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DESIGN OF A COMBINED BURNER BASED ON THE PATTERNS OF INTERACTION BETWEEN AN EXTERNAL SWIRLING JET AND AN AXIAL DIRECT-FLOW JET

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The issue of providing fuel and energy resources to the population depends to a large extent on the wear of thermal networks, as well as heat-generating equipment, which, accordingly, forces the consumer to abandon the centralized heating supply in favor of decentralized supply. However, low-power heat-generating units for autonomous consumers do not most of the time operate under the rated mode.

The most promising way to solve the issue of energy conservation is to improve the utilization rate of fuel and energy resources in heat-generating units for decentralized heating systems that operate under non-stationary regimes.

An experimental study of the velocity field of interaction between the coaxial axial direct-flow and external swirling jets has established that the performance efficiency of a heat-generating plant at a change in the thermal load could be improved by controlling the resulting velocity field. For a more even distribution of temperature within the furnace volume, it has been proposed to supply fuel with an oxidizer in the furnace by the axial direct-flow and swirling coaxial jets.

It was revealed that at a distance of 2 diameters of the axial branch pipe from the cut there occurs a transverse toroidal vortex. The appearance of such a vortex is explained by the emergence of low-pressure regions due to the different angles of opening of the swirling outer jet and axial direct-flow jet. The considered dependence of change in the gas flow rate at a decrease in power has demonstrated that the gas flow rate in the proposed burner is less than that in analogs (vortex burner or direct-flow burner) by 10–15 % when the power of the burner is reduced. At the same time, the specified advantage is limited to the range of the burner's power of 50–130 kW.

The results reported confirm the possibility of controlling the velocity field and temperature distribution when the total fuel and oxidizer flow rate changes within the operational range of low-power heat-generating plants. The correspondence between the temperature field and the velocity field in the interaction of non-isothermal jets has also been shown

Keywords: burners, low pressure, pre-mixing, gas fuel, heat-generating plants

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1. Introduction

In any developed country in the world, the issue of providing fuel and energy resources to the population is acute. At the same time, the worn-out thermal networks, heat-generating equipment, and the inconsistency of services rendered to the consumer forces the latter to abandon the centralized heating supply in favor of decentralized supply. In addition, the centralized heating supply is inertial given its technical features (the lack of compliance with the amount of heat generated required by consumers).

This issue is resolved by installing individual heat-generating plants. In Europe, the choice of heating systems is based on operating costs but the heat-generating plants themselves do not operate most of the time under the rated mode. At the same time, this issue (heat-generating plant operation under a non-rated mode) cannot be solved by increasing the capacity resource of a plant. Since modern heating systems for buildings operate under a hydraulically variable regime, increasing boiler power would lead to a non-linear heating system performance. This issue can be resolved by improving the circuit-design characteristics, the thermal and aerodynamic parameters of the processes taking place in the burner devices of low-power heat generators taking into consideration the interaction of streams [1].

Thus, the most promising way to resolve the issue of energy saving is to increase the utilization rate of fuel and energy resources in heat-generating units for decentralized heating systems operating under non-stationary modes. At the same time, it is necessary to introduce innovative tools to manage combustion processes in the furnace space, which are confirmed by experimental studies [2].

Since there is a significant discrepancy between the experimental and theoretical data [3] while the mechanism for the formation of the resulting velocity and temperature fields is not revealed [4], the benefits of using the aerodynamic properties of such burners are limited. Therefore, studies on improving the aerodynamic structure of streams in the combustion chamber, which has a significant impact on the ability to control the temperature and velocity fields when changing the power of burners with the external swirling and axial gas jets, are relevant. To this end, it is necessary to identify the reasons for the reduction in the efficiency of burner operation when using the specified aerodynamic interaction of the jets, as well as to confirm the temperature field alignment with the velocity field in the interaction of non-isothermal jets.

2. Literature review and problem statement

Work [3] describes a swirling stream coming out of the nozzle in which the increase in the intensity of turbulent pulsations is explained only by the twisting flow. This does not take into consideration the effect of the precessing vortex core (PVC), which has an effect not only on the rotating stream but also on the axial jet. In this case, the issues of the effect of the amplitude of PVC oscillations, varying the resulting flow velocity, which negatively affects the aerodynamic and thermal processes in the combustion chamber, remain unresolved.

