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THE DYNAMIC CHARACTERISTICS RESEARCH OF COMPACT HEAT REGENERATOR USED IN REGENERATIVE BURNERS FOR METALLURGICAL HEATING FURNACES

BADANIA CHARAKTERYSTYK DYNAMICZNYCH KOMPARTOWEGO REGENERATORA CIEPŁA PALNIKÓW REGENERACYJNYCH DLA METALURGICZNYCH PIECÓW GRZEWCZYCH

The gas burner is a device which the main aim is delivering the right number of gas fuel and oxidizing agent and it also has to ensure flame stabilization. The difficult controlling problem appears when the modern and compact high temperature regenerative burners are used. The controlling difficulties in those systems are related to the large number of burners and a periodic change (with high frequency) of temperature field which depends on such parameter as reversion time. The knowledge of the dynamic and static regenerator characteristics makes easier the programming of automatic control and regulation process and helps in creating the new regenerator filling construction in order to improve the heat transfer intensification and the furnaces efficiency. Based on research results the paper presents the selected data research dealing with the dynamic and static regenerator characteristic. The measurement of quick-changing fluctuating thermal field and the way of the temperature sensors selection have been indicated. The regenerator starting state and pseudo-steady state characteristics have also been presented. Finally the qualities of the regenerator and the economic income have been expressed.

Keywords: regenerator, regenerative burner, regenerative characteristic, metallurgical furnaces

Palnik gazowy jest urządzeniem, którego głównym zadaniem jest dostarczanie do procesu spalania odpowiedniej ilości paliwa i utleniacza oraz stabilizacja płomienia. Poważny problem sterowania palnikami pojawia się w nowoczesnych, kompaktowych, wysokotemperaturowych palnikach regeneracyjnych. Trudności w sterowaniu takimi systemami związane są z dużą ilością zainstalowanych palników jak również z szybkimi, periodycznymi zmianami pola temperaturowego, które zależy między innymi od parametru zwanego czasem rewersji. Znajomość statycznych i dynamicznych charakterystyk regeneratora ułatwia programowanie automatycznego sterowania i regulacji procesów, jak również jest bardzo pomocna podczas projektowania konstrukcji nowego wypełnienia regeneratora pod kątem poprawy intensyfikacji transportu ciepła i sprawności pieca. Na podstawie badań zaprezentowano wybrane przykłady charakterystyki dynamicznej i statycznej regeneratora. Poruszono problem pomiaru szybkozmiennego pola temperatury i doboru czujników pomiarowych. Zaprezentowano również charakterystykę rozruchową regeneratora i stanu pseudo-ustalonego. Finalnie przedstawiono wykorzystanie charakterystyk regeneratora w celu określenia jego jakości i ekonomicznych korzyści jego zastosowania.

1. Introduction

The modern regenerative burner allows, directly in the burner, the enthalpy recovery of exhaust outflowing from the working chambers furnaces. The integrated construction of regenerative burners allows faster combustion air preheating, due to the location of the exchanger in the burner. The exhaust temperature losses reach more than 200 K at the central regenerator system, because of the exchanger location or poor insulation the air distribution system. The integrated regenerative burners system is characterized by lower temperature losses and higher factor the air preheats. The lower combustion air temperature is due to the limitations of burner dimensions. The regenerative system is able to preheat the air to the very high temperature - much higher compared to other exchanger types [1], [2], [3]. A temperature of more than 1000°C is obtainable in this system as indicated by some literature materials [4], [5]. The High Preheated Air Combustion (HPAC) technology has already been applied in different kinds of furnaces by means of different fuel type such as gas, oil and even coal and biomass. This new technology provides most effective heat recovery, reduction of energy consumption, cleaner and cheaper production. A few cases could also be found in the literature which proves that this system is characterized by the lower investment costs compared to the conventional ones [6], [7]. Possibilities which can be obtained if the high preheating system is installed are as follows: uniform the chamber temperature $T_{furnace}$-T_{air} <100 K, effective heat flows increasing, energy savings: (40-60) %, installation size decreasing – about 30%.

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2. Operation of regenerative burners

The present situation in the regenerative system development tends towards to resignation of one, big, central regenerator and application the bigger number of burners with the individual regenerators connected to them. That solution is economically justified because of lower energy losses in the air distribution system and higher combustion air preheating. Generally the burners work in pairs in the modern regenerative systems. Moreover, another solution is also known where the regenerative burner is able to work independently. At the time, the regenerator is as a compact and sectional filling in that solution what allowed to avoid connection the burners in pairs. The sections are grouped in the heated and cooled parts [8]. Mostly, in the regenerative system, there is no the high chimney and the short chimney is also not able to work, thus the forced system is needed. Therefore the flue gases are received by the fans.

