ANALYSIS OF EFFICIENCY AND RELIABILITY OF BLAST-FURNACE PROCESS WASTE HEAT RECOVERY SYSTEMS

1. Introduction

To ensure the blast air heating at blast furnace, the unit, which consists of 3–4 hot blast stoves, is commonly used. Hot blast stoves are regenerative type heat exchangers that filled with checker-works with extended heat transfer surface. These devices work cyclically. During the first operation cycle, named the gas period, in the hot blast stove burner fuel is burned, waste gases pass through checker-work and heat it up. During the next operation cycle, named blast period, cold air passes in the opposite direction, takes away accumulated heat and then enters the blast furnace [1].

The hot blast stoves fuel is the blast furnace top gas, usually enriched by the additives of much higher calorific value, such as natural gas or coke oven gas. These additives are used to improve fuel energy value and rising the temperature under the hot blast stove dome to 1300–1450 °C. At the same time they are highly expensive fuel and energy resources, which consumption can be reduced through the waste heat recovery for the purpose of hot blast stoves combustion components preheating [2].

Development of methods and means of the hot blast stoves waste heat recovery equipment is an actual problem in terms of high cost of fuel and energy resources. In addition, using of heat recovery units is the key of negative effects of industry on the environment decreasing. Precise calculation methods of heat recovery units will improve their reliability and working time.

2. The object of research and its technological audit

The object of research is a hot blast generating system, which consists of three hot blast stoves with a remote combustion chamber and with sequential operation mode. The project temperature under the hot blast stove dome was 1350 °C. Excess air factor: α = 1.08. The duration of heating cycle (gas period) was 1.83 hours, cooling cycle (blast period) – 1 hour [3].

The mixture of blast furnace top and coke oven gases was considered as fuel for hot blast stoves [4]. Hot blast stove fuel temperature was 50 °C. The compositions of blast furnace top and coke oven gases are contained in Tables 1, 2.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition of dry blast furnace top gas</td>
</tr>
<tr>
<td>Composition of gas in volume ratio, %</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
<tr>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition of dry coke oven gas</td>
</tr>
<tr>
<td>Composition of gas in volume ratio, %</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
<tr>
<td>2.6</td>
</tr>
</tbody>
</table>

One of the problem areas of the system is the presence of waste gases discharged after hot blast stoves with temperature 200–400 °C. This heat can be recycled and used for combustion air or fuel preheating. Using waste gases heat potential, fuel consumption in cost of production and a negative burden on the environment can be reduced.

Though nowadays waste heat recovery systems are operating, but the methods of analysis of their performance, which must be suitable for their design, maintenance or upgrading stages, need for improvement and refinement.

3. The aim and objectives of research

The research aim is an improvement of hot blast stove efficiency via waste gases heat recovery for their combustion components preheating.
To achieve this aim it is necessary to solve the following problems:
1. Determine the initial data for the calculation of waste heat recovery system.
2. Apply the author’s mathematical model and create a software and computer complex for selected exchanger configuration and specified operating conditions.
3. Get a series of calculated results to assess the effectiveness and reliability of the chosen model of recuperative exchanger.

4. Research of existing solutions of the problem

Evaluating the potential of process sites for waste heat recovery is described in [5]. In addition to the above waste gases heat recovery is considered as one of the promising ways to develop the metallurgy industry [6]. 18 units for hot blast stoves waste gases heat recovery were installed in Europe [7]. The procedures and results of the evaluation of the effectiveness of the hot blast stoves waste gases heat recovery system based on the heat pipe heat exchangers are described in [8]. Description of designing and analysis of waste heat recovery system, which is also based on using of the heat pipe heat exchangers can be found in [9], at the same time there observed that as hot blast stove waste gases heat recovery units can be used other various heat exchangers. For example, in [10] an application opportunity of compact regenerator as heat recovery unit is observed and calculation of such heat exchanger is provided. The comparative characteristic of miniregenerators with ball and tubular checker–works is performed in [11]. In the source [12] the latest model of the heat pipe heat exchanger is described, and in [13] performed and explored completely new cylindrical heat exchanger, comprising four coaxial tubes, this is a prospect heat pipe heat exchanger. [14] refers to the ability and efficiency of recuperative heat recovery units application.

