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Оригинальная статья

Effect of ring groove in a heat-insulating insert on efficiency of its work in blast channel of blast furnace tuyere

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Abstract. One of the main disadvantages when supplying natural gas to the air tuyere of a blast furnace is low intensity of its combustion inside the tuyere blast channel. Ring groove on the surface of blast channel improves the mixing of natural gas with blast and increases completeness of gas combustion in it, but reduces the tuyere durability. One of the ways to simultaneously solve these problems is to install a heat-insulating ceramic insert in the tuyere blast channel. The insert significantly reduces heat losses through the tuyere surface, improves natural gas combustion in the blast channel due to its contact with hot walls of the insert instead of cold copper walls in its absence. This increases the temperature of the hot blast at the tuyere outlet. In addition, the insert affects the tuyere durability by reducing the heat flow acting on the tuyere. In this work, we studied influence of the ring groove and its parts in the insert on efficiency of its work. In the Ansys 21.1 software, the processes occurring in the blast channel of a blast furnace tuyere with a ceramic insert installed in it, having a groove of a quadrangular section in the form of a ring or its part in the circumferential direction, were simulated. It was established that improvement of natural gas combustion in the tuyere blast channel is achieved using a ring groove or part of it from the side of gas supply.

Keywords: blast furnace, air tuyere, blast channel, ceramic insert, ring groove, Ansys modeling, heat transfer, natural gas combustion

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Влияние зоны кольцевой выборки в теплоизолирующей вставке на эффективность ее работы в дутьевом канале воздушной фурмы доменной печи

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Аннотация. Одним из основных недостатков при подаче природного газа в воздушную фурму доменной печи является низкая интенсивность его горения внутри дутьевого канала фурмы. Известно, что кольцевая выборка на поверхности дутьевого канала улучшает смешивание природного газа с дутьем и увеличивает полноту сгорания газа в нем, однако снижает стойкость фурмы. Одним из способов одновременного решения этих проблем является установка в дутьевой канал фурмы теплоизолирующей керамической вставки. Вставка значительно снижает тепловые потери через поверхность фурмы, улучшает горение природного газа в дутьевом канале за счет его контакта с горячими стенками вставки вместо холодных медных стенок при ее отсутствии, что увеличивает температуру горячего дутья на выходе из фурмы. Кроме того, вставка оказывает влияние на стойкость фурмы за счет снижения теплового потока, действующего на фурму. В данном исследовании изучено влияние кольцевой выборки и ее частей во вставке на эффективность ее работы. В среде Ansys 21.1 моделировали процессы, происходящие в дутьевом канале фурмы доменной печи с установленной в него керамической вставкой, имеющей выборку четырехугольного сечения в форме кольца или его части в окружном направлении. Установлено, что улучшение горения природного газа в дутьевом канале фурмы достигается с использованием кольцевой выборки или ее части со стороны подачи газа.

Ключевые слова: доменная печь, воздушная фурма, дутьевой канал, керамическая вставка, кольцевая выборка, моделирование в Ansys, теплообмен, горение природного газа

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Introduction

The air tuyeres supply a mixture of oxygen-enriched blast and natural gas [1 – 3] or natural gas and pulverized coal into the blast furnace. The injection of gas and coal reduces the coke consumption during pig iron manufacturing [4 – 6]. As the share of natural gas increases, its mixing with the blast deteriorates [7 – 9] and blowing efficiency decreases [10 – 12]. We have proposed solutions to enhance the ignition and combustion of natural gas in the tuyere blast channel [13 – 16]. Numerous improved technologies for mixing natural gas with the blast have been invented [17 – 20].

Gas preheating has been proven to be efficient [21; 22].

Another promising approach to improving gas/blast mixing is adding cavities to the blast channel to increase flow turbulence in the tuyere. Such elements could be a groove in the tuyere nose [23], blowpipe, [24], or in the natural gas feed tube [25]. However, more intense gas combustion in the tuyere blast channel may result in blowpipe deformation or burnout. For this reason, as gas combustion improves, the blowpipe should be heat protected. Durable insulating ceramic inserts [26 – 28, 29 – 31] can be used.

A large number of studies [32 – 34] are dedicated to modeling processes occurring in the air tuyere and the blast furnace tuyere zone, including the simultaneous supply of combustible natural gas and pulverized coal into the blast channel of the tuyere [35; 36].