Paper [4] noted an increase in pulsations in the region of quasi-solid rotation (compared to the quasi-potential region). The reason for this could be the emerging transverse vortexes at the boundary between the outer swirling and internal axial jets. However, the proposed mathematical model of swirling flow movement corresponds to the movement of a weakly swirling jet; and the influence of the axial jet on the expansion and evolution of the total flow cannot be described within the proposed model.

In the theory of the calculation and structure of a gas torch [5], the conditions for the formation of the torch structure (including the degree of twisting) and the influence of interjet interaction on the resulting stream are not taken into account. However, the specified theoretical dependences on the assessment of thermal intensity could be used for comparative assessment of different types of gas torches.

In work [6], the reported solution on the turbulent core of a swirling flow, based on experimental data and the potential of the vortex, revealed the presence of deformation of the stream core. In this case, the supposed transition from a quasi-potential (in the outer part of the stream) to a quasi-solid (in the inner part) rotation can be accepted only when considering a two-phase flow.

The most advanced theoretical and experimental approaches on swirling currents are outlined in study [7], which are based on the assumption of the existence of a turbulent exchange factor, in three-dimensional cylindrical coordinates:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\rho r\cdot V_f\right)+\frac{1}{r}\frac{\partial}{\partial\Theta}\left(\rho\omega_f\right)+\frac{\partial}{\partial x}\left(\rho u_f\right)=$$
$$=\frac{1}{r}\frac{\partial}{\partial r}\left(r\cdot G_f\cdot\frac{\partial F}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial\Theta}\left(G_f\cdot\frac{\partial F}{\partial\Theta}\right)+$$
$$+\frac{\partial}{\partial x}\left(G_f\cdot\frac{\partial F}{\partial x}\right)+S_f, \tag{1}$$

where F is a dependent variable (u, ω, V); G_f and S_f are determined from the expressions given in [7].

However, solving such a system in conjunction with several algebraic equations that close the system is quite time-consuming for this particular case. At the same time, it is quite difficult to distinguish the effect of PVC and turbulent pulsations on the structure of the axial flow in the calculations.

Over the last 20 years, most studies into the aerodynamics of combined burners with a swirling jet have been performed only for large capacities (at least 1 MW) [8] while the aerodynamic structure of the current in low-power heat generators (up to 300 kW) is almost non-existent. At the same time, data on the efficiency of gas combustion by leading burner manufacturing companies (Ariston, De Dietrich, Baxi, Weishaupt, Riello, except for Cib Unigas) are given only for standard modes and do not take into consideration the effect of the aerodynamics of the resulting current on gas flow rate when varying the thermal power of burners. The ratio of power to flow rate varies in most cases around 10. In addition, in the proposed burner, a completely different process is principal – the interaction between an external swirling jet and an axial direct-flow jet whose mechanism's mathematical description in the gas burners is currently lacking. That is, the most appropriate in terms of obtaining a numerical adequate pattern of the resulting current is the use of experimental methods of research.

All this allows us to assert that the existing mathematical models are based on the theory of turbulence and cannot yield an adequate theoretical description of the interaction between an external swirling jet and an internal axial gas jet. There is also currently no evidence of a proportional relationship between the temperature and velocity fields and their distribution within the furnace volume.

At the same time, our analysis of known approaches [9–12] predetermines the relevance of the development and experimental study of the aerodynamic and thermal characteristics of the interacting external swirling gas flow and an axial internal gas flow.

To address this issue, it is necessary to improve the circuit-design characteristics, the thermal and aerodynamic parameters of the burner, taking into consideration experimental data. The resulting data on the temperature and velocity fields in the proposed interaction could reveal the impact of emerging transverse vortexes formed in the boundary layer, due to different angles of the opening of jets and the emergence of regions with low pressure.

The lack of data on the formation of the aerodynamic structure of the resulting current of the concentric swirling and axial gas jets does not solve the issue related to the efficient operation of low-power boilers. Resolving this task is especially important when using combined burners in boilers where heat power changes are required during the heating period.

3. The aim and objectives of the study

The aim of this study is to design a combined burner based on the identification of the interaction between an external swirling jet and an axial direct-flow jet, which would improve the operational efficiency of heat-generating plants at reduced thermal power.

