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Original article

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COMPARATIVE ANALYSIS OF KINETIC AND DIFFUSION MODES OF NATURAL GAS COMBUSTION IN EAF BURNERS

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Abstract. In modern electric arc furnaces (EAF), charge heating by natural gas (NG) combustion products with process oxygen is widely used to reduce the power consumption and intensify the thermal performance. In existing EAF burners, gas and oxygen are supplied separately through oxygen gas and refining burners, which ensures the diffusion combustion mode. The diffusion mode in conditions of EAF working space has a number of disadvantages, such as non-optimal distribution of temperature and concentration fields of combustion products, increased burn-off of iron-containing components of the charge. This paper presents the results of a computational study of the physico-chemical properties of combustion products along the torch length for the burners of VAI FUCHS, SMS DEMAG and NTPF Etalon Ltd. companies at oxygen concentration in the oxidizer of 95 wt. %. The results of computer modeling of temperature fields in the torches were analyzed in order to assess the risk of flame “slip” into the burner internal volume. The authors carried out a comparative study of the characteristics of torches in the burner devices with diffusion and kinetic combustion modes. Based on the data obtained, a transition from the diffusion mode of natural gas combustion to the kinetic mode is proposed, which can increase the energy efficiency of using burners, uniformity of temperature and concentration fields of combustion products, and reduce carbon monoxide of the iron-containing charge. The study was performed using computer modeling in ANSYS software package in CFX module. The obtained results can be useful for optimizing thermal processes in EAF working space, reducing power consumption and preventing emergency operation of burners.

Keywords: EAF, burner, natural gas, oxygen, torch, concentration, temperature field, mode, diffusion, kinetic

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ КИНЕТИЧЕСКОГО И ДИФфуЗИОННОГО РЕЖИМОВ ГОРЕНИЯ ПРИРОДНОГО ГАЗА В ГОРЕЛКАХ ДУГОВОЙ СТАЛЕПЛАВИЛЬНОЙ ПЕЧИ

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Аннотация. В современных дуговых сталеплавильных печах (ДСП) для снижения расхода электроэнергии и интенсификации тепловой работы широко применяется нагрев шихты продуктами сгорания природного газа с технологическим кислородом. В существующих горелках, применяемых на ДСП, газ и кислород подаются раздельно через газокислородные и рафинирующие горелки, что обеспечивает диффузионный режим горения. Диффузионный режим в условиях использования в рабочем объеме ДСП имеет ряд недостатков, таких как неоптимальное распределение температурных и концентрационных полей продуктов сгорания, повышенный угар железосодержащих компонентов шихты. В данной работе представлены результаты расчетного исследования физико-химических свойств продуктов сгорания по длине факела для горелок фирм VAI FUCHS, SMS DEMAG и НТПФ «Эталон» при концентрации кислорода в окислителе 95 мас. %. Были проанализированы результаты компьютерного моделирования температурных полей факелов с целью оценки риска «проскока» пламени во внутренний объем горелки. Авторы провели сравнительное исследование характеристик факелов в горелочных устройствах с диффузионным и кинетическим режимами горения. На основании полученных данных предложен переход от диффузионного режима сжигания природного газа к кинетическому, что может повысить энергоэффективность использования горелок, равномерность температурных и концентрационных полей продуктов сгорания, а также снизить угар железосодержащей шихты. Исследование производилось с помощью компьютерного моделирования в пакете программ ANSYS в модуле CFX. Полученные результаты могут быть полезны для оптимизации тепловых процессов в рабочем объеме ДСП, снижения расхода электроэнергии и предотвращения аварийных режимов эксплуатации горелок.