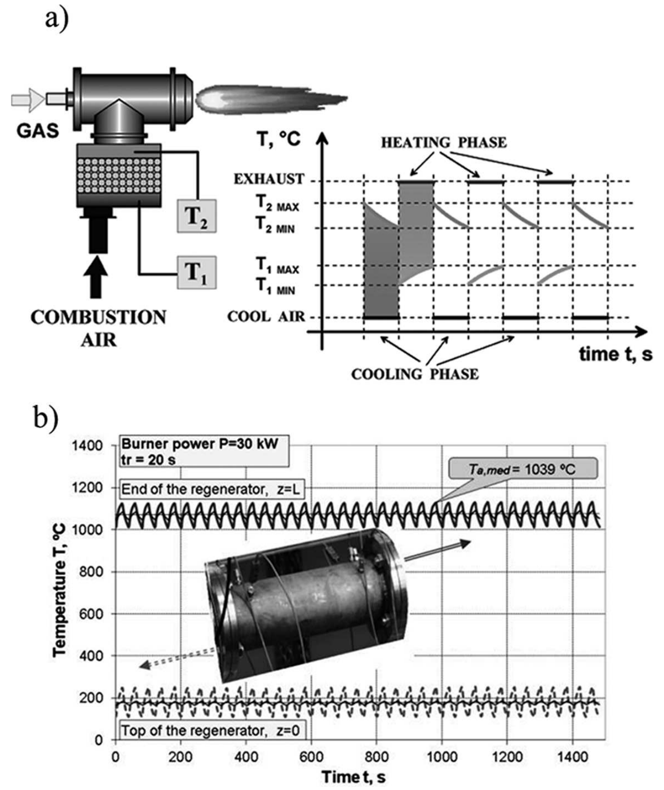

Fig. 1. The temperature pseudo-steady characteristics of regenerator – experimental research

The regenerator is heated and cooled alternately during the each period, as well as the fluids flow direction is changed in each period. The whole process is repeated according to the reversion time which is usually taken in the range from 30 to 240 s (it strongly depends on the power burner and regenerator solution). Therefore it is said that the regenerator works in an unsteady state. Its temperature as well as flowing fluids temperature are always a time and space function. But the most important is outlet temperature of fluids for users, particularly the outflow combustion air temperature. That preheated air temperature, in the regenerator, changes during the whole period from maximum to minimum as in Fig.1. The highest temperature is at the beginning of cooling period and the lowest is at the end of one. The average temperature can be specified for fluids in the outflow when the pseudo-steady state is achieved and then this temperature can be used for different comparisons.

3. The equivalent time-constant for the measurement of rapidly changing temperatures in the regenerator

Temperature is the one of the most important parameters which has to be controlling in the industrial process because of technology. The metallurgical, high temperature heating furnace with regenerative burners [9],[10] is a good example to point the problem appearance. The measurement problem of rapidly changing temperature of hot and cold fluids flows alternately through the regenerator at short intervals is very important. Periodicity of system operation characterized by the interval less than 30 s is quite significant due to the dynamical converting error of sensors. The prepared method of approximation dynamic properties of thermometric sensors by the inertia of the first row with the equivalent time-constant τ_E (1) has a great practical importance [11]. This method provides an easy way to assess the impact of construction and thermophysical parameters of the sensor materials and the heat transfer coefficient, from fluid to the thermocouple, on the thermocouple dynamic properties. The approximation of temperature characteristic $\Theta_A(\tau)$ is defined by

$$\Theta_A(\tau) = 1 - \exp\left(-\frac{\tau}{\tau_E}\right). \tag{1}$$

The two simple and corresponding formulas for τ_E calculation obtains when the Laplace integral transformation L is used for definitional equation. These formulas are very useful for experiments (2) and for analytical research (3), were $\Theta(\tau, \xi)$ is the reduced weld temperature and $G(s, \xi)$ is the operator transmittance the sensor.

$$\tau_E = \int_0^\infty [1 - \Theta(\tau, \xi)]\, \mathrm{d}\tau. \tag{2}$$

$$\tau_E = -\lim_{s \to 0}\left[\frac{1}{G(s,\xi)} \frac{\partial G(s,\xi)}{\partial s}\right]. \tag{3}$$

Comparison the dynamic characteristic of thermocouple and its model with equivalent constant time is presented in Fig. 2. According to definition, the equivalent constant time is a measure of area between the horizontal asymptote and the displacement characteristic of sensor. Therefore, the τ_E is proportional to the increase the internal energy of the sensor in the transient state. The use of constant $\tau_{E,}$ to approximate the dynamic properties of the sensor, gives immutability of the increase in the internal energy in its simplified dynamic model. Furthermore, in the selection of the temperature sensor is a rule (4) – limit the frequency of the sensor processing ω_{gr} have to be larger than frequency ω of changes the measured temperature.

$$\omega_{gr} = \frac{1}{\tau_E} \geqslant \omega \tag{4}$$

The knowledge about the equivalent constant time is helpful and necessary for the determination of reversion time for the regenerative switching valve. Incorrect selection of this time gives erroneous temperature measurements of preheated air in the regenerator.