To accomplish the aim, the following tasks have been set:

– to experimentally investigate the process of forming the aerodynamic structure of the resulting current of the concentric swirling and axial gas jets when their ratio of flow rate changes;

– to investigate the distribution of temperature and thermal intensity during combustion while mixing the external swirling airflow and the axial flow of natural gas at various gas flow rates using thermal imaging control during fire tests.

4. Materials and methods to study the interaction between gas jets in a combined burner

The interaction between an external swirling jet and an internal axial jet is illustrated by a natural-scale model whose general view is shown in Fig. 1. The model consists of two tangential branch pipes for air supply and an axial branch pipe for gas supply.

The strategy of managing the distribution of velocity and temperature is based on controlling the gas and airflow rates. This is achieved by maintaining the appropriate velocity ratio at the inlets to the burner from the axial and tangential branch pipes.

We studied the velocity field at the assembled experimental bench shown in Fig. 2.

The experimental study involved three stages:

– in the first stage, we investigated the field of resulting velocities (axial, tangential, radial) when the ratio of the volume of axial air fed to tangential air fed varied from 1:0.75 to 1:1.5, with a step of 0.25, and isothermal jets;

– in the second stage, the temperature distribution at the above flow rate ratios was investigated (heating was performed only for the axial flow, and the temperature difference between the tangential and axial jets at the inlets to the burner corresponded to a ratio of 1:3);

– in the third stage, fire tests were carried out at a steel-made burner sample registering by thermal imaging the uniformity of heating the outer body of the burner.

In our study, the following parameters were adopted constant:

– the ambient temperature, t_{medium}=22 °C;

– environmental pressure, P_{atm}=101,325 Pa;

– the initial temperature of the axial flow is 22 °C;

– the axial flow mass, 0.01 kg/s.

Variable parameters:

1) the total (axial and tangential) mass air flow rate, kg/s;

2) the temperature of the gases in the axial branch pipe, °C.

Vents RS-1-300 rheostat is used to regulate the engine revs of the fan, allowing the voltage to be smoothly adjusted from 1 to 230 Volts.

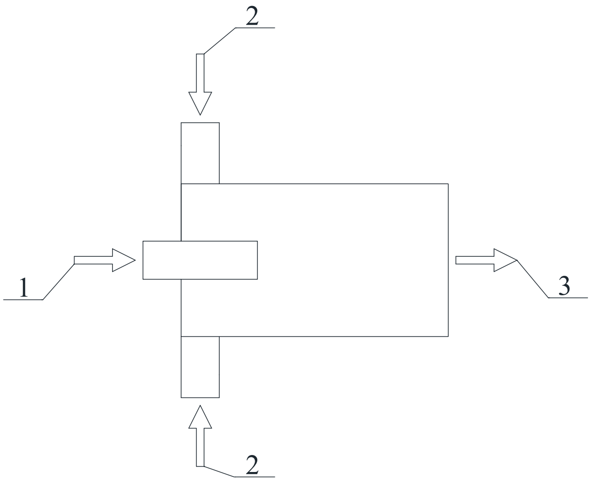


Fig. 1. General view of the natural-scale model of interaction between the external tangential air supply and axial gas supply: 1 – natural gas; 2 – air; 3 – resulting stream

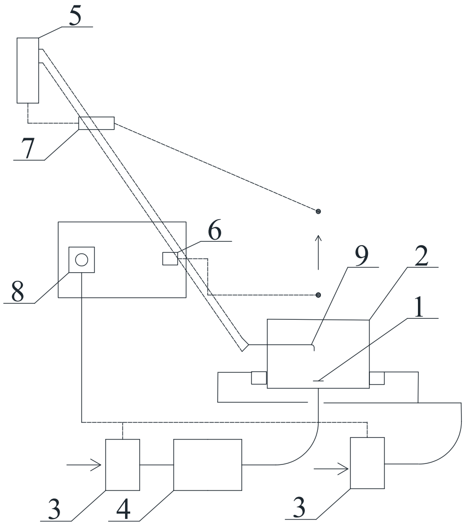


Fig. 2. Scheme of the experimental bench. 1 – axial branch pipe to supply gas to the burner; 2 – the body of the burner; 3 – fan; 4 – air heater; 5 – multifunctional device Testo 480; 6 – thermometer; 7 – Testo probe to measure the velocity and temperature; 8 – fan rheostat; 9 – Pitot tube

To adjust the air heating power, the laboratory autotransformer made by Electropribor plant was used, enabling the voltage on the TEH heater to be adjusted in the range of 0 to 240 Volts with a current power of up to 9 A.