Hot blast stove waste heat recovery system in Ukraine was implemented at the first time at the blast furnace number 2 of metallurgical plant «Zaporizhstal» [15]. The system consisted of tubular recuperators, the first of which was used for air preheating, and the second – for hot blast stove fuel preheating via their waste gases heat recovery. But significant drawback system implementation was the lack of air heat exchanger reliability in the winter due to acid corrosion [16]. This indicates the presence of inconsistencies in the design and calculation methods improvement of this kind of equipment. In addition, the investigated sources refer to waste heat recovery systems efficiency, but do not provide accurate algorithms and methods of calculation for hot blast stove waste gases heat recovery systems, used for combustion components preheating.

5. Methods of research

5.1. Determination of initial data. Necessary initial data for hot blast stoves waste gases heat recovery systems calculation include:
- Hot blast stoves block parameters and fuel parameters.
- Regime parameters and composition of waste gases.
- The necessary level of air combustion preheating.
- Characteristics of waste heat recovery heat exchanger.

Hot blast stoves block parameters can be found in item 2.

Percentage of coke oven gas in the fuel mix ranged within 0–16 %. A temperature of combustion air supplied to the hot blast stove was considered for summer and winter periods for climate zone in Ukraine (3 °C, 33 °C).

Based on the methodology provided in [17], fuel combustion in the hot blast stove was calculated and a valid combustion air volume and combustion products value, waste gases composition in fractions of components were received.

Then, knowing the temperature under the hot blast stove dome (1350 °C), the temperature of the fuel (33 °C) and air (3 °C, 33 °C), interdependence of combustion air preheating from the share of coke oven gas in fuel was obtained from the heat balance equation of fuel burning (considered cold and warm period). The method of calculation is presented in [18].

According to obtained data in [18], to provide the necessary calorimetric, and therefore the project, temperature under the hot blast stove dome, fuel with a share of 16 % coke must be burned.

With combustion air preheating, the share of coke oven gas can be reduced to 9–12 %. This requires combustion air preheating in the range of 178–224 °C. Since with combustion air preheating from 3 °C to 176 °C in the winter and from 33 °C to 222 °C in summer, coke oven gas share decreases from 16 % to 11 %. Stop using coke oven gas entirely due to combustion air preheating is not possible, because in this case air-preheating temperature should reach 780–953 °C.

In subsequent calculations considered fuel containing 10–12 % of coke oven gas.

Determination of the temperature and flow rate of waste gases and combustion components was conducted using the program «Regenerator», developed at the Department of Thermal Engineering and Energy Efficient Technologies of the National Technical University «Kharkiv Polytechnic Institute» (Ukraine) [19].

Waste gases temperature after one stove for all fuel composition is alike and ranges from 90 to 400 °C. Fuel consumption, air and waste gases rates for one hot blast stove are given in Table 3.

<table>
<thead>
<tr>
<th>Coke oven gas share, %</th>
<th>Period</th>
<th>Fuel consumption rate, m³/hour</th>
<th>Combustion air rate, m³/hour</th>
<th>Waste gases rate, m³/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Summer</td>
<td>74751,47</td>
<td>75274,73</td>
<td>139860,00</td>
</tr>
<tr>
<td>11</td>
<td>Winter</td>
<td>73632,05</td>
<td>75178,32</td>
<td>139860,00</td>
</tr>
<tr>
<td>12</td>
<td>Summer</td>
<td>73906,66</td>
<td>77158,55</td>
<td>140940,00</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>72595,66</td>
<td>76878,80</td>
<td>140940,00</td>
</tr>
</tbody>
</table>

As noted above, hot blast stoves are regenerative type heat exchangers and in this case are in sequential mode, and one after another heat the blast air. It means that it necessary to determine the temperature and flow rate of waste gases in common flue. According to the method
given in [20] waste gases regime parameters were obtained. Fig. 1 shows the waste gases temperature dependence on time after one hot blast stove and after mixing in common flue. Fig. 2 shows the waste gases rate dependence on time in common flue.

