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INTENSIFICATION OF THE GAS FUEL COMBUSTION PROCESS IN CHAMBER FURNACE BURNERS

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Annotation. This paper analyzes the methods of intensifying the combustion process of gaseous fuels in chamber furnaces. The characteristics of diffusion and kinetic combustion in burners, which are the main elements of the fuel system, as well as their aerodynamic modes and flame front stability, are examined. Changes in heat load are expressed in mathematical models based on factors related to the turbulent flame propagation velocity and the intensity of heat and mass transfer. In addition, ways to improve heat generation efficiency by increasing the flame surface-to-volume ratio, the advantages of slot and grid burners, the effect of preheating air and fuel, and environmental limitations are analyzed. The results make it possible to determine optimal parameters to increase furnace efficiency and ensure combustion stability.

Keywords: chamber furnace, gas fuel, burner, diffusion combustion, kinetic combustion, flame, heat load, turbulent flow, air preheating, slot burner, heat exchange, stable combustion, NOx emissions.

KAMERALI PECHLARDA YOQILGʻI QURILMALARI GAZ YOQILGʻISINI YOQISH JARAYONINI INTENSIVLASHTIRISH

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Toshkent davlat texnika universiteti dotsenti

Annotatsiya. Ushbu maqolada kamerali pechlarda gazsimon yoqilgʻining yonish jarayonini intensivlashtirish usullari tahlil qilinadi. Yoqilgʻi qurilmasining asosiy elementi boʻlgan gorelkalarda diffuzion va kinetik yonish jarayonlarining xususiyatlari, ularning aerodinamik rejimlari hamda alangalanish frontining barqarorligi koʻrib chiqilgan. Alanganing turbulent tarqalish tezligi, issiqlik va massa almashinuvi intensivligi bilan bogʻliq omillar asosida issiqlik yuklamasining oʻzgarishi matematik modellarda ifodalangan. Shuningdek, alanganing sirt/hajm nisbatini oshirish orqali issiqlik ishlab chiqarish samaradorligini yaxshilash yoʻllari, yoriqli va panjarali gorelkalarning afzalliklari, havoni va yoqilgʻini oldindan qizdirishning ta’siri hamda ekologik cheklovlar tahlil etilgan. Natijalar pech energetikasini oshirish va yonish barqarorligini ta’minlash uchun optimal parametrlarni aniqlash imkonini beradi.

Kalit so’zlar: kamerali pech, gaz yoqilgʻisi, gorelka, diffuzion yonish, kinetik yonish, alanga, issiqlik yuklamasi, turbulent oqim, havoni oldindan qizdirish, yoriqli gorelka, issiqlik almashinuvi, barqaror yonish, NOx chiqindilari.

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Introduction

The combustion of fuel in chamber furnaces is carried out through the fuel system. This system consists of burners, valves for supplying natural gas and air, control, measuring and regulating devices, an automatic control system, and a blower fan that provides the air flow necessary for combustion. One element of the fuel system is the flue gas exhaust pipe, where recuperative heat exchangers are often installed to preheat the combustion air. The combustion of gaseous fuels proceeds through several stages: the formation of the gas–air mixture, its heating, thermal decomposition, ignition, and the combustion of the thermal decomposition products [1].

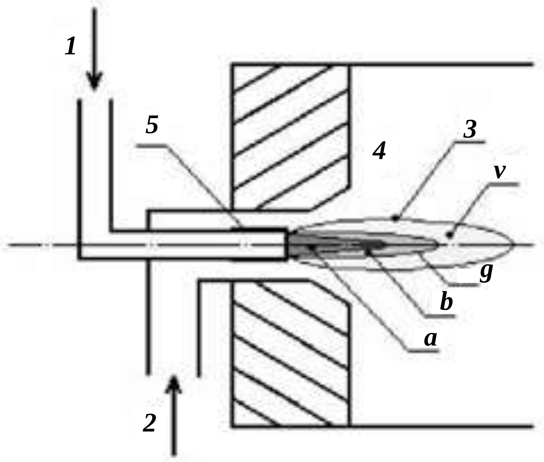


Fig.1. Diffusion burner scheme

1 – fuel supply; ***2*** – preheated air supply; ***3*** – flame; ***4*** – furnace chamber; ***5*** – burner nozzle; ***a*** – flame cone; ***b*** – zone of gas and combustion product mixture; ***v*** – combustion product zone; ***g*** – visible combustion front.

