UDC 669.162.231.38

Experimental Determination of the Effect of Pressure on the Gas-Coolant Heat Regenerative Checker

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The effect of pressure of the gas-coolant heat exchanger of the regenerative checker is investigated. It is shown that increasing the gas pressure coolant leads to intensification of heat exchange between the gas and the checker. With the use of similarity theory, physical and mathematical modeling of the expediency of increasing the gas pressure in the coolant-regenerative real heat exchangers in particular blast heater was explained.

Keywords: REGENERATIVE CHECKER, EXPERIMENTAL RESEARCH, MATHEMATICAL MODEL, GAUGE PRESSURE, EXCHANGE GAS, HEAT-TRANSFER COEFFICIENT, HEATING OF CHECKER, HEATING OF BLAST, REYNOLDS

Introduction

Previously, the authors developed a mathematical model of assessment the thermal state of blast nozzle heater operating in different modes [1] (hereinafter - the model) that takes into account both convective heat transfer and radiant. The simulation results showed that with increasing pressure gas coolant increases its mass flow, and thus increases the rate of heating of the nozzle, thus reducing the time of its heat. To confirm the results of a practical model of an experimental study (hereinafter - the experiment) regenerative nozzle (hereinafter - the nozzle), working under pressure in the heating mode, the authors constructed an experimental apparatus (hereinafter - the setting). The increase in the rate of heating the nozzle with increasing gas pressure, coolant was confirmed [2].

The aim of this study is to determine the effect of pressure on the gas-coolant heat exchanger nozzles real regenerative (hereinafter - the regenerator), in particular, the domain heater, based on the results of experimental studies using the similarity theory and calculations using the model.

Methodology

The main condition of the experiment was equal the actual volumetric flow of air at different excessive pressures of gas coolant. With increasing pressure gas coolant increases its density and, while maintaining its velocity, per unit volume in the same time brought in more gas to the nozzle, and thus more heat.

The investigated nozzle described in [2] was located in a quartz tube diameter of 35 mm and a height of 150 mm. The internal volume of the tube was filled with fireclay brick (particle size 5-8 mm). Regenerator, considered by the authors in [3], which is modeled, is a nozzle of height of 30 m and 8.5 m in diameter, consisting of curved elements in the form of hexagonal cylindrical channels of diameter 30 mm, which corresponds to the parameters of the real blast heater.

Necessary and sufficient conditions for the similarity of the thermal process of heating of nozzles according to [4] are:

- geometric similarity;
- similarity of the traffic flow of liquid or gas at the entrance;
- similarity of physical properties at similar points in the model and the sample (constant density ratio, viscosity coefficients, etc.);
- similarity of temperature fields on the borders;
- comparability of the values defining the similarity of numbers (Re, and Pr) in a single homologous cross-section.

Results and Discussion

The geometric similarity of the investigated nozzles is observed in the case [5], if

$$\frac{s_1}{d_1}=\frac{s_2}{d_2},$$

where d - determining geometric size of the nozzle , m; s - the equivalent thickness of the nozzle element [7, 8], m; $\frac{s_1}{d_1}$ - relative thickness of the regenerator nozzle elements [3]; $\frac{s_2}{d_2}$ - the relative thickness of the particle nozzle of the experimental setup [2].

The equivalent thickness of the nozzle element is calculated by the formula [6]

$$s_1=\frac{\delta}{2}\left(1+\frac{\delta}{2d_1}\right),$$

where δ -thickness of the elements of the nozzle, mm.

For the selected in [3] element of packing $\delta=19$ mm, therefore,

$$\frac{s_1}{d_1}=\frac{12,5}{30}=0.42\cdot$$

The equivalent diameter of the channels for the bulk of the layer used in the experimental setup is defined as follows [7]

$$d_2=d_{\text{ш}}\cdot\frac{2}{3}\cdot\left(\frac{\varepsilon_2}{1-\varepsilon_2}\right),$$

where $d_{\text{ш}}$ - equivalent diameter of the particle of the bulk layer, m; ε_2 - bulk porosity of the layer.

In order to determine average value of porosity two methods were used. The first method is based on determining the volume occupied by the the nozzle material, based on its mass and density of nozzles used to fire clay. To determine the porosity of the second method [7] we used the ratio of the volumes of water, poured into a container until the filling nozzle, the total volume occupied by the nozzle. The average porosity of the layer was $\varepsilon_2=0.39$, which corresponds to studies [8]. This value was used in subsequent calculations.