Fig. 1. The hot blast stoves waste gases temperature depending on time: \( t \) – temperature; \( \tau \) – time

Fig. 2. Waste gases rate depending on time after three hot blast stoves: \( V_g \) – rate; \( \tau \) – time

The average temperature of mixing is defined as the arithmetic mean of reference points of dust–like curve at Fig. 1, for waste gases with coke oven gas share of 11 % was 246 °C. Waste gases rate – 78 m/s.

5.2. Description of heat recovery unit configuration and fundamental principles of the mathematical model for its calculation. Bare-tube heat exchanger with the cross-counter current scheme of heat carrier medium movement was selected as the waste heat exchanger from a wide variety of heat exchange equipment, similar to that used at the first time in Ukraine. The heat exchanger is single-passed in the direction of waste gases flow and double-pass in the direction of air flow. The air is fed into the tubes, waste gases – between tubes. Heat exchanger scheme is shown in Fig. 3. Basic geometric characteristics of the surface heat exchanger are:

- outer diameter – 0,040 m;
- pipe wall thickness – 0,0016 m;
- tube spacing in rows – 0,070 m;
- tube raw spacing – 0,040 m;
- length of pipe of one pass – 3,52 m;
- number of tubes along tube nest length – 50;
- number of tubes along tube nest height of one pass – 50.

Method and algorithm for discrete calculation were proposed to simplify the procedure of determining of the effectiveness of heat exchangers with complex mixed heat carrier mediums scheme and uneven distribution of heat transfer and heat interchange parameters [21]. This method assumes that the elements of which exchanger is composed, are simple cross-flow single-pass scheme with full cross-mixing heat carrier mediums in the direction of their movement.

The calculation of each element was conducted by P-NTU-method [22], taking into account the modes motion of heat carrier mediums and basing on a number of dimensionless values, the use of which leads to a reduction of variables, and hence to a more comfortable computing.

Each tube of each section was divided into 10 elements (micro heat exchangers). Calculation scheme is shown in Fig. 4.

Fig. 3. Scheme of heat exchanger

Fig. 4. Calculation scheme

Thermal-physical properties of each component of waste gases and air are usually selected from tables [23]. But for computer calculations it was necessary to determine the functional dependence of thermal-physical parameters of waste gases components and air on temperature. With Excel charts were built thermal properties depending on temperature. Polynomial trend lines were added to them, reflecting the functional dependence of thermal properties on temperature.

In the proposed method effectiveness of each cross-flow element from Fig. 4 (micro heat exchanger) and heat carrier mediums temperatures at the outlet of elements were calculated taking into account the known expression of efficiency [22] for classical cross-flow schematic with full cross-mixing heat carrier mediums:

\[
P_{\text{eff}} = \frac{1}{\frac{1}{1-e^{-\text{NTU}_1}} + \frac{\text{NTU}_2}{1-e^{-\text{NTU}_2}}} - 1.\tag{1}
\]

Temperatures at the outlet of the elements can be found from the equations (2), (3), °C:
\[ t'_{\text{GAS}} = t'_{\text{AIR}} + P_{\text{AIR}} (t'_{\text{GAS}} - t'_{\text{AIR}}), \]
\[ t'_{\text{GAS}2} = t'_{\text{GAS}} - P_{\text{GAS}} R_{\text{AIR}} (t'_{\text{GAS}} - t'_{\text{AIR}}). \]