The mixing process also determines the combustion rate. Depending on the location where the gas – air mixture is formed, devices for such combustion are divided into two types – diffusion burners (Figure 1) and kinetic burners (Figure 2).

In diffusion burners, depending on the aerodynamic combustion regimes, there are laminar (molecular) and turbulent (diffusion) types of combustion. In such burners, only gas or a gas – air mixture with an insufficient amount of air (a < 1) is discharged from the burner nozzle, while the remaining required amount of air is supplied directly from the area surrounding the burner into the furnace chamber. The primary air forms the flame in the shape of a cone, while outside this cone the combustible gas reacts with the secondary air and burns completely [2].

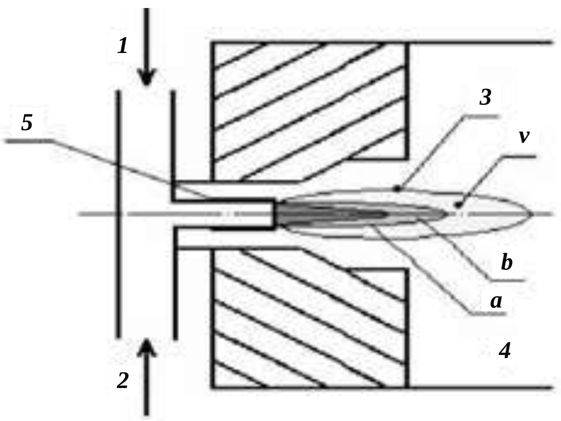
In diffusion combustion, the length of the turbulent flame can be calculated using the following formula:

$$L_{flame} = 173 D_0,\ mm \quad (1)$$

In the laminar flow of the fuel mixture in diffusion burners, the flame becomes elongated and “soft”, with a lower temperature that is close to that of the hot gases in the furnace. A shorter flame, on the other hand, is referred to as a “hard” flame due to the higher intensity of heat transfer from the hot gases to the surrounding environment and the greater flow velocity.

Fig. 2. Kinetic burner scheme

1 – fuel supply; ***2*** – air supply; ***3*** – flame; ***4*** – furnace chamber; ***5*** – burner nozzle; ***a*** – “cold” cone of the flame; ***b*** – visible combustion zone; ***v*** – invisible combustion zone.



A characteristic feature of kinetic burners is that, due to kinetic combustion, the preliminary mixing of the combustible gas and air, and the rapid heating of the mixture, thermal decomposition of hydrocarbons does not occur and soot is not formed. The flame is transparent and slightly shimmering, and combustion can even occur without a visible flame. In addition, laminar and turbulent combustion are also distinguished. In laminar combustion, the normal propagation velocity of the flame front V_n

may be smaller (1), equal (2), or greater (3) than the axial velocity of the gas – air mixture V_{ghm}. Figure 3.

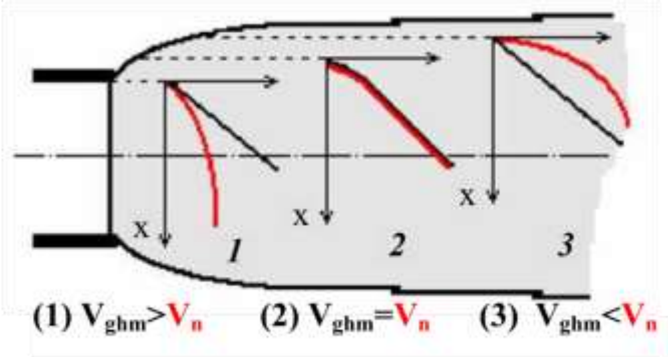


Fig. 3. Variation of velocities V_n and V_{ghm} along the flame length.

