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PHYSICAL MODEL OF INFLUENCE OF CaO-FeO-SiO_2 POWDER FRACTION ON THE HEAT TRANSFER FROM TORCH

Introduction. *One of the main ways of heat transfer in metallurgical units is the interaction of the charge with a burning gas torch. The heat is transferred from the torch mainly by radiation. In particular, oxygen converter process under its typical temperature and chemical conditions of oxidation processes is accompanied by combustion reactions with the formation of a torch both in the cavity of the converter (in the so called reaction zone) and above the converter neck as a result of partial post-combustion of exhaust gases leaving the unit.*

Problem Statement. *The processes in metallurgical units are accompanied by significant smoke and dust, which affect the efficiency of heat transfer from the torch of exhaust gases post-combustion to the metal bath that is an additional source of heat in the converter process.*

Purpose. *The purpose of this research is to study the influence of the introduction of solid powder components into the environment around the torch on its heat transfer.*

Materials and Methods. *The research has been carried out on the physical model of a burning torch when CaO-FeO-SiO_2 system powders are fed into the torch in air flow. The magnitude of the heat flow density has been estimated on the basis of the registered temperature difference in different parts of the model.*

Results. *It has been established that the feed of air or any solid material at a temperature much lower than the torch temperature has a negative effect on heat transfer from the torch by radiation. However, the total heat flow density is not significantly reduced due to the possible involvement of heated solids in other heat transfer methods. For the CaO-FeO-SiO_2 system, the share of silicon dioxide powder as a component with the highest heat capacity has the greatest negative effect on the heat transfer from the torch.*

Conclusions. *The studies based on the physical model have allowed us to qualitatively assess the effect of dustiness of the components of CaO-FeO-SiO_2 system of the burning torch environment on its heat transfer and on the contribution of different heat transfer methods from the torch to the total heat flow density in given conditions.*

Keywords: basic oxygen converter processes, physical modeling of post-combustion converter exhaust gas torch, modeling the dustiness of the torch environment, visual characteristics of torch, and heat transfer

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All processes associated with the production of metal at different stages, from the preparation of raw materials to the finish product, require heat consumption. One of the main ways of heat transfer in metallurgical units is the interaction of a burning torch with a metal bath. In particular, oxygen converter process under typical temperature and chemical conditions of oxidative processes is accompanied by combustion reactions with the formation of a torch both in the cavity of the converter, directly in the reaction zone, and above the converter neck as a result of partial post-combustion of exhaust gases leaving the unit [1, 2]. The last factor brings additional heat to the liquid bath due to the oxidation reaction of CO to CO_2.

In metallurgical units, heat is transferred or exchanged from a burning torch mainly by radiation [3–14]. The total contribution of heat transferred by radiation is 90–98% of the total heat exchange [5–10]. The essence of heat exchange by radiation is that part of the internal energy of the body is converted into energy that is transmitted in the form of electromagnetic waves radiated into space. Other bodies on their way absorb the radiant energy and convert it back into thermal energy. Usually the brightness of the torch increases as the concentration of soot particles and the number of impacted atoms grow.

Many studies have dealt with the issues of qualitative and quantitative assessment of heat transfer from the torch to bodies with different absorption capacity without taking into account the influence of the environment, namely its dustiness with different materials [3–14]. In real conditions of operation of metallurgical units, in most cases, it is rather difficult to find a pure torch inasmuch as the technological processes are followed both by natural dust release since physical and chemical interaction of gas jets with working liquids (metal, slag, etc.) and addition of necessary materials, which is also accompanied by the formation of dust.

In this research, an empirical approach has been applied to the study of the effect of the feed of solid powder components into the burning torch environment on the heat transfer in steelmaking unit.

The burning torch of propane-butane mix (with theoretical calorific value of combustion 2.6 MJ/m^3) is used to simulate the torch, and CaO-FeO-SiO$_2$ system powders are chosen as model reagents as components that are present in the largest amount in the atmosphere of steelmaking unit. The experimental plant consists of a quartz tube *1* (diameter is 100 mm; length is 600 mm; wall thickness is 3 mm) fixed on ceramic supports (Fig. 1).