Ключевые слова: дуговая сталеплавильная печь, горелка, природный газ, кислород, факел, концентрация, температурное поле, режим, диффузионный, кинетический

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INTRODUCTION

Diffusion combustion of natural gas with process oxygen examined under conditions where the gas mixture forms in the free volume of the furnace, outside the burner [1–3]. In the diffusion combustion mode, gas and oxidizer are supplied separately until they meet at the interface between the gas and oxidizer streams. Due to molecular diffusion, a mixture is formed that is characteristic of a laminar diffusion flame at low flow velocities, or a molar diffusion process promoting large-scale turbulence typical of a turbulent diffusion flame. The gas–oxidizer mixture is partially formed both before ignition and during combustion, which complicates analysis of this process. The temperature, composition of combustion products, and their physical and thermophysical properties in the combustion zone – separated by the flame front from the initial mixture – affect both the primary stage of mixing and the rate of chemical reactions.

Temperature in the diffusion flame zone corresponds to the combustion temperature of a stoichiometric pre-

mixed mixture, provided that the thermal diffusivity coefficient equals the mutual diffusion coefficient of the gas and oxidizer and that heat losses to the surroundings are negligible. The fundamental principles of diffusion combustion theory were developed and published in [4–6]. In operating fuel-fired furnaces, taking into account their design features, technological processes, and thermal conditions, it is advisable to implement the kinetic combustion mode of natural gas with oxygen, which involves preparing a well-mixed premixed gas–oxygen mixture [7–10]. In this case, the mixture-formation stage is effectively excluded from the sequence of physicochemical processes. Heating and melting of the initial materials occur primarily through heat and mass transfer from the combustion products, with no unburned hydrocarbons remaining in the gas phase [11–14].

Thus, the aim of this study is to carry out a comparative analysis of kinetic and diffusion combustion modes of natural gas with an oxygen–air mixture (OAM) in EAF burners, based on computer modeling of temperature fields and CO/H₂ concentrations.

Objectives:

To compare the torch characteristics of the VG burner (kinetic mode) and its analogues (VAI FUCHS, SMS DEMAG, and NTPF Etalon) during combustion of natural gas with oxygen and to evaluate the influence of combustion modes on:

- distribution of the temperature fields;
- the maximum concentrations of CO and H₂.

MATERIALS AND METHODS

A comparative study was carried out to analyze the torch characteristics during natural gas combustion with an oxygen–air mixture (OAM) in burners of various designs. The investigation included:

- diffusion burners used in modern electric arc furnaces (EAFs) manufactured by NTPF Etalon, SMS DEMAG, and VAI FUCHS;
- the VG burner, a promising design operating in the kinetic combustion mode, which ensures preliminary mixing of the components in the diffuser (Fig. 1).

Experimental studies of combustion require significant time and financial resources for developing test procedures and using specialized measuring equipment.

In contrast, computer modeling makes it possible to optimize burner design without manufacturing intermediate prototypes and to quickly analyze how design parameters and operating modes affect torch formation and its characteristics. Computer modeling greatly shortens development time and provides a reliable basis for evaluating the efficiency of various design modifications and technical solutions [15 – 17].

Combustion modeling was performed in the ANSYS software package (CFX module) using the following models and settings:

- extended Coherent Flamelet Model (ECFM);
- Total Energy heat transfer model;
- k – ϵ turbulence model.

Boundary conditions for the burners were as follows:

- oxygen flow rate: 0.553 kg/s (95 wt. %);
- natural gas flow rate: 0.092 kg/s (the natural gas composition was normalized to an equivalent methane concentration of 100 wt. %).

The variation of temperature (T , K) and the maximum CO and H₂ concentrations in the cross-section of combustion products along the torch length were determined (Figs. 2 – 4).