If $V_{ghm} > V_n$, the flame front detaches from the burner outlet and moves away from it. This occurs because, in the root region of the flame, the gas–air mixture becomes highly rarefied, and the necessary conditions for ignition (sufficiently high temperature and concentration) are not present. The flame detachment velocity V_{dv} and the extinction velocity V_{ev} depend on the diameter d (mm) of the burner nozzle orifice [3].

$$V_{dv} = 8.65\sqrt{1+0.2d^2}\ , \quad m/s \tag{2}$$

$$V_{ev} = 15\sqrt{1+0.2d^2}\ , \quad m/s \tag{3}$$

If $V_{ghm} = V_n$ (near the burner outlet), the flame remains stable and forms a steady ignition ring that ensures continuous combustion of the incoming fuel mixture at the periphery of the flow. If $V_{ghm} < V_n$, flame flashback (backfire) occurs; the flame being held directly inside the burner causes shocks, noise, and whistling sounds, creating a risk of explosion. To prevent flame detachment and combustion extinction, the fuel mixture flow is pre-turbulized and given a swirling motion.

There are various types of burners differing in design, capacity, and function:

• Swirl burners for rotary kilns, allowing adjustment of the flow velocity;

• Low-pressure and low-flow gas burners;

• Gas burners for high-temperature ceramic furnaces, in which primary (~20%) and secondary (~80%) air are preheated to 850–900 °C before being supplied.

Intensification of Gas Fuel Combustion

Combustion intensification is mainly achieved in two ways: by increasing the turbulent flame propagation velocity and by enlarging the surface area of the flame front.

The turbulent propagation velocity of the flame depends on the intensity of heat and mass transfer between the flame and the furnace chamber environment; therefore, it is necessary to create an optimal aerodynamic combustion regime [4].

The turbulent propagation velocity can also be increased by enhancing the chemical reaction rate, which is achieved by raising the temperature of the air (or fuel). However, excessive preheating of the fuel should be avoided, as it may lead to the thermal decomposition of heavy hydrocarbons, which is undesirable. It should be noted that the main heating of the combustible mixture occurs through the diffusion of highly heated combustion products in the furnace chamber. The rate of the chemical reaction can also be increased by raising the concentration of the reacting substances.

Increasing the flame front surface area is another key approach to intensifying the combustion process. The surface area of the flame front depends on the ignition method and the nature of the gas flow. To evaluate the heat load of the flame, the following equation is used:

$$\frac{Q}{V} = \frac{V_m F Q_\partial^p}{V}, \qquad kW/m^3 \tag{4}$$

or, after certain modifications and assumptions, the following expression is obtained:

$$\frac{Q}{V} = \frac{3V_n Q_\partial^p \rho\sqrt{V_{am}^2 + V_n^2}}{rV_{am}}, \qquad kW/m^3 \tag{5}$$

where: V_m – mass velocity of gas, *kg/(m*s)*; *F* and *V* – respectively, surface area *(m^2)* and volume *(m^3)* of the flame; V_n – normal propagation velocity of the flame front, *m/s*; *r* – burner radius, *m*; *ρ* – density of the combustible gas leaving the burner, *kg/m^3*. From the analysis of formula (5), it follows that the heat load is inversely proportional to the burner radius. This is explained by the fact that combustion occurs on the flame surface (an inert volume is formed inside the flame), and as the burner radius decreases, the flame surface area per unit volume increases, resulting in an increase in its volumetric heat load [5].

If the core of the flame breaks up into many microflames (small flames), the total combustion surface area per unit volume increases, and accordingly, the heat load also rises. Technically, this can be achieved by installing a grid at the burner outlet, resulting in the formation of multiple microflames.

