Development of optimization criterions of regenerative heat exchangers

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Abstract. The paper offers a simple method for analyzing the operation of regenerative heat exchangers, which significantly reduces the amount of calculations. Similarity criterions of regenerative heat exchange are obtained, which can be used to analyze the relationship of their thermophysical, structural and operating parameters. Similarity criterions were formulated by reducing the differential equation of regenerative heat transfer to a dimensionless form. These mathematical transformations were performed under the condition of regular regime of heating (cooling) of the checkerwork. As a result, three similarity criterions are obtained. The first criterion Kp₁ determines the ratio between the heat-accepting capacity of the heat transfer agent and the heat-accumulating capacity of the checkerwork. The second criterion Kp₂ is the ratio between the heat-receiving capacity of the heat transfer agent and the intensity of convective heat exchange. The third criterion Kp₃ is the ratio between the heat-accumulating capacity of the checkerwork and the intensity of convective heat exchange. Similarity criterions include both the design and performance characteristics of the regenerative heat exchanger. Using these criterions, it is possible to choose a rational operating mode for existing heat exchangers. The proposed method of criteria analysis of regenerative heat exchangers was applied to hot-blast stove. In particular, the conditions for implementing a regular regime in heat exchangers are found. The regular mode is characterized by a linear temperature distribution over the height of the checkerwork, which can be obtained by selecting the appropriate ratio of the reduced costs and the time of the cooling and heating periods. It is also shown in what range it is advisable to change the design and operating parameters of the heat exchanger in order to obtain the maximum heating temperature of the blast-furnace air and the maximum heat availability factor. Since the similarity criteria are universal, the proposed method can be applied to other types of regenerative heat exchangers.

1. Introduction

Regenerative heat exchangers are widely used in power engineering, metallurgy and other industries. Heat exchange in regenerative heat exchangers between heat transfer agent through the checkerwork. During the working cycle, the checkerwork is consistently heated and cooled by gaseous or liquid heat carriers, while the temperature changes both in time and in the volume of the checkerwork. Despite the General principle of operation, these heat exchangers are very diverse.

Designers strive to reduce the dimensions and hydraulic resistance of the heat exchanger. For recuperative devices, this task can only be performed by increasing the heat transfer coefficient. In regenerative heat exchangers, the checkerwork material and operating mode also have a noticeable effect on the size of the device. In turn, the operating regime of the regenerative heat exchanger is determined...
by the ratio of cold and hot heat transfer media consumption, the duration of the heating and cooling periods of the checkerwork.

The process of unsteady heat transfer that takes place in regenerative heat exchangers depends on many factors, the mutual influence of which is not always clearly visible. Therefore, when designing attachments, designing new devices and developing their modes of operation, the engineer has to conduct a large number of complex calculations, moving towards the intended goal "by touch".

The authors offer a fairly simple method for analyzing and calculating regenerative heat exchangers.

Various designs of regenerative heat exchangers are used in industry and power engineering. This article describes the hot-blast stove, which are designed to heat the blast-furnace air to a temperature of 1100...1250 °C due to the heat of the combustion products of the blast-furnace gas. The temperature of the combustion products at the entrance to the checkerwork is maintained constant (1300 ... 1500 °C). The temperature of cold blast-furnace air is also constant (70 ... 100 °C). The height of the ceramic checkerwork of the devices is 30 ... 40 m, the checkerwork is made of blocks with channels of various shapes. Gas flows are passed through the checkerwork alternately. In the block of the blast furnace there are 3...5 hot-blast stoves. The relative flow rate of the checkerwork is 2 ... 2.5 m$^3$/(m$^2$·s), the duration of the heating period of the checkerwork is 2...3 hours, the cooling period of the checkerwork (the blowing period) is 1...1.2 hours.

2. Analysis of heat transfer in regenerative heat exchangers

Heat exchange in the regenerative apparatus during the cooling period of the checkerwork can be described by a system of differential equations:

$$
\begin{align*}
\frac{\partial t}{\partial \tau} + Q_1^* \frac{\partial t}{\partial x} &= \frac{\alpha_1 f_0}{C m} \vartheta(x, \tau);
\frac{\partial t_1}{\partial \tau} + \frac{1}{Q_1^*} \frac{\partial t_1}{\partial x} &= \frac{\alpha_1 f_0 \rho^*}{C_1 Q_1^*} \vartheta(x, \tau);
\vartheta(x, \tau) &= t_1(x, \tau) - t(x, \tau)
\end{align*}
$$

(1)

Single-valuedness condition

- when $\tau = 0$, $t_1' = t_{21}$,
- initial temperature distribution of the checkerwork $t = \varphi(x)$,
- when $\tau = t_1$, $t_1' = t_{12}$,
- the thermophysical properties of the checkerwork are determined in accordance with its temperature,
- the reduced flow rate of the cold heat transfer agent $Q_1^*$ (per 1 m$^2$ of the checkerwork) and the heat-transfer coefficient $\alpha_1$ are constant throughout the entire cooling time.