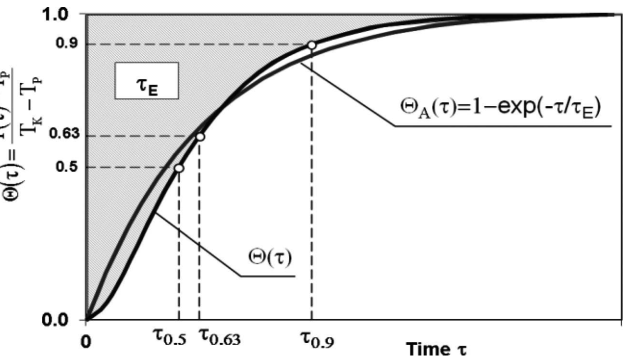

Fig. 2. Impulse performance of the shell thermoelectric sensor: $\Theta(\tau)$ – operating characteristic, $\Theta_A(\tau)$ – approximation characteristic, $T(\tau)$ – measuring junction temperature; T_p, T_k – initial and final temperature of measuring junction, where T_p =0

4. The dynamic characteristics of regenerator – research results

Research the dynamic characteristics of regenerator are connected to static characteristics and they show the regenerator transition form from one fixed temperature level to another one. Very specific is a start-up characteristic presented in Fig. 3a (15 s of reversion time and fluids flow for 50 kW burner power). Figure demonstrates as though the nature of regenerator behavior. The two time ranges can be distinguished on the graph – starting phase and pseudo-steady state. Whereas, the most important is an average temperature of preheated

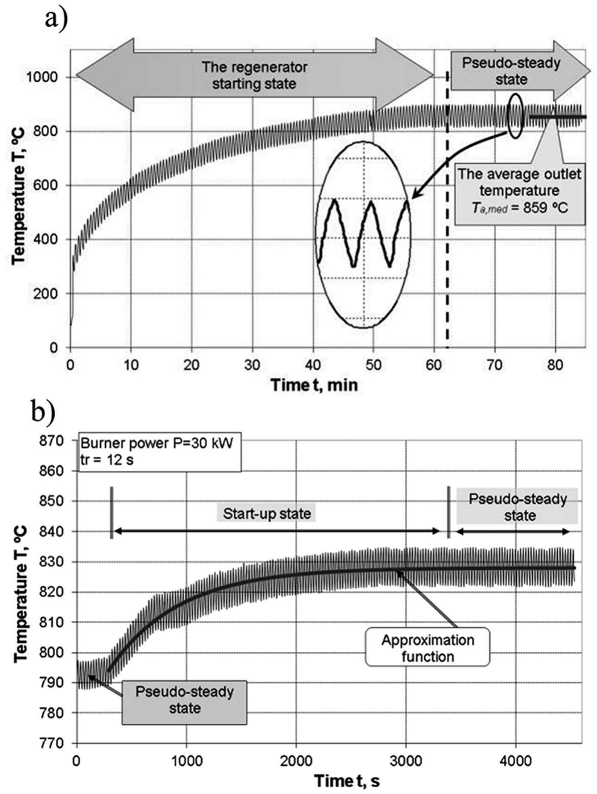

Fig. 3. Characteristic of regenerator (experiment): a) Start-up; b) Dynamic

air which appears in the pseudo-steady state what is indicated as well. This course type of the dynamic characteristic is basis to determine the average temperature ($T_{a,med}$) of the preheated air [8]. The dynamic characteristic of the regenerator filling is very important for the quality of steering processes, because it gives a lot of informations needed for the right settings of automation equipment. The regenerative characteristic during transition between two pseudo-steady states is presented in Fig. 3b. Factor causing the change was in that case of closing the window of furnace chamber.

5. The pseudo-steady characteristics of regenerator – research results

The average temperature can be specified for fluids in the outflow when the pseudo-steady state is achieved and then this temperature should be used for comparisons. The research of pseudo-steady characteristic ought to be conducted for different temperature levels of chamber, reversion times and values of fluid flows. The knowledge about static characteristics is very important and usefully for the determination of the filling temperature fluctuations and fluid flowing through it, heated air average temperature for different reversion times, regenerator temperature distribution and the optimum switching frequency the phase of regenerator.