Average temperatures in the element (local), °C:
\[ \bar{t}_{\text{AIR}} = t_{\text{AIR}} + \bar{\theta}_{\text{AIR}} (t'_{\text{GAS}} - t'_{\text{AIR}}), \]
\[ \bar{t}_{\text{GAS}} = t_{\text{GAS}} - \bar{\theta}_{\text{GAS}} (t'_{\text{GAS}} - t'_{\text{AIR}}). \]

where \( \bar{\theta}_{\text{AIR}}, \bar{\theta}_{\text{GAS}} \) — relative average temperatures of air and waste gases in the element respectively:
\[ \bar{\theta}_{\text{AIR}} = P_{\text{AIR}} \left( \frac{1}{1 - e^{-NTU_{\text{AIR}}}} \right)^{\frac{1}{NTU_{\text{AIR}}}}, \]
\[ \bar{\theta}_{\text{GAS}} = P_{\text{GAS}} \left( \frac{1}{1 - e^{-NTU_{\text{GAS}}}} \right)^{\frac{1}{NTU_{\text{GAS}}}}. \]

The number of heat transfer units from air and waste gases sides in accordance with [22]:
\[ NTU_{\text{AIR}} = \frac{k F_{\text{AIR}}}{W_{\text{GAS}}}, \]
\[ NTU_{\text{GAS}} = \frac{k F_{\text{GAS}}}{W_{\text{AIR}}}, \]

where \( F_{\text{AIR}}, F_{\text{GAS}} \) — heat transfer area from the side of the heat carrier medium, which is heated, and the heat carrier medium, that heats, \( m^2 \); \( W_{\text{AIR}}, W_{\text{GAS}} \) — heat capacity rate of the heat carrier medium, which is heated, and the heat carrier medium, that heats, \( J/(s \cdot ^\circ \text{C}) \); \( k \) — heat transfer coefficient, \( W/(m^2 \cdot ^\circ \text{C}) \).

Characteristic parameters \( R \) and \( R \) were defined by equations:
\[ P_{\text{AIR}} = \frac{t'_{\text{AIR}} - t'_{\text{GAS}}}{t'_{\text{GAS}} - t'_{\text{AIR}}}, \]
\[ R_{\text{GAS}} = \frac{t'_{\text{GAS}} - t'_{\text{GAS}2}}{t'_{\text{GAS}2} - t'_{\text{AIR}}}. \]

It is impossible to make sequential element wise calculation of countercurrent scheme. Therefore refinement occurred simultaneously for all elements and values of temperature and pressure at the inlet of each element and the outlet of the exchanger. The interval-iterative method was applied.

6. Research results

Methodology, algorithms and software products created on the basis of a mathematical model allow to analyze processes in the heat exchanger for hot blast stoves combustion components preheating. Analysis of the effectiveness and reliability of the air preheater was performed at different initial temperatures of supplied air: +2 °C, +8 °C, +14 °C, +20 °C, +26 °C, +34 °C.

Blocks of calculation results consisted of the values of final gases and air temperatures, the pipe wall surface temperature from the side of gases and air, the difference between the saturated vapor temperature of gases and wall temperature. These values were obtained for each element, in which heat exchanger was divided.

Based on these values, numerous surface temperature diagram have been built, the most important of them are shown in Fig. 5, 6. There were obtained resulting overall parameters characterizing the performance of the heat exchanger (Table 4).

The methodology gave an opportunity to determine the temperature distribution in the walls at every point of the heat exchanger surface. Negative difference between the saturated temperature and the outer wall area temperature indicates condensate formation and corrosion of the surfaces in a given location (Fig. 5). The calculations showed that such area is present at values of supplied air temperature from +26 °C and below. Hereafter waste gases final temperature was less than 80 °C, corresponding to...
the known value temperature at which corrosion occurs. The absence of sulfur components in the composition of fuel does not guarantee the absence of corrosion, since dust and impurities can get to the heat exchanger with combustion air. The risk of recovery system implementation is theoretically possible coke oven gas price reduction, which will increase the payback period of heat recovery system.