A wattmeter is used to capture the power consumed by TEH and calculate the actual power, showing the instant power of the connected TEH and registering consumption over time.

Electronic thermometers with a remote thermal sensor on a flexible wire are used to control temperatures.

Pressure control is carried out with the help of Pitot tubes. The velocity and temperature of the air along the entire working length of the jet are controlled by the Testo 480 sensor. The Testo 480 sensor readings are captured using the Testo 480 multifunctional device.

The overall instrumental error of our experiment did not exceed 5 % when Testo 480 (Germany) was used for temperature and velocity measurements [9]. In the third stage of our research, the Testo 882 (Germany) thermal imaging camera was used with an appropriate representation of the thermogram and the temperature profile line along the length of the burner.

5. Results of studying the aerodynamic and thermal characteristics of the interaction between gas jets in a combined burner

5. 1. Experimental results of investigating the dependence of the temperature and velocity fields on the ratio of the volume of air supplied to the axial and tangential jets

The results of our experimental study are shown in Fig. 3–6 where the abscissa axis is the distance from the cut of the nozzle of the burner along its axis, m. The ordinate axis in Fig. 3–5 shows the velocity in m/s, and Fig. 6 – the temperature in °C.

It should be noted that Fig. 3 displays the chart of the change in the axial component of velocity; Fig. 4 – the chart of the tangential component of velocity; Fig. 5 – the chart of the radial component of velocity; Fig. 6 – the chart of temperature change in the resulting jet when the axial jet is heated to 70 °C.

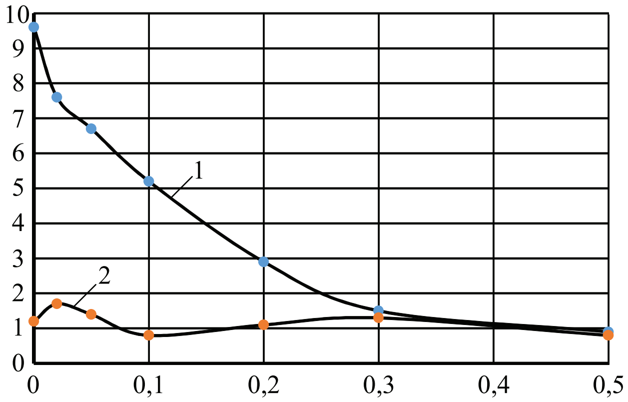


Fig. 3. Chart of the axial component of the resulting velocity after mixing the isothermal external swirling and axial direct-flow jets: 1 – the central axis of the burner, 2 – the middle line between the axial branch pipe and the burner case

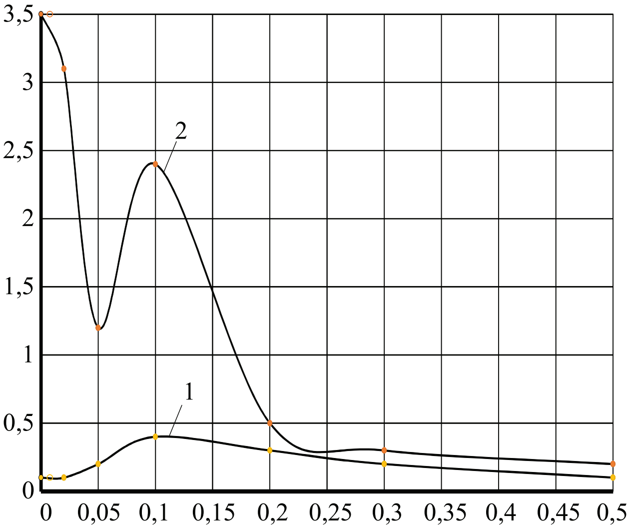


Fig. 4. Chart of the tangential component of the resulting velocity after mixing the isothermal external swirling and axial direct-flow jets: 1 – the central axis of the burner; 2 – the middle line between the axial branch pipe and the burner case

