Запропонована універсальна методика проектування промислового газопальникового обладнання на основі струменево-нішевої технології спалювання палива (СНТ). Представлено рекомендації щодо вибору основних геометричних параметрів паливо розподілу у пальникових пристроях (ПП) з можливістю спалювання природного та скрапленого пальних газів. Ціллю роботи є створення універсального ПП, який би задовольняв умовам широкої номенклатури існуючого вогнетехнічного обладнання (ВО)

Ключові слова: стабілізатор полум'я, пальниковий пристрій, «бідний» зрив полум'я, паливорозподіл, зріджений газ

Предложена универсальная методика проектирования промышленного газогорелочного оборудования на основе струйно-нишевой технологии сжигания топлива (СНТ). Предложены рекомендации по выбору геометрических параметров топливораспределения в горелочных устройствах (ГУ) с возможностью сжигания природного и сжиженного горючих газов. Целью работы является создание универсального горелочного устройства, которое бы удовлетворяло условиям широкой номенклатуры существующего огнетехнического оборудования (ОО)

Ключевые слова: стабилизатор пламени, горелочное устройство, «бедный» срыв пламени, топливоподача, сжиженный газ

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IMPROVEMENT OF RELIABILITY OF FIRE ENGINEERING EQUIPMENT BASED ON A JET-NICHE TECHNOLOGY

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1. Introduction

The use of gas as the primary energy carrier and the major chemical raw material underlies the functioning and development of such important industries as power generation, metallurgical, chemical, oil refining, cement manufacturing industries, machine-building, and others. A high percentage of gas is consumed by public services [1].

Such a widespread use of natural gas in industry and power sector is explained by its high energy and environmental indicators in comparison with other types of organic fuel. An important aspect in this regard is the simplicity of its transportation and distribution. The use of liquefied natural gas is becoming more common due to the intensification of power consumption [2]. The benefits of using gas-like fuel include a possibility to automate complex fire-technical processes, improve the culture of production, create high sanitary-hygienic working conditions, and decrease environmental burden on the air basin.

It should be noted that the disruption of technology of fossil fuel burning leads to a significant increase in chemical and mechanical underburning, as well as to an increase in the concentration of nitrogen oxides whose quantities are clearly defined and regulated [3].

2. Literature review and problem statement

One of the main elements of fuel consuming equipment is a burning device (BD) whose operational characteristics largely determine the efficiency, reliability and environmental friendliness of the unit's work [4].

Devices that implement technology of combustion based of the system of flame stabilizers occupy a special place among known designs of burners. Poorly streamlined bodies, for example in the form of a cylinder [5], a perforated surface [6], an angle [7], or a plate [8], are used as stabilizers in such burners.

The methods of computer simulation have been used recently quite effectively to study peculiarities of the process of technical combustion. The influence of geometrical and operational parameters on combustion efficiency, the boundaries of stable flame fixation, temperature fields beyond a poorly streamlined body, was numerically established in paper [9]. One of the main parameters, which determines the boundaries of steady fuel combustion in the stabilizer, is the process of mass exchange between an active flow of burning mixture and the circulation area beyond stabilizers [10]. However, in all these works, the studies apply only to the interaction between a flow of burning mixture and the stabilizer. This scheme has some limitations in practice, especially when using such a design for FE, operating under stoichiometric conditions. The specified features can be largely solved by organizing the interaction between a flow of an oxidizer and the perpendicular system of fuel jets, which has a number of advantages in comparison with the stabilization by poorly streamlined bodies. The first advantage is ensured by a smooth regulation of physical dimensions of the so-called «jet screen». The second advantage is provided by the auto-model processes of mixture formation in the area of reverse jets, which occurs in the shaded area of the screen and the area of circulation at the minimum mixture flow rate. The jet-niche system (JNS) operates bases on this principle and it is a more effective means of flame stabilization compared with a variety of different options for simple jet stabilization or stabilization by a poorly streamlined body. JNS makes it possible to control the operation process of BD in a wider range of thermal loads [11].

Placing JNS on a flat autonomous collector-pylon laid the basis for the creation of industrial JNS-based gas burner equipment. The following principles are at the core of the technology: rational fuel distribution in the oxidizer flow; a steady regulated aerodynamic structure of the flow of fuel, an oxidizer and combustion products; self-regulation of the composition of burning mixture in the area of flame stabilization [12]. The proposed design has such advantages compared with the most common registering BD with a twist of the oxidizer flow as a much lower aerodynamic drag along the tracts of fuel and an oxidizer and an increased coefficient of working load regulation [13]. The specified technology is based on the work carried out at KPI named after Igor Sikorsky.

The prospects of the proposed design were proved by a rather wide industrial implementation of the technology. At present, modernization of a great number of FE in Ukraine and abroad, which include objects in power industry, metallurgy, chemical and light industry, was carried out based on JNT [13].

A cycle of works on the improvement of operating parameters of JNT has been performed lately. The most significant ones include the work on development of the cooling systems of stabilization burners [14]. Recommendations were obtained regarding design implementation of the burners' self-cooling systems by heating an oxidizer and fuel.

An important requirement to reliable and efficient operation of FE is the possibility to maintain the rated level of temperatures in a furnace space. During start, it is necessary to prevent a «thermal shock» and temperature non-uniformity in the volume. Most often, organization of the working process of BD, which mostly operate according to the principle of a «twist» in the flow of fuel and an oxidizer, does not allow starting the equipment at loads that are less than 20 % of the rated, which does not contribute to the uniformity of a temperature field in the operating space and leads to the destruction of thermally loaded elements of FE and BD. Paper [15] describes a technique for the estimation calculation of the influence of local non-uniformity of heat flows on the damage and residual resource of power equipment. Considering the results obtained in the work, the issues related to advantages of the devices of this type in comparison with register burners remain unresolved.