In addition, the increasing of blast temperature aimed at coke economy will change blast furnace material balance that will necessitate further research aimed at studying this factor in the context of changing parameters of blast generating system.

8. Conclusions

1. Using the developed methodology, parameters of hot blast stoves block waste gases (see item 5.1) and required combustion air flow rate were calculated. This data were used as initial parameters for the calculation and analysis of the recovery heat exchanger. When calculating the required combustion air preheating temperature was found that the increase in air temperature from 3 °C to 176 °C in winter and from 33 °C to 222 °C in the summer will reduce the share of coke oven gas in fuel from 16 % to 11 %. The methods, algorithms and software for discrete calculation based on the P-NTU-method for multisec- tor-tube heat exchanger with the cross-counter current scheme of heat carrier medium movement were developed. Blocks of mediums and walls parameters distribution in terms of heat transfer area, result parameters at the heat exchanger outlet (gases temperature, air temperature, the temperature of the pipe wall surface from the side of gases, temperature of the pipe wall surface from the side of the air, difference between saturation vapor temperature in the gases and the temperature of the wall) that allow to analyze the effectiveness and reliability of heat exchanger were obtained.

2. On the basis of obtained data concerning the temperature distribution, areas with corrosion on the heat exchanger surface were detected in various modes. Areas of corrosion pitting occur at an initial air temperature below +26 °C, it made possible to make conclusion about the unreliability of selected modes of performance and heat exchanger design. To improve the reliability of heat recovery system offered a number of solutions, such as heat exchanger redesign, replacement of tube material or previous air preheating to a temperature at which there are no corrosive effects.

3. Developed methods and tools of analysis and synthesis of blast-furnace process waste heat recovery systems take into account the specific of thermal-physical properties distribution on the surface and operating factors and allow to develop new and improve existing systems that reduce fuel production consumption and negative impact on the environment.

References

4. Koshelnik, A. V. Основні проблеми зовнішнього поділу і рабіт
водогазопроводних систем доменних печей при заробному природному
gazu iskuskstvennym gazobraznym toplivom [Text] / A. V. Koshelnik,

5. Oluleye, G. Evaluating the potential of process sites for waste
heat recovery [Text] / G. Oluleye, M. Johnson, R. Smith, S. J. Per-

in the Metals Industry [Text] / M. Vatanakul, E. Cruz, K. McKenna, R. Hynes, J. Sarvinis // Energy Technology. –
2011. – № 1. – P. 1–16. doi:10.1002/9781186188636.ch1

7. Pardo, N. Prospective scenarios on energy efficiency and CO 2
doi:10.1016/j.energy.2013.03.015

8. Lin, P.-H. Efficiency improvement of the hot blast generating
system by waste heat recovery [Text] / P.-H. Lin, P.-H. Wang,
2007. – P. 113–121. doi:10.2495/esu070121

to Improve the Performance of Blast Furnace [Text] / K. N. Rao,
№ 03. – P. 12–19.

10. Gubinskii, V. I. Teploobmennik v metallicheskom trubchatom re-
generatore [Text]: Collection of Scientific Papers / V. I. Gu-
binskii, L. A. Vorobieva // Metallurgicheskaia teplochnetki. –

11. Vorobieva, L. A. Sravnitel’nye karakteristikи miniregenerators
s sharikovoi i trubnoi nasadkoi [Text]: Collection of Scientific
Papers / L. A. Vorobieva, V. I. Gubinskii // Metallurgicheskaia

12. Tian, E. Research on a new type waste heat recovery gravity

13. Muszynski, T. Design and experimental investigations of a
cylindrical microjet heat exchanger for waste heat recovery systems [Text] / T. Muszynski // Applied Thermal Engi-
applthermaleng.2017.01.021

14. Soroka, B. S. Modern State and Efficient Analysis of Heat Re-
cover in Fuel Furnaces Using High Temperature Recuperators.
and power engineering associations. – 2013. – № 3. – P. 60–68.