For the heating period of the checkerwork, the system of differential equations has the form

$$
\begin{align*}
\frac{\partial t}{\partial \tau} + Q_2^* \frac{\partial t}{\partial x} &= \frac{\alpha_2 f_0}{C m} \vartheta(x, \tau);
\frac{\partial t_2}{\partial \tau} + \frac{1}{Q_2^*} \frac{\partial t_2}{\partial x} &= \frac{\alpha_2 f_0 \rho^*}{C_2 Q_2^*} \vartheta(x, \tau);
\vartheta(x, \tau) &= t_2(x, \tau) - t(x, \tau)
\end{align*}
$$

(2)

Single-valuedness condition

- when $\tau = 0$, $t_2' = t_{11}$,
- when $\tau = t_2$, $t_2' = t_{22}$,
• initial temperature distribution of the checkerwork \( t = \varphi(x, \tau) \),
• the thermophysical properties of the checkerwork are determined in accordance with its temperature,
• the reduced flow rate of the hot heat transfer agent \( Q_2^* \) (per 1 m\(^2\) of the checkerwork) and the heat-transfer coefficient \( \alpha_2 \) are constant throughout the entire heating time.

A sequential numerical solution of systems (1) and (2) by substituting the corresponding checkerwork temperature distributions at the end of each period into the initial conditions of the subsequent period allows us to calculate a quasi-stationary operating regime of the regenerative heat exchanger, in which there is a stable distribution of the checkerwork temperature after each period. The calculations show that with the appropriate selection of the ratio of the reduced costs and the time of the cooling and heating periods, it is possible to obtain a linear distribution of the checkerwork temperature along the height in quasi-stationary regime. In this case, we have a regular regime of heating and cooling of the checkerwork, since the linear temperature distribution of the checkerwork is maintained throughout the entire period [1]. Analysis of published works [2-5] and research of devices show that in operating regenerative air heaters of boiler installations and hot-blast stove, the temperature distribution of the checkerwork and heat transfer agents in height is really close to linear.

For the regular regime of the system, the equations can be written in integral form. For example, for the heating period of the heat transfer agent "1" during the time period \( \tau_1 \), the temperature change of the checkerwork will be

\[
\Delta t = \frac{C_1 Q_1^* \tau_1}{C \rho^* H} (t_{12} - t_{11}) .
\]  

In this case, the temperature drop is equal to temperature

\[
g = \frac{m C_1 Q_1^*}{\alpha_1 \rho^* f_0 H} (t_{12} - t_{11}) .
\]

Dimensionless complexes in the right parts of equations (3) and (4) are the similarity criterions of a regenerative heat exchanger. The criterion \( Kp_{11} = \frac{C_1 Q_1^* \tau_1}{C m \rho^* H} \) is the ratio between heat-absorption capacity of cold fluid \( f=1 \) or hot fluid \( f=2 \) and the heat storage capacity of the checkerwork, and the criterion \( Kp_{21} = \frac{C_1 Q_1^*}{\alpha_1 \rho^* f_0 H} \) is the ratio between heat-absorption capacity of cold fluid \( f=1 \) or hot fluid \( f=2 \) and intensity of convective heat transfer.

Note that reducing the system of differential equations (1) – (2) to a dimensionless form allows us to obtain not only the above criteria \( Kp_{31} = \frac{C m}{\alpha_1 f_0 \tau_1} \), but also a criterion representing the ratio between the heat storage capacity of the checkerwork and the intensity of convective heat exchange.

If the regular mode of heat exchange in a regenerative heat exchanger is observed, it can be described by a system of criteria equations:

\[
\Theta_{12} = \frac{1 + \Theta_{11}(Kp_{11} + Kp_{21})}{Kp_{11} + Kp_{21} + 1} ;
\]

(5)

\[
\Theta_{12}' = -\frac{Kp_{11}(1 - \Theta_{11})}{Kp_{11} + Kp_{21} + 1} ;
\]

(6)

\[
\Theta_{22} = \frac{\Theta_{11} + Kp_{11} + Kp_{21}}{Kp_{11} + Kp_{21} + 1} ;
\]

(7)
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\( \Theta' = \Theta_{11} + \frac{Kp_1(1-\Theta_{11})}{Kp_1 + Kp_2 + 1} \) \hspace{2cm} (8)

Dimensionless temperatures \( \Theta \) are the ratio of the corresponding temperatures of the heat transfer agent or checkerwork to the temperature of the hot heat transfer agent at the entrance of the checkerwork \( t_{21} \), which is usually assumed to be known and constant. Thus, the temperature of the heating agent can be determined

- at the entrance of the checkerwork at the beginning of the period \( \Theta_{11} = \frac{t_{11}}{t_{21}} \)
- at the exit of the checkerwork at the end of the period \( \Theta_{12} = \frac{t_{12}}{t_{21}} \), etc.