Specific surface heating the nozzle model was determined by the formulas [6] for the bulk layer

$$f=\frac{6\cdot(1-\varepsilon)}{d_{\text{ш}}\cdot K_{\text{ф}}},$$

Given that the specific surface area for the nozzle heating with solid channels is defined as

$$f=\frac{4\cdot d}{(d+\delta)^2},$$

value of thickness of the equivalent brick can be defined as follows

$$\delta=\sqrt{\frac{4\cdot d\cdot d_{\text{ш}}\cdot K_{\text{ф}}}{6\cdot(1-\varepsilon)}}-d\cdot$$

The relative thickness of the the nozzle elements of the experimental set-up

$$\frac{s_2}{d_2}=\frac{1.08}{2.77}=0.39\,.$$

The values of the relative thickness of the nozzle elements of the real heater and the experimental setup are comparable, so the geometric similarity is observed.

By the influence of the parameter $\frac{L}{d}$ (L – distance from the entrance to the nozzle to a level that was studied, m), in accordance with the recommendations of [5] is neglected, since the value of the heat transfer coefficient varies only slightly at the entrance to the nozzle, and then it takes the stable value. Besides the influence of the Prandtl number is also immaterial effect on the coefficient of convective heat transfer [5]. Effect of physical constants in the similarity criteria with sufficient accuracy can be considered an appropriate choice of the reference temperature [5].

For all these reasons, the similarity of the processes of heating is ensured by the equality of numbers Re in the model and the actual attachment of the regenerator, and the dependence of the coefficient of heat transfer in regenerative nozzles can be represented by the equation

$$Nu=f(\mathrm{Re}),$$

where Nu - Nusselt number, Reynolds number.

To calculate the heating nozzle of the experimental setup and the actual regenerator selected the following criterial equation [6, 8]

$$Nu=0,106\cdot\mathrm{Re};\quad \mathrm{Re}\le 200;$$

$$Nu=0,61\cdot\mathrm{Re}^{0,67};\ \mathrm{Re}>200.$$

Calculations of the coolant pressure effect on the operation of regenerative nozzle preceded its check on the results of experimental studies on the physical model.

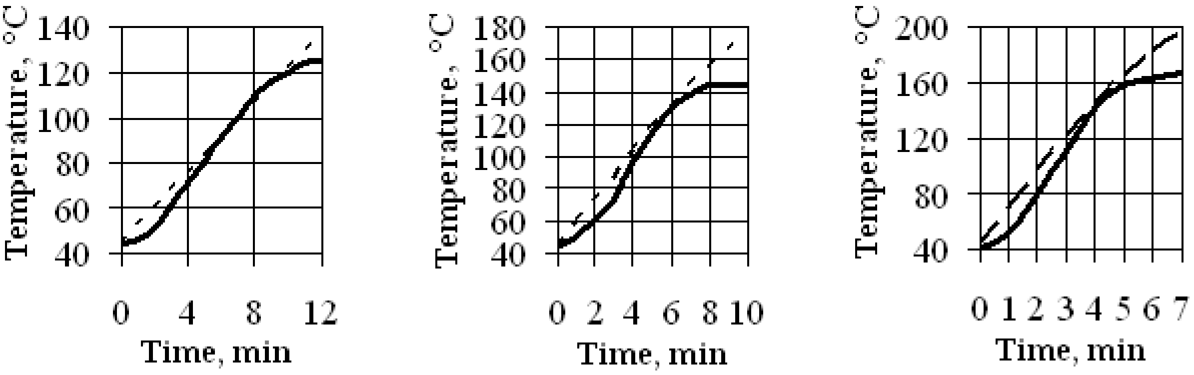
In order to determine adequacy of the calculation results of the model [1] at its entrance were substituted the following initial parameters of the pilot study [2]:

- geometric dimensions of the investigated nozzles;
- change in temperature of the gas-coolant during the experiment at the entrance to the nozzle;
- initial temperature distribution of the

nozzles;
- pressure and flow rate gas-coolant.