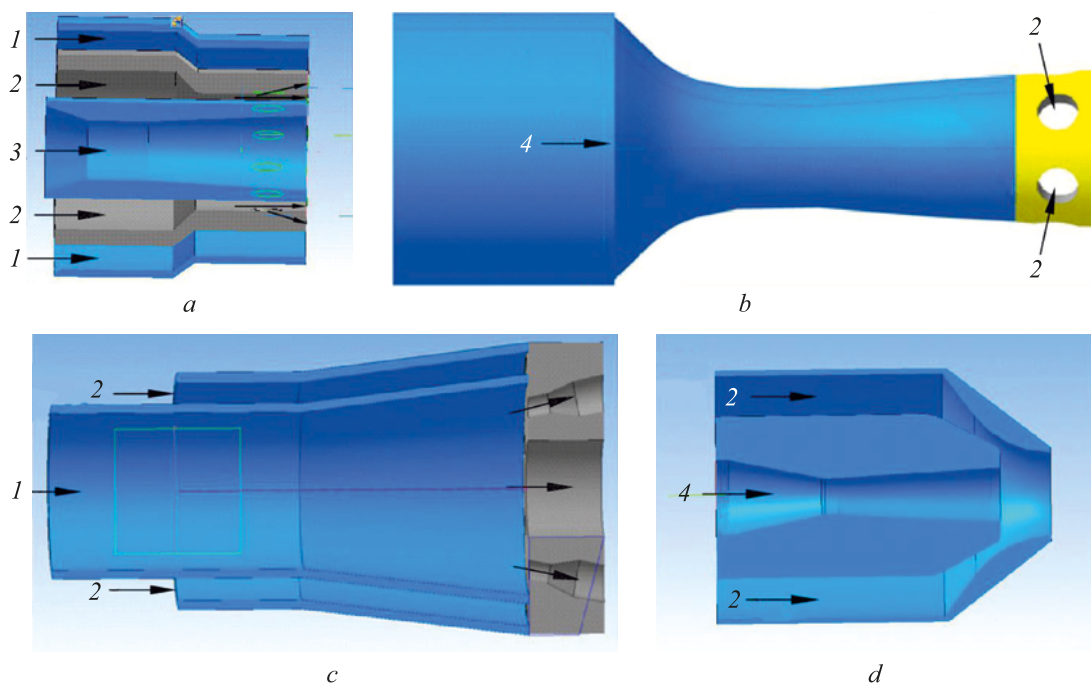


Fig. 1. Schemes of gas-oxygen burners designs:

a – VAI FUCHS; *b* – VG; *c* – NTPF Etalon; *d* – SMS DEMAG

1 – oxygen supply for combustion; 2 – natural gas supply;

3 – oxygen supply in refining mode; 4 – oxygen supply for combustion and refining mode

Рис. 1. Схемы конструкций газокислородных горелок:

a – фирмы VAI FUCHS; *b* – версии VG; *c* – фирмы НТПФ «Эталон»; *d* – фирмы SMS DEMAG

1 – подвод кислорода на горение; 2 – подвод природного газа;

3 – подвод кислорода в режиме фришевания; 4 – подвод кислорода на горение и в режиме фришевания