Problem statement

We investigated the effects of a ring roove or its segments on ceramic insert performance.

The purpose of this study is to simulate the flow, heat exchange, and gas combustion in the blast channel. We considered the following ceramic insert designs:

– no groove in the insert (basic design);

– with a quadrangular section (3 mm deep, 40 mm wide) ring groove located 20 mm from the insert bottom;

– with a semi-ring groove of the same size located at the top (on the gas feed pipe side);

– with a semi-ring groove of the same size located at the bottom (opposite the gas feed pipe side).

The depth and width of the groove were selected to meet two conditions: provide a measurable improvement in the gas combustion process and maintain structural integrity. The groove was placed near the edge of the insert to intensify gas combustion in the area close to the tuyere nose and the tuyere zone.

We conducted CFD, combustion, and heat transfer simulations in Ansys Fluent 21.1 using the actual tuyere operating conditions and some simplifying assumptions proposed by Levitskii I. et al. [18]. The key assumptions are:

– extended boundary conditions include heat transfer to the cooling water;

– radiation heat exchange inside the air passage is neglected;

– the *Finite Rate / Eddy dissipation model* is employed to simulate chemical reactions and turbulence;

– to reduce computational costs, half of the symmetrical structure is simulated;

– the problem is assumed to be stationary;

– the pressure solver is utilized;

– the *realizable* k-ε turbulence model with standard wall functions is used to solve the energy and convective diffusion equations for the methane-air mixture, taking possible combustion into account.

In contrast to the approach presented in [18], our approach involved solving a combined heat transfer problem, explicitly analyzing heat transfer through solid bodies (specifically, the insert).

We constructed a symmetric geometric model using Design Modeler and subsequently generated the mesh using Ansys Meshing.

The simulation addressed a stationary problem. The components of the methane-air mixture were treated as perfect gases, meaning we assumed that density varies with pressure and temperature. The tuyere nose and the blowpipe were composed of copper, with their properties available in the Ansys Fluent database. The insert was fabricated from corundum, characterized by a density of 3583 kg/m^3, specific heat capacity of 1291 J/(kg·K), and thermal conductivity of 83 W/(m·K). The gap between the insert and the blowpipe was assumed to be filled with sealant, featuring a density of 1200 kg/m^3, specific

Table 1

Blast parameters in the inlet section

Таблица 1. **Параметры дутья во входном сечении**

Property	Value
Section type	mass flow inlet
Mixture composition	30 % O_2, 70 % N_2
Air temperature	1200 °C
Air mass flow	4.539 kg/s
Air pressure	405.3 kPa
Turbulent pulsations	5 %
Hydraulic diameter	0.18 m

Table 2

Parameters of natural gas in the inlet section

Таблица 2. **Параметры ПГ во входном сечении**

Property	Value
Section type	mass flow inlet
Composition	100 % CH_4
Natural gas mass flow rate	0.283 kg/s
Natural gas temperature	27 °C
Turbulent pulsations	5 %
Hydraulic diameter	0.033 m

heat capacity of 840 J/(kg·K), and thermal conductivity 0.4 W/(m·K).

The boundary conditions for the blast process are detailed in Table 1, while those for the natural gas feed are outlined in Table 2.

In order to account for the 2 mm thick gap and the 6 mm thick copper layer on the outer surface of the insert within the simulation domain, the boundary conditions on this surface were extended. Convective heat exchange with the environment occurred on the outer surface of the copper layer, maintaining a temperature of 27 °C and a heat conductivity of a = 5815 W/(m^2·K).

The boundary conditions at the fluid-to-tuyere nose interface were also extended due to the presence of a 14 mm thick copper layer. Similar to the 6 mm thick copper layer, there was convective heat exchange with the environment occurring on the outer surface of this copper layer.

Simulation results and discussion

Table 3 presents the crucial simulation results, and Figs. 1 and 2 illustrate the distribution of turbulent kinetic energy.