The dimensionless temperature determines the maximum temperature of the checkerwork (its upper layer) at the end of the cooling period, and the minimum temperature of the checkerwork (lower layer) at the end of the heating period.

Quasi-stable current condition of the operation cycle of the regenerative heat exchanger has the form

\( Kp_1 (\Theta_{12} - \Theta_{11}) = Kp_1 (1 - \Theta_{22}) \) \hspace{2cm} (9)

The criterion equations (5) – (9) make it possible to calculate and analyze the characteristics of a regenerative heat exchanger.

The obtained similarity criterions include both the design and performance characteristics of the regenerative heat exchanger. Using these criterions, a rational mode of operation can be selected for existing devices.

The inverse problem can also be solved. If the heating temperature of a cold heat transfer agent is set, the necessary values of design and operating parameters can be obtained. Of course, the results obtained will be approximate, but they will allow you to evaluate the effectiveness of implementing new checkerwork designs and select the appropriate mode of operation.

3. Analysis of regenerative heat exchanger operation based on similarity criteria

Here is an example of an analysis of the operation of a hot-blast stove. Let's set the average temperature of the cold heat transfer agent (blast-furnace air) at 1150 °C. The temperature heads are approximately \( \vartheta_1 = 60...100 \) °C, and \( \vartheta_2 = 40...60 \) °C. The temperature of the top of the checkerwork at the end of heating is assumed to be equal to the temperature of the hot heat transfer agent (furnace gas) \( t_{21} = 1300 \) °C, the temperature of the bottom of the checkerwork at the beginning of cooling is equal to the temperature of the cold blast-furnace air \( t_{11} = 70 \) °C. Flow rate of the cold heat transfer agent \( Q_1^* = 2.25 \text{ m}^3/(\text{m}^2 \cdot \text{s}) \).

Based on the accepted values of temperatures and temperature heads, we can get an approximate distribution of the temperature of the heat transfer agents and the checkerwork by height, based on the assumption that the operating mode of the hot-blast stove is close to regular. Based on the obtained temperature distribution, the height-averaged thermal properties of the checkerwork and heat transfer agents are determined.

The obtained temperatures of the checkerwork and heat transfer agents are used to determine the value of the similarity criterions \( Kp_1 \) and \( Kp_2 \) for the periods of heating and blowing. They are respectively equal \( Kp_1 = 0.152, Kp_2 = 0.035 \). At the specified blast-furnace air rate, the value of the criterion can be implemented for the duration of the blow period \( \tau_1 = 50...70 \) min. The durations of the blast and heating periods for a block of hot-blast stoves are rigidly related to each other, so, knowing \( \tau_1 \), we can find \( \tau_2 = 130...190 \) min. Based on the value of the criterions, we get the flue gas (fuel) consumption required for heating the checkerwork \( Q_2^* = 0.75...0.8 \text{ m}^3/(\text{m}^2 \cdot \text{s}) \).

The values of the criteria and are implemented at the value of the heat transfer coefficients \( \alpha_1 = 45...50 \text{ W}/(\text{m}^2 \cdot \text{K}) \) and \( \alpha_2 = 15...20 \text{ W}/(\text{m}^2 \cdot \text{K}) \). Thus, the operating parameters of hot-blast stoves at
a given average blast temperature are obtained. To obtain a different value of the blast temperature, the corresponding operating mode of the blast furnace is developed in the same way.

Refine the results based on calculations using the mathematical model (1) – (2). At the values of \( \tau_1 = 60 \text{ min}, \tau_2 = 160 \text{ min}, \) \( Q_1^* = 2.25 \text{ m}^3/(\text{m}^2\cdot \text{s}) \) and \( Q_2^* = 0.8 \text{ m}^3/(\text{m}^2\cdot \text{s}) \), the average temperature of blast-furnace air is 1142 °C, the temperature distribution of the checkerwork and the heat transfer agent is close to linear (figure 1).

Figure 1. Temperature distribution of the checkerwork and heat transfer agents by height.

Thus, the results obtained by the proposed method of criterion evaluation of the operating parameters of the hot-blast stove have a good convergence with the results of the calculation using the mathematical model (1) – (2).