Its function is to eliminate the effect of convection on the heat transfer between the torch and the copper plate of sensor *9*. At one end of the pipe, there is installed gas burner *2* (*Sturm* 5015-KL-01) and a nozzle for feeding gas-powder mix *3*. Powder for making gas-powder mix comes from hopper *4*, and the air pressure is created by compressor *5*. To regulate and control the air flow, needle valve *6* and float rotameter *7* are used. During the experiments, the readings of electronic thermometers *8* that measure the air

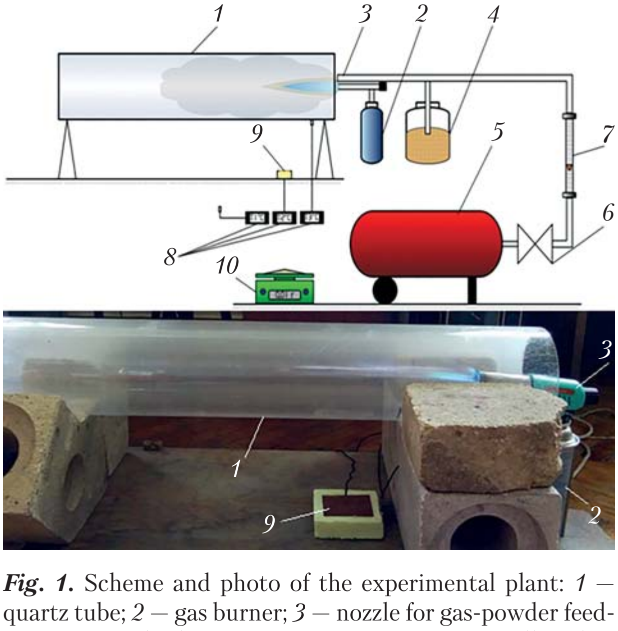

Fig. 1. Scheme and photo of the experimental plant: *1* — quartz tube; *2* — gas burner; *3* — nozzle for gas-powder feeding; *4* — powder hopper; *5* — compressor; *6* — needle valve; *7* — rotameter; *8* — electronic thermometer; *9* — copper plate; *10* — electronic scale

temperature in the room near the pipe (t_1), the temperature of the copper plate of sensor *9* (t_2) located horizontally at a distance of 15 cm from the pipe, and the temperature of the outer surface of the pipe (t_3) under the torch are continuously recorded. The mass of the powder before and after each experiment is measured by electronic scales *10*. The flow of propane-butane mix is controlled in accordance with a pre-set change in the mass of the cylinder over time. The experiments are carried out at the maximum consumption of propane-butane mix on the burner. Since the quartz tube (thermal conductivity 1.8 W/m × K) is inevitably heated during each experiment and thus becomes a source of heat transfer to the copper plate itself, it is cooled to room temperature before each experiment.

The copper plate that receives the torch radiation has a thickness of 1 mm (thermal conductivity of copper at room temperature 394 W/m × K) and is glued to a polystyrene bar (thermal conductivity 0.032 W/m × K). The electronic thermometer sensor is attached to the back of the plate. Thus, the heat from the plate is not dissipated into the environment. Instead, it is accumulated in the plate during the experiment and quickly dissipated from its open surface after the experiment.

At the first stage, pilot tests of the experimental installation are made to verify the efficiency of heat transfer by convection through a quartz tube. Seven series of experiments are conducted, three experiments in each (Table 1).

According to theoretical data, it has been established that the highest heat flow density should be observed in the fifth option, because, in this case, heat is transferred by radiation and forced convection [15]. The use of a quartz tube, as described above, should completely eliminate the effects of convective heat transfer. The injection of compressed air into the torch without a pipe should reduce the temperature of the torch and, consequently, the heat flow density, both by radiation and convection. Blowing compressed air into the torch reduces not only the temperature of the torch, but also convective heat transfer.