The pseudo-steady characteristic is presented in Fig. 1b and it is obtained for the 20 s of reversion time and fluids flow for the burner power of 30 kW. The more important is the preheated air temperature from the engineering point of view because of steering of heating process. Therefore, the temperature characteristic for the fluids only on the end of the regenerator may be presented in charts.

6. Quality the regenerator

The regenerator quality is represented by the relative fuel saving Φ, relative air preheat κ and combustion-system efficiency η [2]. The last parameter is obtained from the energy balance which may be expressed as

$$\dot{H}_f + \dot{H}_{air} - \dot{H}_{exh} = \sum \dot{Q}, \tag{5}$$

where: $\dot{H}_f$ – fuel enthalpy flow, W; $\dot{H}_{air}$ – enthalpy flow of the preheated air, W; $\dot{H}_{exh}$ – enthalpy flow of the exhaust leaving the furnace, W; $\sum \dot{Q}$ – used or lost heat flow, W.

Converting (5), it follows (6) where the denominator is defined as combustion-system efficiency η.

$$\dot{H}_f = \sum \dot{Q} \cdot \left(1 + \frac{\dot{H}_{air}}{\dot{H}_f} - \frac{\dot{H}_{exh}}{\dot{H}_f}\right)^{-1}. \tag{6}$$

Based on research results (static and dynamic characteristics) the regenerator quality has been checked. The relative fuel saving factor shows that the considered regenerator construction is quite an interesting solution, being able to reduce the fuel consumption considerably. For this case, the relative fuel saving factor has a range 48-51% (dependent on the material type) and this is a very satisfactory value. The relative air preheat factor has been calculated according to the air temperatures in the regenerator outlet. The range of this factor has been noted between 87 and 93% – the average factor for a recuperative system is about 30%. The combustion-system efficiency has been also calculated and it was about 83-86%.

7. Profits the regenerative system

The preheating of combustion air up to the high temperature level is the main target of using the regenerator. It is known that this is one of the ways to obtain the reduction of fuel consumption and the CO_2 emission. The main benefits of air preheating with reference to the results are presented below. The combustion air temperature increased from 500°C up to 1100°C has been considered. The chamber furnace has been examined: furnace power 8.5 MW, productivity 10 000 kg/h, exhaust temperature 1200°C.

The reduction in fuel consumption of 29% has been obtained. Additionally, the furnace efficiency increase (up to 17%) has been noted, as presented in Fig. 4. The fuel saving with reference to the furnace workday numbers per year can be calculated. The European average fuel price of 0.042 €/kWh has been assumed [12]. Each non-emitted tonne of CO_2 can be sold at the carbon market like a CER credit units. The annual average of 4€/CER can be taken into calculations [13].

The fuel saving of $1.38 \cdot 10^6$ m_N^3 (1024 Mg) or about € 556400 has been obtained for 250 days of furnace work. The reduction of fuel consumption has resulted in the limitation of CO_2 emissions up to 27.4% compared to the emission for 500°C air preheat. It means that about 2620 Mg of CO_2 would not have been emitted into the environment when the combustion air temperature was raised from 500°C up to 1100°C. This value can be converted to CER which would give an additional € 10500.

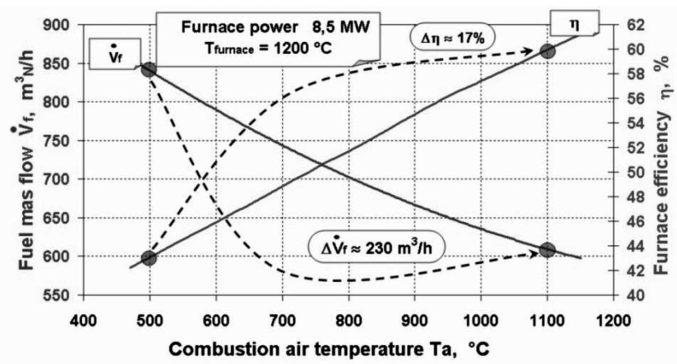

Fig. 4. The fuel consumption and the furnace efficiency as a function of the air preheat

8. Conclusion

The using of equivalent time-constant during the thermocouple diameter selection for measurement of rapidly changing temperature has been considered.

The regenerator quality for obtained results (dynamic and static characteristics) has been checked. All quality factors have achieved a very high value. They guarantee a significant fuel saving and CO_2 emission reduction.

The 8.5 MW chamber furnace case has been considered to demonstrate the use of regenerative characteristics. The furnace was working 250 days per year in one of the assumptions. Increasing the combustion air temperature from 500°C up to 1100°C decreased the fuel consumption and the CO_2 emission as well. Generally, the fuel saving as big as 1024 Mg has been obtained. It would mean that 2620 Mg of CO_2 were not emitted into the environment. Considered additional CER credit units the total savings of almost € 567000 could be achieved and it should be interesting for industry to consider.

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