Figure 1 shows graphs of the temperature control point (top nozzle) [2]. The coincidence of the results obtained by mathematical modeling and experimentally is clear. This is confirmed by the values of the correlation coefficient is not lower than 0.97.

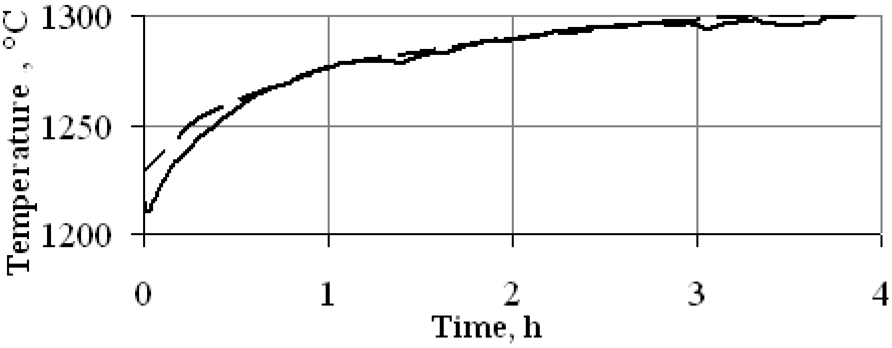
Using the model we also investigated the process of heating nozzle of real heaters operating a blast furnace of one of the steel plants in Ukraine (**Figure 2**). The initial parameters substituted in the model simulation are similar to the pilot study.



a) 0 кPa; b) 120 кPa; c) 240 кPa

(-) – experimental data, (---) – calculated data (model)

Figure 1. Changes in temperature at the reference point for various values of gas- coolant overpressure



(-) – real heaters, (---) – calculated data (model)

Figure 2. The temperature of the dome of the real heater

The temperature of the dome is virtually the real data (**Figure 2**).

The table below shows some of the parameters of the experimental setup nozzles and real regenerator and heat transfer for different values of the pressure of gas coolant.

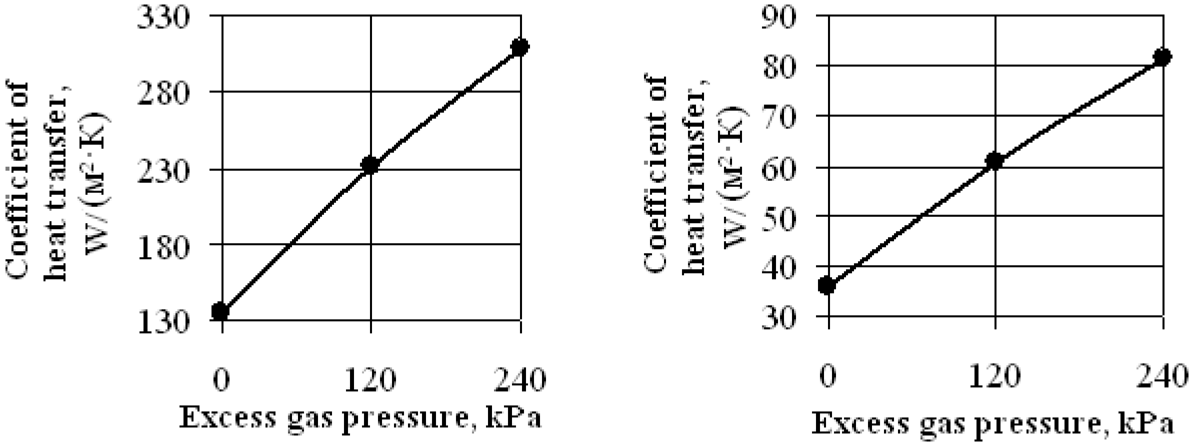
Comparable values of the order of the Reynolds number for the study and the real regenerator confirms the effect of pressure on the gas-coolant on heat transfer in a real regenerator.

With increasing gas pressure, a decline in the coolant nozzle heating time and the decrease of temperature values at a height of nozzle are observed [9]. Accumulated heat nozzle is reduced, which is the reason for the reduction of time of heating the blast, as given parameters of hot-blast (flow and temperature) remain unchanged. The rate of heating of the blast remains constant. Parallel to it increase in the coefficient of heat transfer and mass flow rate of of gas-coolant is observed (**Figures 3, 4**).