The specified average temperature of blast-furnace air can be obtained by various combinations of values included in the similarity criterions \( K_{p1} \) and \( K_{p2} \). In other words, you can analyse how the operation mode of the blast-furnace air should change when the design parameters of the checkerwork change. Let's illustrate this with an example.

Using a checkerwork with high heat transfer coefficients, in order to obtain the set temperatures, it is necessary either to reduce the mass of the checkerwork, i.e. its dimensions, or to reduce the duration of the heating and cooling periods. Otherwise, the checkerwork will overheat at a sufficiently high altitude, which will make the operation of the hot-blast stove irrational and reduce the coefficient of heat use. The same must be done when using attachments with a larger specific heat transfer surface. When implementing high-performance attachments, it is necessary to change the design of devices or intensify their operation mode, reducing the time periods and increasing fuel consumption.

Calculations show that for the accepted initial data, the regular regime can be implemented when the duration of the blast is no more than 50 minutes, which corresponds to the value of the criterion \( K_{p1}=0.16 \). Given the generalized nature of the criterion, its value of 0.16 is the limit for the implementation of a regular regime for any type of checkerwork. It was also proved that with the appropriate selection of the ratio of the reduced costs and the time of the blowing and heating periods, it is possible to obtain an almost linear distribution of the checkerwork temperature along the height in quasi-stationary regime (Fig. 1), i.e. perform regular heating (cooling) regime of the checkerwork.

Parallelism of temperature lines allows us to formulate a condition for regularity of heating (cooling) modes of the checkerwork

\[ t_{12} - t_{11} = t_{21} - t_{22} \text{ or } K_{p1_1} = K_{p1_2}. \]  

(10)
Condition (10) allows to select such parameters of the hot-blast stove operation that you can get the maximum temperature of blast-furnace air at the lowest cost.

On the basis of equations (5) – (9), a criterion analysis of the operation of the checkerwork of blast-furnace air heaters was also carried out. In particular, the range of changes in the thermal characteristics of the checkerwork is determined, when there is a significant increase in the temperature of the blast-furnace air. Calculations have shown that it is advisable to use checkerwork with a specific surface area $f_0 = 0.025-0.1 \text{ m}^2/\text{kg}$, providing a heat transfer coefficient $\alpha = 30-60 \text{ W/(m}^2\text{K)}$; this will increase the temperature of blast-furnace air to $\Theta_{12} = 0.959 – 0.974$ (depending on the time of the blast period).

It should be noted that the vast majority of regenerative heat exchangers do not currently use a regular regime. The regime of their operation is far from optimal, while up to 15% - 20% of the checkerwork of blast-furnace air heaters is overheated up to the input temperature of the heating medium during the period. Approximately the same part of the checkerwork is supercooled to the input temperature of the cold coolant.

4. Conclusion
The operation of a regenerative heat exchanger can be described using similarity criterions derived from the analysis of differential equations of regenerative heat exchange under regular regime. Similarity criterions allow you to analyse the operating regime and design characteristics of the checkerwork without performing a large number of calculations. In addition, the analysis becomes more visual. Based on the similarity criterions, a method for selecting the operating mode of a regenerative heat exchanger at a given heating temperature of the heat transfer agent and a known checkerwork contraction is developed.

Using the proposed method, we can consider the operation of other regenerative heat exchangers. Based on similarity criterions, it is possible to calculate how the dimensions of regenerative heat exchangers will change when using high-performance checkerwork.

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Appendices
List of designations
$C$ – heat capacity of the checkerwork, J/(kg·K);
$C_f$ – heat capacity of the heat transfer agents, J/(kg·K);
$f_0$ – specific surface area of the checkerwork, m$^2$/kg;
$H$ – height of the checkerwork, m;
$K_{p1}$, $K_{p2}$, $K_{p3}$, $B_i$ – similarity criterions;
$m$ – massive coefficient of the checkerwork;
$Q_f^*$ – reduced flow rate of the heat transfer agents, m$^3$/(m$^2$·s);
$t$ – average temperature of the checkerwork, °C;
$t_f$ – temperature of heat transfer agent at the moment of time, °C;
$t_f1$ – temperature of heat transfer agent at the entrance of the checkerwork, °C;
$t_f2$ – temperature of heat carriers at the exit of the checkerwork, °C;
$x$ – coordinate of the vertical axis;
$\alpha_f$ – heat-transfer coefficient, W/(m$^2$·K);
$\rho^*$ – density of the checkerwork, kg/m$^3$;
$\tau$ – time, s;
$\Theta$ – average temperature drop between the heat transfer agent and the checkerwork temperature, °C.

Indexes:
$f$ – the number of the heat transfer agent: $f=1$ – cold heat transfer agent, $f=2$ – hot heat transfer agent.
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