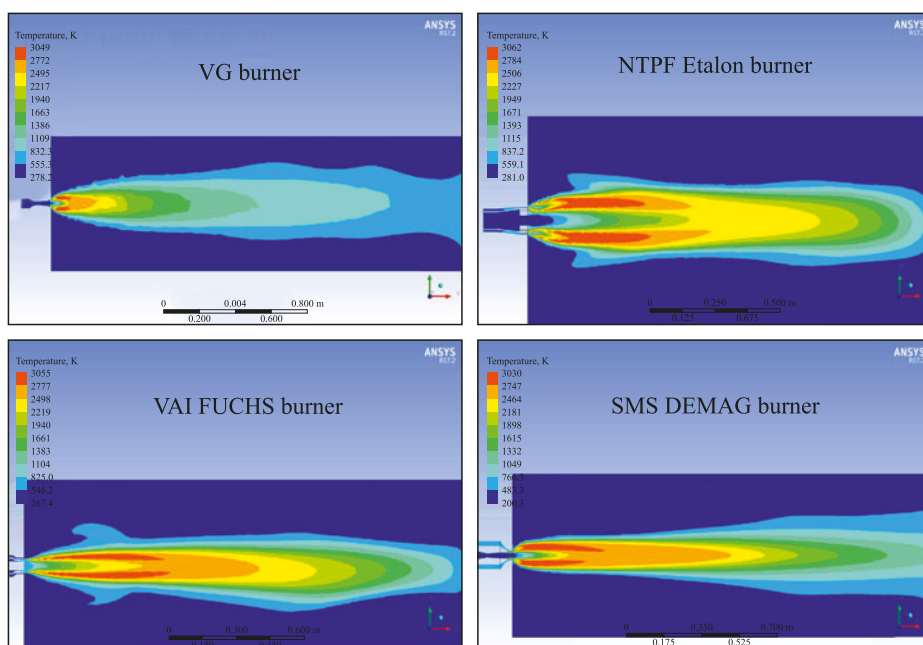


Fig. 2. Temperature fields of combustion products of the burner when burning natural gas with oxygen-air mixture, oxygen mass concentration – 95 %

Рис. 2. Температурные поля продуктов сгорания горелок при сжигании природного газа с КВС, массовая концентрация кислорода составляет 95 %

As a result, comparative performance characteristics were obtained for burners with kinetic and diffusion combustion modes: the VG burner (kinetic mode) and the diffusion burners of NTPF Etalon, VAI FUCHS, and SMS DEMAG, operating at equal natural gas and oxygen flow rates.

Based on the analysis of the results, zones of intensive combustion were identified, corresponding to regions of minimal CH_4 concentration and maximum temperature:

- for the NTPF Etalon burner – at a torch length of about 500 mm;
- for the VG burner – at a torch length of 100 – 200 mm;
- for the SMS DEMAG burner – at a torch length of about 500 mm;
- for the VAI FUCHS burner – at a torch length of over 1000 mm.

Afterburning regions can be diagnosed by elevated CO and H_2 . The VG burner showed the lowest maxima –

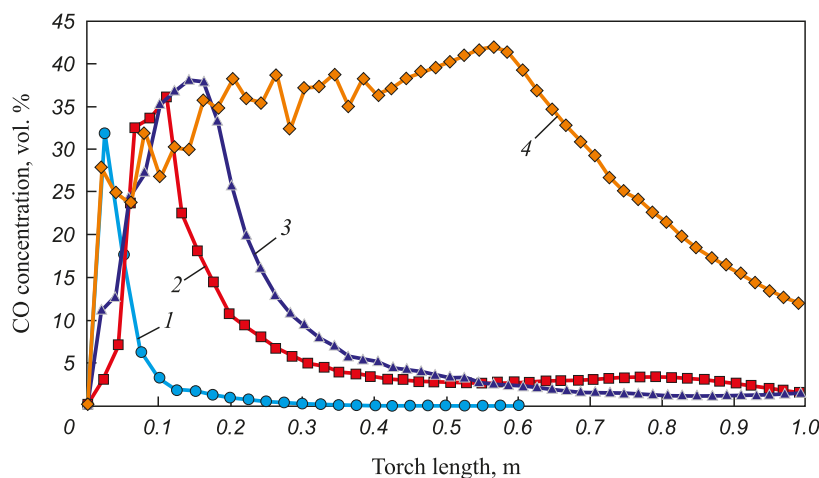


Fig. 3. Change in the maximum concentration of CO in cross-section of combustion products along the torch length of the burners: 1 – VG; 2 – SMS DEMAG; 3 – NTPF Etalon; 4 – VAI FUCHS

Рис. 3. Изменение максимальной концентрации оксида углерода в поперечном сечении продуктов сгорания по длине факела горелок: 1 – версии VG; 2 – фирмы SMS DEMAG; 3 – фирмы НТПФ «Эталон»; 4 – фирмы VAI FUCHS