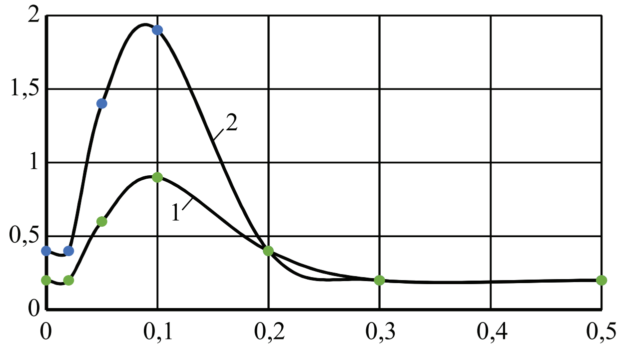


Fig. 5. Chart of the radial component of the resulting velocity after mixing the isothermal external swirling and axial direct-flow jets: 1 – the central axis of the burner; 2 – the middle line between the axial branch pipe and the burner case

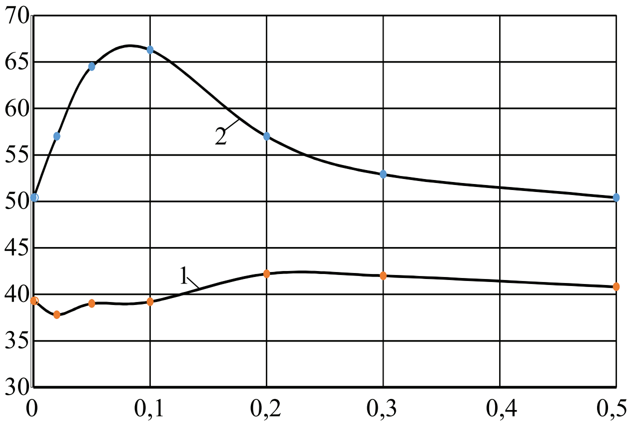


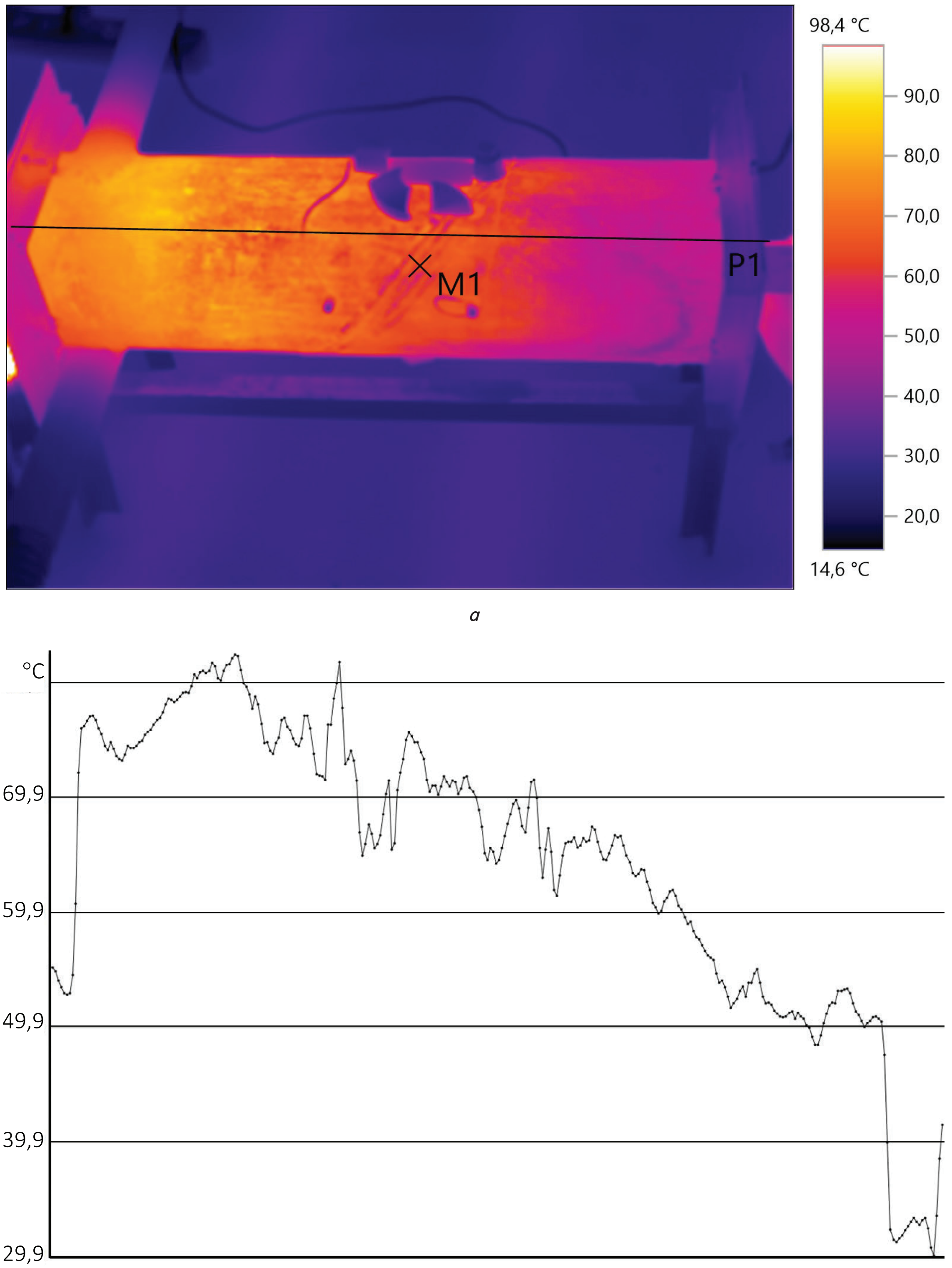
Fig. 6. Chart of temperature change after mixing the external swirling and axial jets: 1 – the central axis of the burner; 2 – the middle line between the axial tube and the burner case