15. Gres, L. P. Povyszenie energoeffektivnosti nagreva domennogo
dutitza na ekspluatiruemyh domennyh pechah putem ustanovki
sistemy teploobmennikov dlia nagreva komponentov gorenia
i modernizatsii vozduhonagrevatelei [Text] / L. P. Gres,
E. A. Karakash, S. A. Karpenko, S. V. Koldomass // Metall

16. Karpenko, S. A. Sistemy utilizatsii teplovyh otdiashchikh gazov
vzduhonagrevatelei domennih pechey v proektah GP «UKrigrpro-
mez» [Text] / S. A. Karpenko, S. L. Stasevskyi, A. N. Ste-
panenko, V. S. Zaslavskyi, B. N. Vishnevskii, A. S. Gusarov,
N. B. Sopikova, E. I. Grigorenko // Metallurgicheskaia i gor-


18. Zaiets, O. Influence of the coke gas share in the fuel on the
required level of heating of blast stoves combustion air using
doi:10.20998/2413-4295.2016.42.07

19. Koshelnik, A. Metodyka stvorennia universalnoho obchys-
liuvnoho kompleksu dla modeluvannia reheneratyvnych
teploobminnykhvysokoteperatureturnykh plavlynnykh ahrhe-
tiv [Text] / A. Koshelnik // Eastern-European Journal of

20. Koshelnik, A. Determination features of flow rate and tempera-
ture of combustion products in the wastegas pipeline of the hot
of the National Technical University «KhPI» Series: New
Solutions in Modern Technologies. – 2012. – № 50 (956).–
P. 133–139.

recovery units for energy technology systems and units [Text] / A. Ganzha, O. Zaiets, V. Pidkopai, N. Marchenko // Bulletin
of the National Technical University «KhPI» Series: Power and
Heat Engineering Processes and Equipment. – 2016. – № 10
(1182). – P. 56–60. doi:10.20998/2078-774x.2016.10.08

976 p. doi:10.1002/9780470172605

dlia raschetov i proektirovania [Text] / E. I. Kazantsev. –
Ed. 2. – Moscow: Metallurgiya, 1975. – 368 p.

АНАЛИЗ ЕФФЕКТИВНОСТІ І НАДЕЖНОСТІ СИСТЕМ УТИЛИЗАЦІЇ СБРОСНОЇ ТЕПЛОНОСІЇ ДОМЕННОГО ПРОИЗВОДСТВА

Рассмотрена система утилизации теплоты дымовых газов доменных воздухонагревателей для подогрева их воздуха горения. Описаны аспекты определения исходных данных и со- здание программного-вычислительного комплекса для расчета рекуперативного утилизатора на основе авторской методики. Продемонстрированы результаты расчетов при различных на- чальных параметрах воздуха и получены температурные диа- граммы поверхности теплообмена, на которых можно выявить области коррозии.

Ключевые слова: доменные воздухонагреватели, продукты сгорания, дымовые газы, утилизация теплоты, рекуператор.

Ganzha Anton, Doctor of Technical Sciences, Professor, Department of Thermal Engineering and Energy Efficient Technologies, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: ganzha_371@ukr.net, ORCID: http://orcid.org/0000-0003-3967-2421

Zaiets Olena, Lecturer-Intern, Department of Thermal Engineering and Energy Efficient Technologies, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: helena.lz487@gmail.com, ORCID: http://orcid.org/0000-0003-0562-9548

Koshelnik Aleksandr, PhD, Assistant Professor, Department of Thermal Engineering and Energy Efficient Technologies, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: pishti@mail.ru, ORCID: http://orcid.org/0000-0001-6521-4403