Heat transfer intensity has been compared in terms of average heat flow to the copper plate, which is calculated by the formula [15]:

$$q = \frac{c_{Cu} m_{Cu}\left(t_{fin}^{Cu} - t_{start}^{Cu}\right)}{f_{Cu}\tau} \pm 3.26 \cdot \left|\bar{t}_{Cu} - \bar{t}_{env}\right|^{5/4}, \text{ W/m}^2, \quad (1)$$

c_{Cu} is specific heat of the copper plate, J/(kg×K); m_{Cu} is mass of copper plate, kg; t_{start}^{Cu} and t_{fin}^{Cu} are the initial and final temperature of the copper plate, respectively, K; f_{Cu} is the surface of the plate, m^2; τ is duration of one experiment, s; $\bar{t}_{Cu}$ and $\bar{t}_{env}$ are the average temperature of the copper plate and the environment during the experiment, respectively, K.

In formula (1), the first term is the heat flow density absorbed by the copper plate from the environment. Given that, depending on the ambient temperature, the plate can additionally give off or absorb heat by convection from the environment, the second term is introduced. This term takes into account the heat exchange by natural convection between the horizontal copper plate with heat transfer from the top surface and the environment [15]. The plus sign in the formula is used if the temperature of the copper plate is higher than the ambient temperature (i.e. the plate is cooled by natural convection), and

Table 1. **Options for Pilot Experiments to Measure Heat Transfer from a Burning Torch in Different Conditions of Its Combustion**

Pilot experiment number	A option of the experiment of the effect on the radiation from the torch		
	Influence of the quartz tube	Influence of the compressed air supply	Influence of the feed of powder mix
P1	–	–	–
P2	+	–	–
P3	+	+	–
P4	+	+	+
P5	–	+	+
P6	–	+	–
P7	+*	–	–

* — radiation of heated quartz tube; “+” — the presence of an impact factors in the experiment

the minus sign means that the plate is heated by ambient air.

The next step is to study the effect of various chemical compounds fed in a stream of compressed air to a burning torch on heat transfer by the radiation. Mixes of powders of the three-component system CaO-FeO-SiO$_2$ with a fraction of 420 μm are used as powders to simulate the dustiness of the torch. For experiments, a simplex lattice design of the experiments, which includes 10 experiments, is used (Table 2). The reproducibility of the experiments is checked by the Cochren test. The regression coefficients of linear, quadratic, cubic, and special cubic model are determined by the regression analysis. The adequacy of each model is assessed by the coefficient of determination and Fisher's test and the most adequate model is chosen. To verify the adequacy of the experiment, each experiment is repeated three times.

According to the results of the first stage experiments, the hypothesis about the influence of the quartz tube and the injection of compressed air into the torch on the total heat flow density from the torch has been confirmed (Fig. 2).

According to the experiments, it has been found that the largest heat flow corresponds to the option of pure combustion of the gas torch without the influence of the quartz pipe or the feed of air flow. The presence of quartz tube reduces the heat flow from the torch by 25–28%. Feeding room temperature air to the burning torch without the additional influence of the quartz tube decreases the heat flow 2.5 times. The greatest negative impact (the most significant reduction in the heat flow) corresponds to the option of the presence of quartz tube with air supply to the burning torch: there is reported an 8 times reduction in the heat flow, in the conditions of the experiment. Feeding the powder particles with the air stream reduces the negative impact of the air flow, probably due to the possible involvement of the particles in the formation and transfer of heat flow by other mechanisms. In this regard, the results of the experiments are used to calculate the contribution of different heat transfer mechanisms to the total heat flow density by the example of the supply of iron oxide (II) particles (Fig. 3).

