiency criterion. For some devices (for example, a hot-blast stove), this is the heating temperature of a cold heat transfer agent (a blast furnace). For others (for example, rotating air heaters) – efficiency factor.

An important feature of regenerative heat exchangers is the significant relationship between the operating mode and the structural and thermophysical characteristics of the checkerwork. It is obvious that the design of a regenerative heat exchanger should ensure maximum efficiency at a minimal cost. Traditionally, an increase in the efficiency of heat exchange is associated with an increase in the temperature drop between the heat transfer agents, and the heat transfer coefficient. However, for regenerative heat exchangers, this approach does not always give the expected result.

For example, from the standpoint of heat exchange efficiency, the maximum temperature difference should be maintained between the checkerwork and the heat transfer agent during the whole heating/cooling period, and over the entire height of the checkerwork. This is possible only if the temperature is distributed linearly over the height of the checkerwork at each moment, and the heat exchanger has to operate in a quasi-stationary mode. In this case, we have a regular regime of heating and cooling of the checkerwork, since the linear distribution of the checkerwork temperature is maintained throughout the whole period.

Based on the mathematical model of a regenerative heat exchanger [1, 2], calculations were performed for a device with a fixed checkerwork. The following initial data are used in the calculations: hot heat transfer agent – flue gases resulted from burning gaseous fuel (the lower heating value is 4 MJ/m³); cold heat transfer agent – air; the flow rate of the cold heat transfer agents is 92 m³/s, the temperature of the cold heat transfer agents at the inlet to the heat transfer is 70°C, the temperature of the hot heat transfer agents at the inlet to the apparatus is 1300°C, the maximum permissible temperature of the hot heat transfer agents at the outlet of the apparatus is 400°C. The total water section of the checkerwork is 42 m², and the height of the checkerwork is 40.2 m. During the calculations, the fuel consumption, the temperatures of the hot and cold transfer agents at the outlet of the checkerwork at the beginning and end of the heating period were determined.
The calculations show that the linear distribution of the checkerwork temperature along the height in the quasi-stationary regime can be obtained with the appropriate selection of the ratio of heat transfer agent flow rates and the heating/cooling time periods. An increase in the heating/cooling time leads to a distortion of the linear distribution of the checkerwork temperature and a transition to an irregular regime characterized by overheating of the upper and supercooling of the lower layers of the checkerwork (figure 1). Thus, it is possible to increase the efficiency of existing regenerative heat exchangers by organizing a regular mode of their operation.

**Figure 1.** Change in the temperature of the checkerwork and the coolant along the height of the checkerwork:

- *a* – cooling time 0.5 h; *b* – heating time 1.5 h

### 3. Study of block checkerwork

Currently, most technical solutions for heat exchange enhancement are aimed at developing heat exchange surfaces that provide a higher heat transfer coefficient and a more developed heat exchange surface per unit volume. Calculations have shown that in regenerative heat exchangers, this approach gives results only under certain conditions.

The checkerwork of regenerative heat exchangers are characterized by two parameters:

- the equivalent diameter of the channel $d_e$;
- relative water section of the checkerwork $f$.

If the checkerwork does not have transverse protrusions and horizontal passages, the specific heat exchanger surface of the checkerwork, $m^2/m^3$, can be expressed as

$$H' = \frac{4f}{d_e}. $$

The volume of the refractory in 1 m$^3$ checkerwork, m$^3$/m$^3$ is

$$v_f = 1 - f.$$ 

The equivalent half-thickness of the wall in the block is calculated by

$$R_e = \frac{(1 - f)d_e}{4f}. $$

While considering heat exchangers with a fixed checkerwork, at present, checkerwork with an equivalent diameter of 0.025-0.06 mm and a relative water section of 0.25-0.4 m$^2$/m$^3$ are mainly used. Based on the mathematical model [1, 2], calculations of regenerative heat exchangers with stationary checkerwork were performed. The calculations were performed for the duration of the heating period $\tau_1 = 9600$ s and the cooling period $\tau_2 = 3600$ s. At the same time, the types of block checkerwork used in existing heat exchangers were considered (table 1) [3, 4].
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Table 1. Geometric characteristics of the checkerwork

| № | \( d_e \), m | \( f \), \( m^2/m^2 \) | \( H' \), \( m^2/m^3 \) | \( v_k \), \( m^3/m^3 \) | \( R_e \), m |
|---|---|---|---|---|---|
| 1 | 0.06 | 0.298 | 19.8 | 0.702 | 0.035 |
| 2 | 0.0425 | 0.26 | 24.45 | 0.74 | 0.030 |
| 3 | 0.045 | 0.28 | 24.85 | 0.72 | 0.029 |
| 4 | 0.0501 | 0.3265 | 25.71 | 0.6735 | 0.026 |
| 5 | 0.0513 | 0.3685 | 28.208 | 0.6315 | 0.022 |
| 6 | 0.0501 | 0.3668 | 28.86 | 0.6332 | 0.022 |
| 7 | 0.0525 | 0.3908 | 29.35 | 0.6092 | 0.020 |
| 8 | 0.041 | 0.335 | 32.7 | 0.665 | 0.020 |
| 9 | 0.0375 | 0.3618 | 38.08 | 0.6382 | 0.017 |
| 10 | 0.0375 | 0.3764 | 39.52 | 0.6236 | 0.016 |
| 11 | 0.0345 | 0.3681 | 41.18 | 0.6319 | 0.015 |
| 12 | 0.0339 | 0.3594 | 41.85 | 0.6406 | 0.015 |

The results of the calculations are shown in figure 2. A decrease of the channel leads to an increase in the heat transfer coefficient, and as a result, to an increase in the air heating temperature \( t_{12} \), the average for the cooling period. The influence of the relative water section is not so unambiguous. With an increase in the relative water section, with the equivalent diameter of the channel unchanged, the specific heat exchanger surface of the checkerwork increases. This should lead to an increase in the air heating temperature or to a decrease in the dimensions of the heat exchanger if the air temperature is set. But the peculiarity of regenerative heat exchangers is that with an increase in the relative live section, the accumulating mass of the checkerwork material decreases. As a result, the air heating temperature decreases. Therefore, there is an optimal value of the relative water section, at which the air heating temperature is maximum.