Both Table 3 and Figs. 1 and 2 indicate that the presence of a ring groove in the insert or a groove on the natural gas feed side enhances the mixing of natural gas and hot air. Consequently, this leads to increased gas combustion heat, higher CO_2 content, and as a result, elevated temperature and flow velocity at the tuyere out-

Table 3

Design parameters of the air tuyere

Таблица 3. **Расчетные параметры работы воздушной фурмы**

Variables*	Design options			
	without groove	with groove		
		ring	semi-ring, top	semi-ring, bottom
Q_{out}, kW	–3207.2	–3230.9	–3223.3	–3158.7
Q_{nose}, kW	–26.3	–27.8	–26.4	–26.5
Q_{comb}, kW	289.2	314.7	305.2	240.6
ΔQ, kW	–0.042	–0.018	0.019	0.012
T_{out}, K	1399.3	1407.2	1404.7	1385.7
$CO_{2\ out}$	0.0105	0.0114	0.0111	0.0088
υ_{out}, m/s	217.8	218.9	218.7	216.1
K_{out}, m^2/s^2	61.6	84.9	66.1	67.5

[*] Since the simulation domain represents half of the real structure, all the heat values should to be doubled.

Q_{out} is heat flux at the blast channel, kW; Q_{nose} is heat flux at the tuyere nose, kW; Q_{comb} is combustion heat, kW; ΔQ is heat disbalance, kW; T_{out} is average air temperature at the tuyere outlet, K; $CO_{2\ out}$ is mass fraction of CO_2 at the tuyere outlet; υ_{out} is average flow velocity at the tuyere outlet, m/s; K_{out} is turbulent kinetic energy at the tuyere outlet, m^2/s^2.

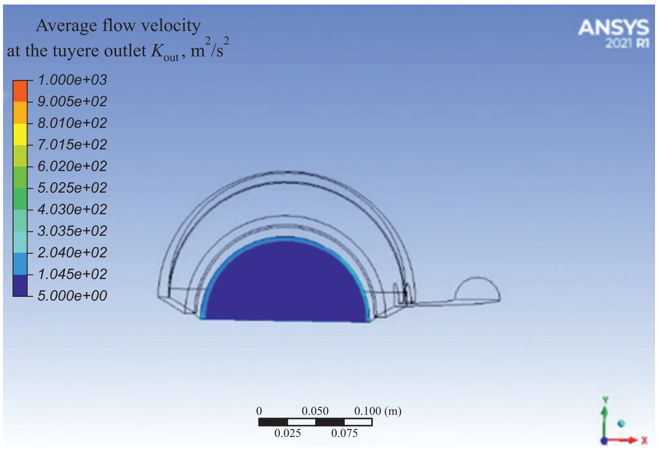

Fig. 1. Distribution of turbulence kinetic energy at the outlet of a serial tuyere

Рис. 1. Распределение кинетической энергии турбулентности на выходе из серийной фурмы

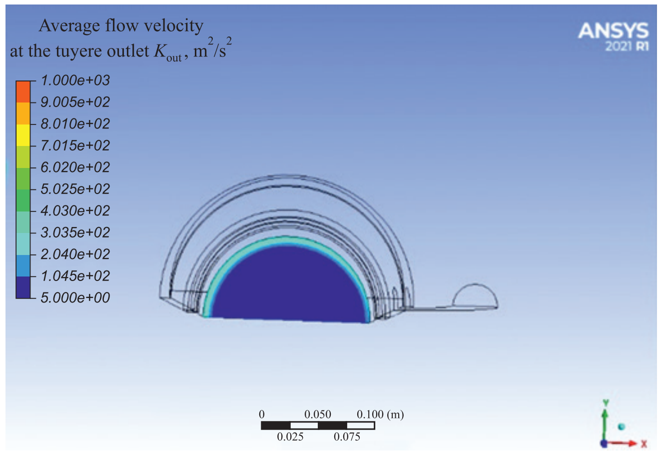

Fig. 2. Distribution of turbulence kinetic energy at the outlet of a tuyere with ring groove

Рис. 2. Распределение кинетической энергии турбулентности на выходе из фурмы с кольцевой выборкой

let. This implies that the natural gas ratio in the tuyere mixture can be raised.

Conclusions

The presence of a ring groove in the tuyere blowpipe's heat-insulating insert has a significant impact on gas combustion:

– a semi-ring groove located at the gas feed pipe side enhances gas/hot air mixing and accelerates combustion;

– an ring groove further improves the gas/hot air mixing and accelerates combustion;

– a semi-ring groove opposite the gas feed pipe side leads to a deterioration in gas/hot air mixing and combustion compared to the standard, no-groove design.

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