According to the conducted researches, without air injection, the share of the heat transferred by radiation is 73% (Fig. 3, *a*), while in the case of the air injection into the flame, it is about 30% (Fig. 3, *c*). Such a sharp change in the heat transfer mechanism is explained by a drop in the torch temperature when cold air (in comparison with the temperature of the torch) is injected to it. When iron oxide (II) powder is fed into the

Table 2. **Simplex Lattice Design of the Experiments for Studying the Effect of Dusty Solid Particles on Heat Transfer from Torch**

No	Mass fraction of the component		
	FeO	CaO	SiO$_2$
1	0	0	1
2	0	1	0
3	1	0	0
4	0	1/3	2/3
5	0	2/3	1/3
6	2/3	0	1/3
7	1/3	0	2/3
8	2/3	1/3	0
9	1/3	2/3	0
10	1/3	1/3	1/3

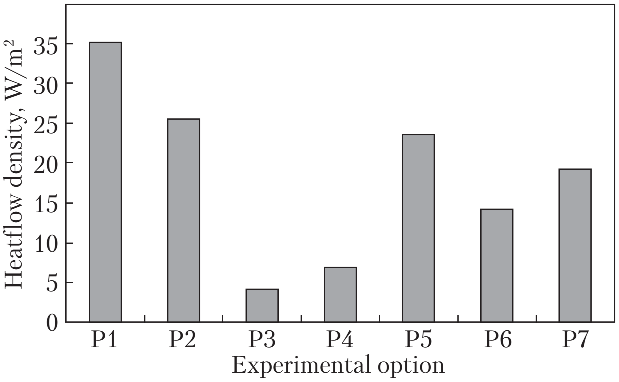

Fig. 2. Comparison of the total heat flow density from the torch under different experimental conditions (the number of the experiment corresponds to the ordinal number in the datasheet of pilot experiments)

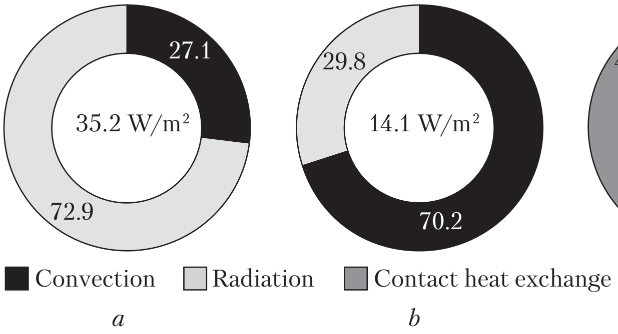

Fig. 3. Comparison of the share of heat flow transferred from the torch by radiation, convection, and contact heat exchange by pure torch (*a*), in the case of air feed to the torch (*b*), and in the case of air + powder feed to the torch (*c*)

blown air, the heat flow density increases more than 1.5 times (Fig. 3, *b*). The ratio of convective to radiation heat transfer in this case is almost 1:1, and the increase in heat flow density as compared with the injection of ordinary air can be explained by contact way of heat transfer from heated powder particles to the surface of the copper plate of the temperature sensor. Its value in such experimental conditions accounts for 40% of the total transferred heat.

Subsequently, according to the experimental plan, a series of 10 experiments that involve feeding mix of powders in a stream of compressed air in a burning torch is made. The average excess heat flow density for the experiments with feeding CaO-FeO-SiO_2 powders is given in Table 3, given the amount of powder supplied during the experiment (the experiment number corresponds to the number of the lattice plan in Table 2).