![Figure 2](image1.png)  
Figure 2. The dependence of the average air temperature at the outlet of the checkerwork on the equivalent diameter over the period  

![Figure 3](image2.png)  
Figure 3. The dependence of the average air temperature at the outlet of the checkerwork on the relative water section over the period

Figure 3 shows the dependence of the air heating temperature on the relative water section with the channel diameter \( d_e = 0.041 \) m unchanged by the equivalent. The calculations were performed for the heating period \( \tau_1 = 9600 \) s and the cooling period \( \tau_2 = 3600 \) s. Since the relative water
section of the checkerwork affects the accumulating capacity of the checkerwork, it is necessary to reduce the duration of heating/cooling periods for checkerwork with an increased value.

4. Research of compact checkerworks

It should be noted that the heat transfer coefficients obtained are relatively small. To increase them, it is necessary to use a checkerwork with a smaller equivalent diameter, the so-called compact checkerworks. These checkerworks are performed in different ways: brick blocks with channels of relatively small diameter \( d_c \), ranged from 12 to 30 mm, or a bulk checkerwork made of balls of the correct shape or gravel. Using the mathematical model [1, 2], calculations were also performed for a compact checkerwork, whose characteristics are given in Table 2.

| №  | Checkerwork                                      | \( d_c, \) m | \( f, \) m²/m² | \( H', \) m³/m³ | \( v_3, \) m³/m³ | \( R_c, \) m |
|----|-------------------------------------------------|--------------|---------------|----------------|----------------|-------------|
| 1c | A block with 12 channels with a diameter of 30 mm | 0.03         | 0.36          | 48             | 0.64          | 0.013       |
| 2c | A block with 27 channels with a diameter of 25 mm | 0.025        | 0.35          | 56             | 0.65          | 0.012       |
| 3c | A block with channels with a diameter of 4 mm    | 0.004        | 0.184         | 184            | 0.816         | 0.004       |
| 4c | Bulk nozzle made of balls \( d=20 \) mm           | 0.00579      | 0.37          | 255.69         | 0.63          | 0.002       |
| 5c | Gravel bulk nozzle \( d_{cp}=15.6 \) mm           | 0.0057       | 0.43          | 821.9          | 0.57          | 0.002       |

The calculation results are shown in Table 3. For comparison, the calculation results for block checkerwork 8 are given in Table 1.

| №  | Checkerwork                                      | Full heat exchanger surface \( F, \) m² | \( \tau_1, \) c | \( \tau_2, \) c | Fuel consumption \( Q, \) m³/c | \( t_{12}, \) °C | Heat transfer coefficient \( \alpha_2, \) W/(m²·K) |
|----|-------------------------------------------------|----------------------------------------|----------------|----------------|--------------------------|----------------|---------------------------------|
| 8  | A block BCP-12-2                                | 55211                                  | 9600           | 3600           | 13.70                    | 1223           | 32.12                           |
| 1c | A block with 12 channels with a diameter of 30 mm| 81043                                  | 9600           | 3600           | 13.84                    | 1268           | 37.39                           |
| 2c | A block with 27 channels with a diameter of 25 mm| 189101                                 | 9600           | 3600           | 13.96                    | 1278           | 39.05                           |
| 3c | A block with channels with a diameter of 4 mm    | 15456                                  | 900            | 300            | 11.85                    | 1171           | 74.16                           |
| 4c | Bulk nozzle made of balls \( d=20 \) mm          | 21478                                  | 900            | 300            | 11.44                    | 1148           | 53.75                           |
| 5k | A block with 12 channels with a diameter of 30 mm| 69041                                  | 1800           | 600            | 13.00                    | 1267           | 35.08                           |
It should be noted that the device with a compact checkerwork 3c, 4c, 5c has significantly smaller dimensions, namely, a height of 1 m, cross-section of 84 m². It is also shown that for the effective use of a compact checkerwork, it is necessary to drastically reduce the duration of the heating/cooling period, or use checkerwork with a higher density and heat capacity.

5. Conclusion
The paper presents the results of a computational study of the checkerwork of regenerative heat exchangers. The effects of the equivalent diameter and the relative water section on the efficiency of the heat exchanger are shown. Compact checkerworks are also studied. It is shown that the use of compact checkerworks is possible only with a significant change in the dimensions and operating regime of the regenerative heat exchanger. Otherwise, the checkerwork will overheat at a sufficiently high height, which will make the operation of the regenerative heat exchanger irrational, and reduce its thermal efficiency. The same must be done when organizing heat exchange in a checkerwork with a large heat transfer coefficient. Thus, when implementing highly efficient checkerwork, it is necessary to change the design of devices or intensify their operation regime, reducing the duration of periods and increasing the consumption of heat carriers.

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