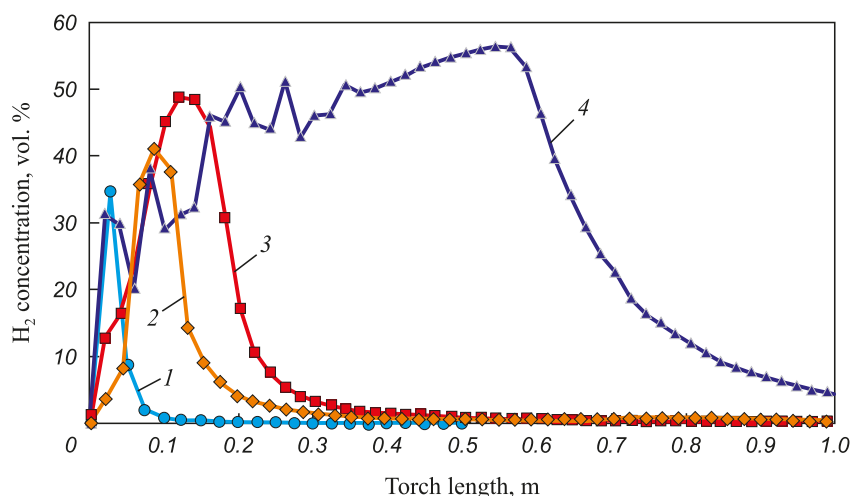


Fig. 4. Change in the maximum concentration of hydrogen in cross-section of combustion products along torch length of the burners: 1 – VG; 2 – SMS DEMAG; 3 – NTPF Etalon; 4 – VAI FUCHS

Рис. 4. Изменение максимальной концентрации водорода в поперечном сечении продуктов сгорания по длине факела горелок: 1 – версии VG; 2 – фирмы SMS DEMAG; 3 – фирмы НТПФ «Эталон»; 4 – фирмы VAI FUCHS

32 vol. % CO and 35 vol. % H_2 – whereas diffusion burners exhibited 36 – 42 vol. % CO and 41 – 56 vol. % H_2 . These reductions (by 4 – 12 vol. % for CO and 6 – 14 vol. % for H_2) indicate more complete and uniform natural-gas combustion in the kinetic combustion mode than in diffusion systems.

The criterion for the absence of flame-slip risk was taken to be the absence of regions with temperatures above 800 °C inside the burner’s internal cavity. No such high-temperature zones were detected for any of the burners examined. The maximum temperature of the combustion products in the torch ranged from 2757 to 2792 °C, while, at the same time, the gas-dynamic velocity in local flow regions varied widely – from 250 to 750 m/s (see Table). It should be noted that the temperature of the combustion products in the VG burner torch (2776 °C) corresponds to a gas-dynamic flow velocity 1.15 – 3.75 times higher than that of burners operating in the diffusion combustion mode [18; 19].

The optimal efficiency of the VG burner under EAF operating conditions can also be achieved by maintaining the proper vertical distance from the molten bath surface (bath level), the angle of inclination in the vertical plane, and the tangential direction of combustion product flow in the horizontal plane [15; 20]. This configuration enables the most efficient utilization of the thermal energy of the combustion products for rapid and uniform heating of the charge, which enhances the steelmaking intensity, reduces power consumption, and increases overall productivity.

CONCLUSIONS

This study shows that the VG burner, operating in the kinetic combustion mode, outperforms diffusion burners. It provides complete, rapid combustion of hydrocarbons in the premixed stream and prevents flame slip into the burner internal volume.

Performance indicators of the burners

Показатели работы горелок

Parameter	VG burner	NTPF Etalon burner	SMS DEMAG burner	VAI FUCHS burner
Maximum local velocity of combustion products, m/s	750	200	650	250
Length of the intensive combustion zone, mm	100	500	300	>1000
Maximum local temperature, K (°C)	3049 (2776)	3062 (2789)	3030 (2757)	3065 (2792)
Maximum local hydrogen (H_2) concentration in combustion products, vol. %	35	49	41	56
Maximum local carbon monoxide (CO) concentration in combustion products, vol. %	32	38	36	42

The results support the adoption of kinetic-type burners in modern steelmaking operations.

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O. Yu. Sheshukov – setting the research task, editing the text.

M. V. Kalganov – discussion of the results, editing the text.

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И. В. Глухов – постановка задачи исследований, выполнение компьютерного моделирования, написание статьи.

Г. В. Воронов – постановка задачи исследований.

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