The results of the experiment show that at the boundary of mixing the outer swirling and axial direct-flow jets there is a transverse vortex ring. This phenomenon is based on the obtained velocity jumps along the middle line between the axial branch pipe and the burner case (Fig. 3–5, line 2).

5. 2. Results of thermal imaging tests of the uniformity of the heating of the outer case of the burner

Fig. 7 shows a photograph of the burner with the external tangential air supply and axial gas supply, designed for fire tests. Fig. 8 demonstrates the thermogram and temperature distribution along the profile line along the length of the burner, which is 0.5 m.

Fig. 7. Burner for fire tests with tangential air supply and axial gas supply



a

b

Fig. 8. Thermogram and temperature distribution along the burner axis: *a* – thermogram of the outer surface of the burner when burning natural gas; *b* – temperature distribution along the profile line (by the length of the burner)

The charts shown in Fig. 8 confirm the relationship between the distribution of the velocity field and the temperature field within the volume of the burner. Thus, the comparison of highs for temperature (Fig. 6) and a maximum of the axial velocity (Fig. 4, 5) with the maximum received on the thermogram (Fig. 8, *b*) shows their match for the ordinate, which confirms our earlier assumption of their directly proportional relationship. In addition, a sharp drop in temperature (Fig. 6, 8, *b*) suggests a shortened torch of burning in the burner at the proposed interaction, which might reduce the design dimensions of heating devices.

Because the data from the manufacturers of burners with a capacity of up to 300 kW are almost the same (gas-burning efficiency is at least 96 % at maximum load, up to 83 % at a minimum (30 %) load). However, they do not take into consideration the effect exerted on heat generator efficiency by the dependence of the actual heat load to the amount of heat needed to maintain a minimum temperature in the furnace. Therefore, the characteristic of the proposed technique to form a torch for the most common, with a power of up to 300 kW, direct-flow round torch, and for the vortex one, is given for heat intensity (Fig. 9). A comparison of the change in the gas flow rate to the power of the burner (Fig. 10) has also been made. The ordinate axis in Fig. 9 shows heat intensity in kW/m^3, Fig. 10 – gas flow rate, nm^3/h; the axis of abscissa demonstrates the power of the burner, kW.

The dependence of change in the gas flow rate on reduced power (Fig. 10) has revealed that the proposed burner is characterized by the lowest gas flow rate (given the decrease in heat generator efficiency).