In circular burners, the possibilities for intensifying combustion are limited, since a decrease in the burner nozzle diameter leads to a reduction in both its capacity and heat generation. To eliminate this drawback, slot burners are used; in such burners, even when the outlet cross-sectional area is equal to that of circular burners, the slot width is much smaller relative to their radius. As a result, in slot burners, the ignition velocity is higher from the flow periphery toward the central axis.

Based on formula (5), the volumetric heat load Q/V is considered as a parameter dependent on the ratio of the normal flame propagation velocity V_n to the axial flow velocity V_{ghm}. When $\beta = V_n / V_{ghm}$ is substituted, the expression takes the form $\frac{Q}{V} = \frac{3\rho Q_p}{r}\beta\sqrt{1+\beta^2}, \quad kW/m^3$. In physical terms, this indicates a linear increase with the enthalpy of combustion products (Q_p) and gas density (ρ), an increase in volumetric heat load as the burner radius decreases, and a monotonic rise in heat release with an increase in velocity. As the flow velocity V_{ghm} increases, β decreases; therefore, if other parameters remain unchanged, Q/V decreases. Conversely, if the flame front velocity V_n increases, Q/V rises with 1–2 times greater sensitivity (β ≈ 1× when small, β ≈ 2× when large). This result shows that the volumetric heat load can be increased by expanding the surface composed of many micro flames (reducing r, using slot or grid burners), reasonably preheating the air/fuel to increase β, and inducing swirl in the flow; however, a balance must be maintained considering constraints such as flame detachment or flashback, the thermal load on the refractory lining of the furnace walls, and NO_x limitations. For the calculations, $\rho = 0.8\ kg/m^3$, $Q_p = 5.10^4\ kJ/kg$, $r \in \{0.015, 0.02, 0.03\} m$, $V_{ghm} \in [5, 40]\ m/s$ and $V_n \in [0.05, 12]\ m/s$ were selected, and the graphs clearly demonstrated the following trends: (I) When r is small, Q/V becomes significantly larger; (II) For a given V_n, as V_{ghm} increases, Q/V decreases; (III) in areas V_n and V_{ghm}, the maximum zones Q/V are located V_n above, V_{ghm} below.

These observations confirm that, in increasing furnace efficiency, enlarging β within a safe range, selecting the burner shape to improve the surface-to-volume ratio, and enhancing heat and mass transfer are the most effective approaches.

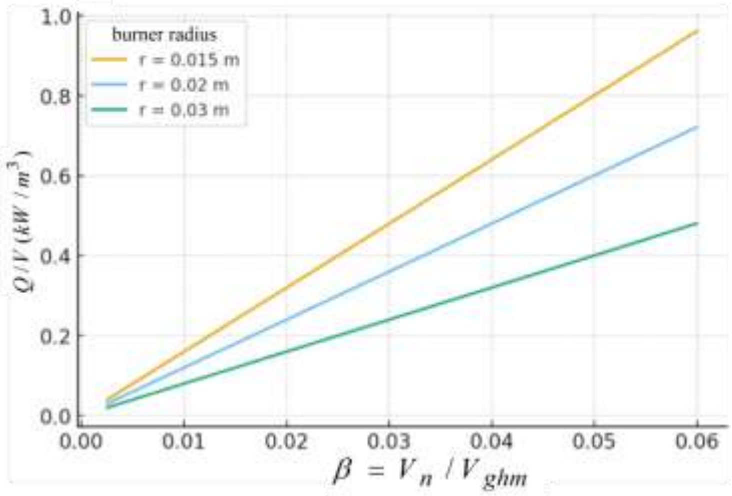


Fig. 4. Dependence of Q/V on $\beta = V_n / V_{ghm}$ (comparison by *r*)