It has been noted that the largest specific heat flow density corresponds to the options for feeding powder mixes that contain two parts of iron oxide powder (II) or two parts of calcium oxide powder (at the level of 2.4–2.5 kW/kg×m²). The presence in the mix of two parts of silicon dioxide powder corresponds to low heat flow density. The obtained results are in good agreement with the known values of the average heat capacities of the components for the temperature corresponding to the torch temperature (about 1273 K): 0.892 kJ/kg × K, for CaO; 0.783 kJ/kg×K, for FeO; and 1.051 kJ/kg×K, the largest one among the components, for SiO_2 [16]. Accordingly, silicon dioxide in these experiments is a substance that accumulate heat to a greater extent during the experiment, and iron (II) oxide is a substance that is most likely heated and is able to contribute to the formation of a positive heat flow. In addition, in the powdered state, silicon dioxide forms airy loose aggregates. The actual density of SiO_2 is 2200 kg/m³, the bulk density of silicon dioxide is about 50 kg/m³ [16]. The bulk densities of iron (II) oxide and lime powders are 1030 kg/m³ and 1000 kg/m³, respectively [16]. Therefore, with equal mass fractions in the mix, the volume of silicon dioxide powder is twice as much and, accordingly, the amount of heat it accumulates from the torch, given that it is not a combustible material with a high heat capacity, is also very significant.

A model of the combined effect of the powder components of the CaO-FeO-SiO_2 system on the

Table 3. **Average Excess Heat Flow Density in the Conditions of Feeding CaO-FeO-SiO_2Gas-Powder Mix to the Torch**

Number of experiment, according to the plan	1	2	3	4	5	6	7	8	9	10
Average excess heat flow density, kW/kg×m²	1.1	1.5	1.4	1.9	2.5	2.4	1.5	2.4	1.7	1.8

heat flow density of the burning torch (2) has been obtained by the statistical processing of the experiment results. The approximation coefficient and the significance of the Fisher test for the obtained function are 0.998 and 9.99×10^{-4}, respectively. The graphic representation of the mathematical model is presented in Fig. 4.

$$\begin{aligned}
\Delta q = {} & 6.1(CaO)+0.2(SiO_2)+6.9(FeO)+\\
& +42.3(CaO)(SiO_2)+8.6(CaO)(FeO)+\\
& +25.3(SiO_2)(FeO)+\\
& +18.6(CaO)(SiO_2)\big[(CaO)-(SiO_2)\big]+\\
& +0.2(CaO)(FeO)\big[(FeO)-(CaO)\big]+\\
& +15.4(SiO_2)(FeO)\big[(FeO)-(SiO_2)\big]-\\
& -137.4(CaO)(SiO_2)(FeO)
\end{aligned} \qquad (2)$$

The analysis of the diagram has shown that the smallest excess heat flow density could be a result of the introduction of pure SiO_2 and CaO. At the same time, their mix in a ratio of approximately 1:1 could increase the excess heat flow density. Quite a high value of the excess heat flow density could be observed when increasing the content of iron (II) oxide in the mix to 60–90%. This content of iron (II) oxide in the converter dust is characteristic of the initial stages of blowing in the absence of slag on metal mirror [17]. At the final stages of blowing in the converter, the level of iron (II) oxides in the dust accounts for 5–10% that corresponds to low excess heat flow density. Also, it should be noted that the presence of calcium oxides (5–10%) in the converter dust corresponds to a fairly high excess heat flow density.

The results are in good agreement with those obtained in [18] on the basis of mathematical modeling of heat transfer patterns in the gas phase of oxygen converter during post-combustion of the exhaust gases.

The physical model of the heat transfer process from a burning torch in a dusty medium that is formed by injection of compressed air with solid powder components of the CaO-FeO-SiO_2 system has been proposed. It has been established that the supply of both air and any solid material of the CaO-FeO-SiO_2 system with a temperature much lower than the torch temperature has a negative effect on heat transfer by radiation. However, the total heat flow is significantly less affected by solid materials supplied to the burning torch than by air, due to the possible involvement of heated solids in other heat transfer methods (convection and direct contact heat exchange). It has been found that for the CaO-FeO-SiO_2 system, the greatest negative impact on heat transfer is exerted by the share of silicon dioxide as material with the highest heat capacity, while the influence of calcium and iron (II) oxides manifests itself to a lesser extent. Given the fact that in real conditions of the oxygen converter, all dusty components are heated to a significant temperature, the next step is to determine the effect of the studied triple powder system in the case of preheating its components to the torch temperature.