6. Discussion of results of studying the aerodynamic and thermal characteristics of interaction between gas jets in the combined burner

The result of our experimental study into the velocity field of the isothermal and non-isothermal interaction between the coaxial axial direct-flow and external swirling jets is the established possibility to improve the efficiency of a heat-generating plant. It has been shown that to control a velocity field by the volume of the furnace and when the heat load changes, it is necessary to supply fuel and oxidizer in the furnace by coaxial jets – an axial direct-flow jet and an external swirling jet.

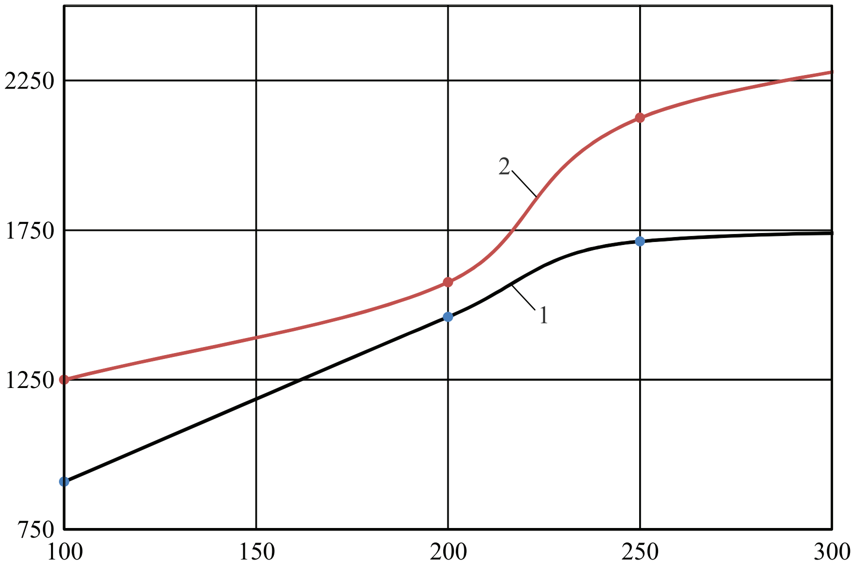


Fig. 9. Chart of heat intensity change due to burner power: 1 – proposed combined burner; 2 – a burner with a round, axial torch

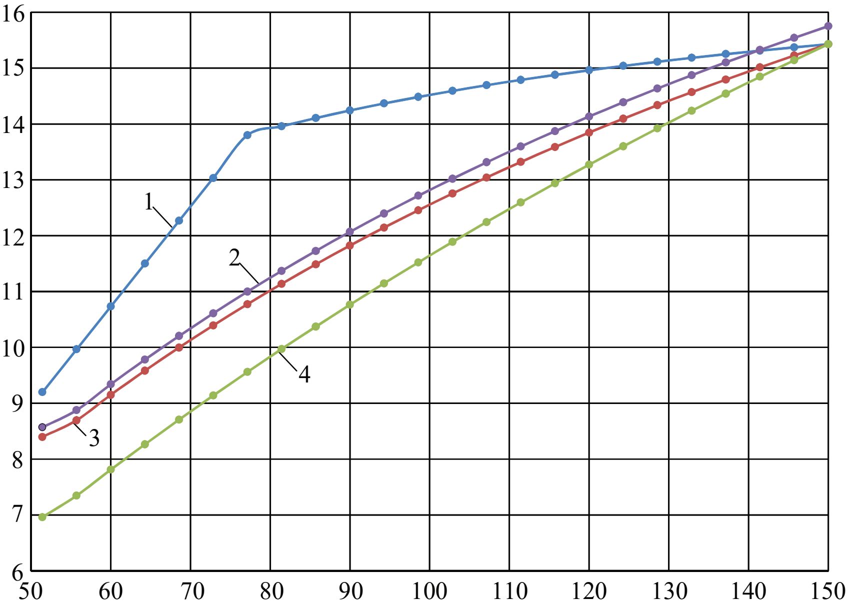


Fig. 10. Chart of the dependence of gas flow rate on a change in the power of the burner considering the heat generator efficiency: 1 – burner with a round, axial torch; 2 – IDEA burner (kW 35÷200); 3 – vortex burner; 4 – the proposed combined burner

At the same time, the degree of a swirl of the external jet can vary in the range of $0.3<S<1.2$ by changing the ratio of the volume of the fed external swirling jet to the volume fed through the axial branch pipe. This range corresponds to the development of the jet from weakly swirling to strongly swirling with a developed central region of reverse currents.