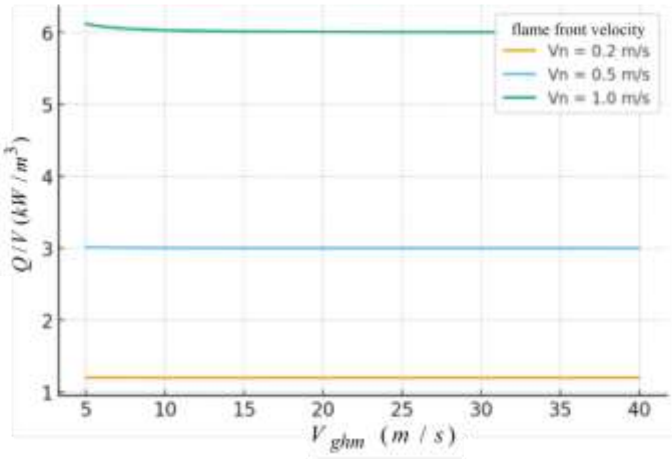


Fig. 5. Dependence of Q/V on $\beta = V_n / V_{ghm}$ along the axis (*r* = 0.02 m)

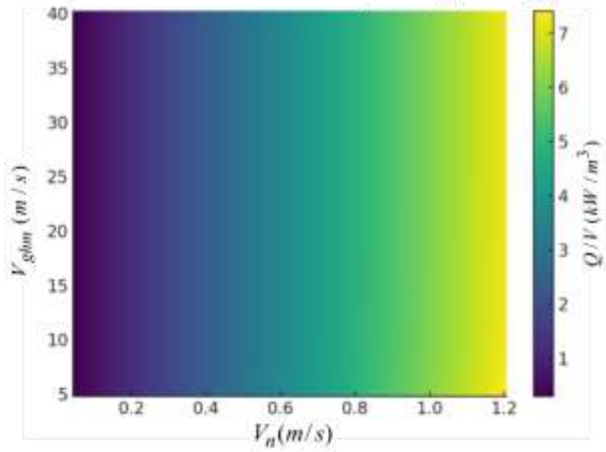


Fig. 6. Field of Q/V is $(V_n - V_{ghm})$.

In burners that impart a swirling motion to the gas mixture, accelerated ignition also occurs. In this case, rarefaction zones are formed along the flow axis, and the stream of high-temperature combustion products is directed toward the root of the flame. As a result, the flame takes the shape of a hollow cone, and combustion occurs both at the periphery and inside this cone.

Various methods of intensifying the gas fuel combustion process must be carefully analyzed and applied, as each of them may produce side effects related to the economic and environmental efficiency of furnace units. Improving one parameter is often associated with the deterioration of one or more other parameters.

The conducted modeling and graphical analysis showed that the volumetric heat load is primarily determined by the ratio of the normal flame propagation velocity to the axial flow velocity. As this ratio increases, heat release rises steadily and uniformly. When the fuel's mass combustion heat and the gas density are high, the volumetric load increases linearly. The burner shape is a highly influential factor: as the radius decreases, the ratio of the flame surface area to its volume increases, resulting in a significant rise in the heat load per unit volume. Conversely, an excessive increase in the axial flow velocity reduces the flame ratio and decreases the heat load, which may negatively affect energy efficiency.

The results show that, within practical ranges, a moderate increase in flame propagation velocity and selecting a smaller burner radius significantly improve the heat load. However, these approaches must be balanced with stability and safety constraints: at very high velocities, the risks of flame detachment or flashback increase, the load on the refractory lining and heat exchange surfaces of the furnace walls rises, and emissions (especially NO_x) may increase. Therefore, the most effective strategy is to increase the flame propagation velocity through turbulence, optimal preheating, and imparting swirl to the flow; maintain the axial flow velocity at the "necessary minimum" level; and use slot or grid-type burners with a high surface-to-volume ratio. Applying these principles in practical designs enhances furnace efficiency, maintains combustion stability, and ensures effective performance within environmental and operational constraints.

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