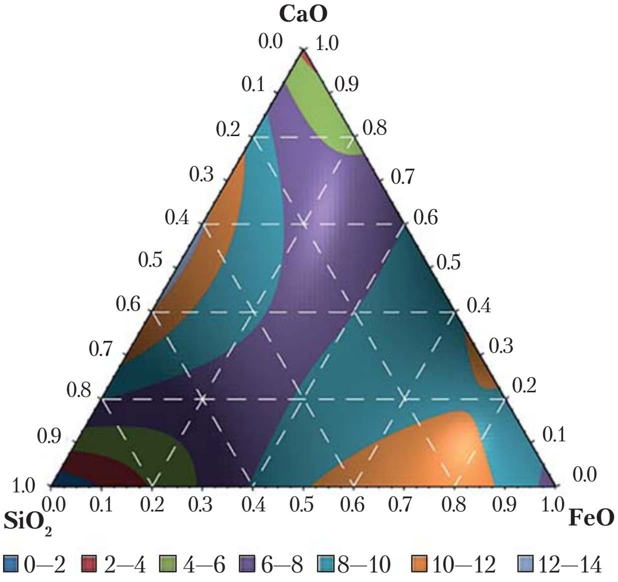

Fig. 4. Three-component diagram for the excess heat flow density in the system CaO-FeO-SiO_2

Therefore, to understand the heat transfer processes that actually take place in the converter from the bath torch, it is necessary to take into account the current conditions of torch combustion, which depend on the technological features and periods of melting.

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ДОСЛІДЖЕННЯ НА ФІЗИЧНІЙ МОДЕЛІ ВПЛИВУ ПИЛОПОДІБНОЇ ФРАКЦІЇ СИСТЕМИ CaO-FeO-SiO$_2$ НА ТЕПЛОПЕРЕДАЧУ ВІД ФАКЕЛУ

Вступ. Одним з основних шляхів передачі теплоти в металургійних агрегатах є взаємодія шихти з палаючим газовим факелом, перенос теплоти від якого здійснюється переважно випромінюванням. Зокрема, кисневе конвертування за властивих йому температурних і хімічних умов протікання окислювальних процесів супроводжується реакціями горіння з утворенням факелу як в порожнині конвертера, безпосередньо в реакційній зоні, так і над горловиною конвертера в результаті часткового допалювання газів, що виходять з агрегату.

Проблематика. Процеси у металургійних агрегатах супроводжуються значним димо- та пиловиділенням, що повинно чинити вплив на ефективність передачі теплоти від факелу допалювання вихідних газів металевій ванні, яка є додатковим джерелом тепла в процесі конвертування.

Мета. Дослідження впливу введення твердих порошкоподібних компонентів в середовище навколо факелу на його теплопередачу.

Матеріали й методи. Дослідження проведено на фізичній моделі палаючого факелу при подачі в факел у потоці повітря порошків системи CaO-FeO-SiO$_2$. Величина теплового потоку оцінювалася за зареєстрованою різницею температур на різних ділянках моделі.

Результати. Встановлено, що введення як повітря, так і будь-якого твердого матеріалу з температурою значно нижчою за температуру факела, негативно впливає на теплопередачу від факела випромінюванням. Однак загальний тепловий потік не зазнає значних змін через можливу участь твердих частинок, що нагріваються, в інших способах теплопередачі. Для системи CaO-FeO-SiO$_2$ найбільший негативний вплив на теплопередачу від факела чинить частка порошку діоксиду кремнію як компонента з найбільшою теплоємністю.

Висновки. Проведені на фізичній моделі дослідження дозволили якісно оцінити вплив запиленості компонентами системи CaO-FeO-SiO$_2$ середовища палаючого факелу на його тепловіддачу та внесок різних способів теплопередачі від факела в сумарну величину щільності теплового потоку у заданих умовах.

Ключові слова: кисневo-конверторний процес, фізичне моделювання факелу газів, що відходять з агрегату після допалювання, моделювання запиленості середовища факелу, візуальні характеристики факела, теплообмін.