Figure 5 shows graphs of the temperature control point for various values of excess pressure of gas-coolant for the pilot study (**Figure 5a**) and a real regenerator (**Figure 5b**). By reference point it was chosen: the end of the nozzle of the unit (6th min of the experiment, **Figure 5a**) and a point located at a distance of 5 meters from the beginning of the nozzle (30 min heating of nozzle, a real regenerator, **Figure 5b**). As can be seen from the graphs, the temperature of the reference point increases with increasing pressure of gas coolant.

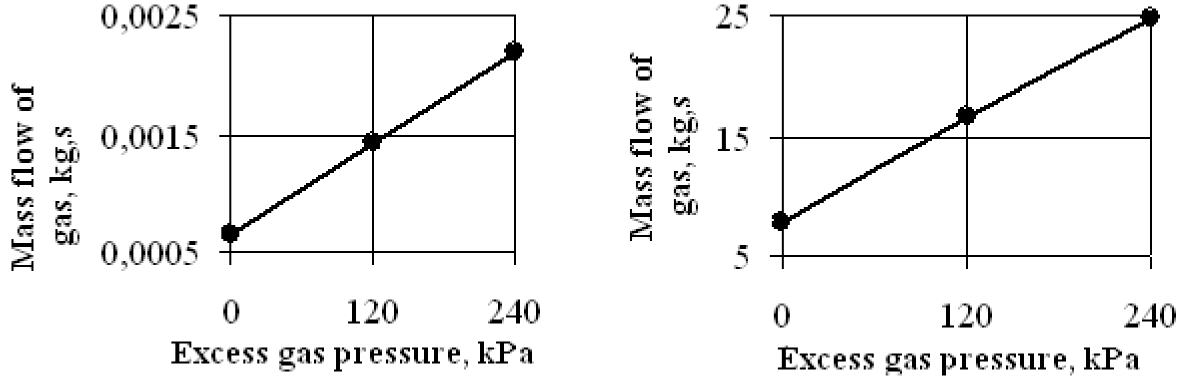
Table 1. The main parameters of nozzles and heat transfer

Parameter	Unit	Experiment			Regenerator		
Excess gas pressure	kPa	0	120	240	0	120	240
Equivalent diameter of the ball	m	0.0065			0.07453		
Sectional area of nozzles	m^2	0.001225			56.7		
Porosity	m^3/m^3	0.39			0.376		
Gas rate	m/s	1.17	1.17	1.17	0.75	0.75	0.75
Average gas temperature	°C	172.03	171.86	173.57	833.6	859.07	904.44
Density of the combustion products	kg/m^3	0.74	1.63	2.51	0.29	0.64	0.99
Volumetric flow rate	m^3/s	$143\cdot10^{-5}$	$143\cdot10^{-5}$	$143\cdot10^{-5}$	42.525	42.525	42.525
Mass flow rate of gas	kg/s	$65\cdot10^{-5}$	$142\cdot10^{-5}$	$218\cdot10^{-5}$	7.767	16.583	24.589
Thermal conductivity	$\frac{W}{m\cdot K}$	0.0347	0.0347	0.0347	0.0806	0.0806	0.0806
Kinematical viscosity	$\frac{m^2}{s}\cdot10^5$	2.92	1.33	0.865	14.4	6.55	4.24
Heat transfer coefficient	$\frac{W}{m^2\cdot K}$	135.63	230.02	307.92	35.8	60.72	81.28
Reynolds criterion	–	260.9	574.12	885.25	387.94	853.46	1319
Nusselt criterion	–	25.37	43.04	57.53	33.1	56.13	75.14
Heat accumulated by the nozzle	J	$8.921\cdot10^3$	$8.067\cdot10^3$	$7.591\cdot10^3$	$1.391\cdot10^{12}$	$1.255\cdot10^{12}$	$1.098\cdot10^{12}$
Time of heating nozzle	h	0.23	0.17	0.12	3.9	1.4	0.8
Rate of heating nozzle	J/h	$38.233\cdot10^3$	$48.407\cdot10^3$	$65.070\cdot10^3$	$0.356\cdot10^{12}$	$0.896\cdot10^{12}$	$1.373\cdot10^{12}$
Heat received by blast	J	–	–	–	$1.306\cdot10^{12}$	$1.174\cdot10^{12}$	$1.021\cdot10^{12}$
Heating time of blast	h	–	–	–	2.69	2.41	2.1
Heating rate of blast	J/h	–	–	–	$0.49\cdot10^{12}$	$0.49\cdot10^{12}$	$0.49\cdot10^{12}$