Our data confirm the possibility to regulate and evenly distribute temperature by the volume of the furnace in the proposed way. It has also been revealed that at a distance of 2 diameters of the axial branch pipe from the cut there is a transverse toroidal vortex (Fig. 4–6) whose occurrence is explained by different angles of opening of the swirling outer jet and axial direct-flow jet. That is, there is a formation of low-pressure zones due to the divergence of border layers of interacting jets.

Our results also confirm the possibility to control the field of velocity and temperature distribution when the total fuel and oxidizer flow rate changes. At the same time, the fire tests (Fig. 8) confirmed the conformity of the temperature field to the velocity field when an external swirling jet and an axial direct-flow jets interact, as shown in the burner thermogram.

The comparison of burners' heat-intensity (Fig. 9) showed that heat intensity under the proposed technique grows with an increase in power over 200 kW and more than that in a standard burner, which could cause heating surfaces to overheat. Therefore, the use of the proposed burner is recommended within the power of up to 200 kW.

The considered dependence of change in the gas flow rate at the reduction of power revealed that the gas flow rate in the proposed burner is less than that in analogs (a vortex burner, or a direct-flow burner) by 10–15 % when the burner power is reduced (Fig. 10). At the same time, this advantage is limited to the range of power of the burner of 50–130 kW.

Thus, the most rational way to use the proposed technique of gas combustion with the formation of the aerodynamic structure of the axial direct-flow jet of gas by the outer swirling jet in the range of power from 50 to 130 kW. The resulting range likely fits the region when the outer swirling jet brakes, along the inner boundary, the axial gas jet (at minimal power). As the power increases, the outer swirling jet increases the angle of its opening to 43°, which, given the angle of the axial jet opening of 12–14°, forms a region of low pressure between the jets. This fact explains the phenomenon of the appearance of a transverse vortex ring revealed as a result of the aerodynamic experiments (Fig. 3–5).

The special feature of the proposed method and our results is to conduct an experiment in the actual range of gas burner operation. In contrast to existing ideas about the development of the way of jet mixing, it was revealed that at a distance of 2 diameters of the axial branch pipe from the cut there is a transverse toroidal vortex. The emergence of such a vortex is explained by the appearance of low-pressure regions due to the different angles of opening of the swirling outer jet and axial direct-flow jet.

The current study is limited to the region of experimental measurements performed (for the velocity, temperature, and the degree of a swirl of the outer jet), that is, to extrapolate the results one would need to perform relevant studies.

The disadvantage of the current work is the lack of a theoretical model of the studied process; however, there is a high probability that the standard theoretical model can be verified. At the same time, it should be emphasized that the aerodynamic and thermal studies were carried out under the modes as close as possible to the actual modes of low-power burner operation.

It is obvious that in the further research of the process of interaction between an external swirling jet and an axial jet aimed at deriving a full-fledged theoretical model, it would be necessary to use the stochastic deterministic models of the process.

7. Conclusions

1. A combined burner has been designed on the basis of results from our experimental study into the velocity field of interaction between the coaxial axial direct-flow and external swirling jets. The study findings related to a given structure confirm the possibility to control the fields of velocity and temperature within the volume of the furnace when the heat load changes. This indicates that the low-pressure zones are formed due to the divergence of the boundary layers of interacting jets.

2. The results of our experimental study of the non-isothermal interaction between an external swirling jet and an axial direct-flow jet during fire tests confirm the possibility of achieving even temperature distribution within the volume of the furnace when using the proposed burner. In addition, the experimental study of the proposed combined burner at the designed experimental bench has revealed the appearance, at a distance of 2 diameters of the axial branch pipe from its cut, of a transverse toroidal vortex. The emergence of such a vortex is explained by the different angles of opening of the swirling outer jet and axial direct-flow jet. It was revealed that the most rational is to use the proposed technique of gas combustion with the formation of the aerodynamic structure of the axial direct-flow gas jet by an outer swirling jet in the range of power from 50 to 130 kW.

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