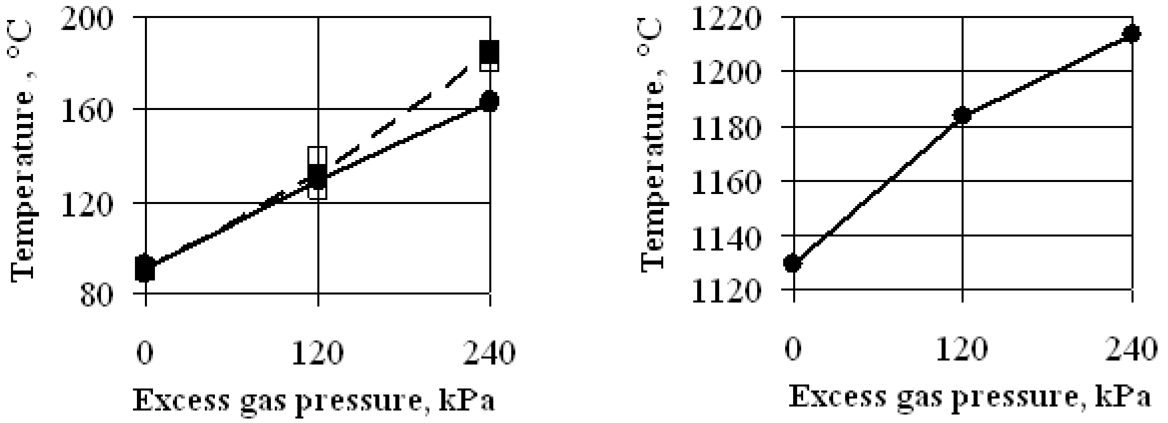
a) experiment b) real regenerator (model)

Figure 3. The dependence of the coefficient of heat transfer from the excess pressure of gas-coolant



a) experiment b) real regenerator (model)

Figure 4. The dependence of the mass flow of gas from the excess pressure of gas-coolant



a) experiment b) real regenerator (model)

(-) experimental data; (---) calculated data (model)

Figure 5. Temperature of the reference point for various values of excess pressure of gas-coolant

Temperature of the unit nozzle in the reference point after a fixed period of time increases with the increase of pressure of gas-coolant (**Figure 5a**). The tendency to an increase in temperature at the reference point for a real regenerator with increasing pressure of gas-coolant is retained (**Figure 5b**).

Conclusions

1. Similarity criteria for comparing the heating mode of the experimental setup nozzles

and real regenerator are determined and proved. The results of the comparison suggest that the impact of pressure of the gas-coolant in the real regenerator - a blast furnace air heater - will be the same.

2. Comparison of experimental data with the results of calculations by the mathematical model developed earlier by the authors [2, 3], confirmed its adequacy for the experimental conditions and real regenerator.

3. It is shown the qualitative influence of pressure of the gas coolant on the nozzle heating mode. With an increase of gas-coolant pressure, after the heater of a blast furnace is released at the quasistationary mode, the value of the ballast heats of the nozzle increases. The amount of heat accumulated in the nozzle during the period of heating is somewhat reduced (up to ~ 21% with excess pressure of the coolant 240 kPa), with a reduced time of heating of the nozzle increases (in ~2.7 times at pressure 120 kPa and ~ 4.8 times at pressure 240 kPa). The heating time of the blast decreases slightly (~ 22% with increasing pressure up to 240 kPa), while maintaining the rate of heating.

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* Published in Russian

Received January 13, 2012

Экспериментальное определение влияния давления газа-теплоносителя на нагрев регенеративной насадки

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Исследовано влияние давления газа-теплоносителя на нагрев насадки регенеративного теплообменника. Показано, что повышение давления газа-теплоносителя приводит к интенсификации теплообмена между газом и насадкой. С использованием теории подобия, физического и математического моделирования обоснована целесообразность применения повышения давления газа-теплоносителя в реальных регенеративных теплообменниках, в частности доменных воздухонагревателях.