Universality of the technology regarding the possibility of using several kinds of fuel is essential, because the situations, which require reserving the fuel supply system, repeatedly arise at the facilities of low-power industry, municipal economy, or agriculture.

An example is the unexpected disruptions in gas supply to certain settlements when a power supply delay can result in significant losses. The need to organize autonomous operation of a fire-technical object (FO) very often occurs under conditions of mobile movable power plants. In this regard, the mixture of liquefied propane-butane is considered to be very promising. Attractiveness of its characteristics is explained by the presence in its composition of hydrocarbons, which are liquefied at the minimal pressure, as well as the absence of such inert gases as nitrogen and carbon dioxide [16].

Analysis of papers in the examined field makes it possible to determine the vectors of development of JNT in accordance with the modern state of fuel and energy complex and capabilities of the industry in general.

At the first stage of development it is necessary to determine the improvement of regulated characteristics of burners with the purpose of decreasing a technical minimum of load on the modernized equipment.

The next step implies defining the possibilities of application of gases that differ by their heat generation capacity during FE modernization based on JNT. The stated tasks can be solved to a large extent by the rational selection of fuel distribution parameters.

3. The aim and objectives of the study

The aim of present study is to determine the ways to improve effectiveness of FE operation under conditions of variable modes in its operation by expanding the boundaries of steady work of JNT burners and the coefficient of working regulation of modernized facilities. This would make it possible to decrease fuel consumption in starting modes, as well as to adapt the fuel distribution system of burner devices (BD) to the combustion of gases with different stoichiometry and to enhance FE reliability in general.

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

– to explore the boundaries of steady fuel combustion in the working range of change in the mode and geometrical parameters of the system by determining «detachment» boundaries in the area of depleted combustion mixture at the stages of flame ignition and flame die-out;

– to construct regression dependences for the coefficient of air excess in the system (α) under the modes of flame ignition and flame die-out depending on the basic geometrical parameters of the system – the diameter of gas openings (d), the distance from the detachment edge of the niche to gas openings (L_1), as well as a relative step of location of gas openings ($\bar{S} = S/d$) at minimum starting speeds of incident air flow W_A=5 m/s and working speeds (W_A=15 m/s) (Fig. 2);

– to explore the obtained dependences for the presence of a maximum and to determine the range of recommended values for natural and liquefied gases (the use of a liquefied propane-butane mixture is considered as a reserve fuel at acting FE);

– to take into account the results in the procedure for designing industrial gas burner equipment for a wide range of heat engineering problems, which are mostly related to the modernization of existing fire-technical equipment.

4. Test bench, fuel gases, and procedure for conducting the experiment

4. 1. Description of the test bench

The experimental part of the research was carried out at a fire-testing bench, specially equipped with all necessary equipment; its schematic is shown in Fig. 1.

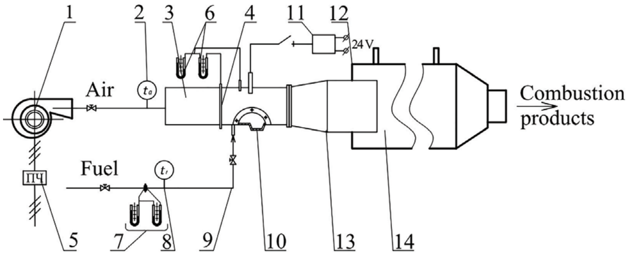


Fig. 1. Schematic of the laboratory fire-testing bench: 1 – fan; 2 – thermoelectric transducer for measurement of air temperature; 3 – starting section; 4 – integrated Pitot tube; 5 – device for frequency regulation of fan rotations; 6, 7 – manometer units; 8 – thermoelectric transducer for measurement of fuel temperature; 9 – fuel feed to the main collector, located on jet-niche module; 10 – jet-niche module with a view window; 11 – spark-plug; 12 – chokes for sampling and measurement of gases temperature along the flame length; 13 – diffuser; 14 – lined fire section

The air for combustion is fed to the operating area by fan 1 with the possibility of adjusting its consumption due to a change in frequency of working wheel rotation of the blower by frequency converter 5. The flow rate is measured by two integrating Pitot tubes 4, established cross-wise in the air channel, the signal of which is displayed by laboratory micromanometers 6. Fuel gas is fed to gas collector 9, which is placed directly in the working zone of stabilizer 10; its design allows quick replacement of working modules. Fuel consumption is measured by the weighing device, pressure changes are fixed by cup micromanometers 10.

Combustible mixture is ignited by spark-plug 11. Combustion products, as well as non-reacted burning mixture, are removed to the smoke pipe of the laboratory. The place of flame stabilization 10 is equipped with a view window, made of quartz, which is designed to study the processes of ignition/die out of the flame in the stabilizer (Fig. 2). To determine the temperatures of fuel and an oxidizer, thermoelectrical resistance converters (TRC) 2, 8 were additionally used. To provide permissible temperatures of the most thermally stresses elements of the stabilizer, its forced air cooling was implemented.

Schematic of location of JNS on a flat fuel propagating collector-pylon is shown in Fig. 2.

The procedure for experimental research is a repeated measurement of fuel consumption under the mode of flame ignition and die out at the assigned flow rate of an oxidizer. Measurement at each point was repeated at least four times with the subsequent statistical analysis of results. Further interpretation of results was considered as arithmetic mean of the value of the studied parameter considering shortcomings of the experiment. The level of significance of measurements is 95 %.

Results of the experiment were processed with the use of methods of mathematical planning of the experiment. The used approach allows us to study simultaneously the impact of a larger number of factors and to establish existence in the system of inter-factor interactions with quantitative consideration of each factor, and to assess the effects of these interactions [17, 18].

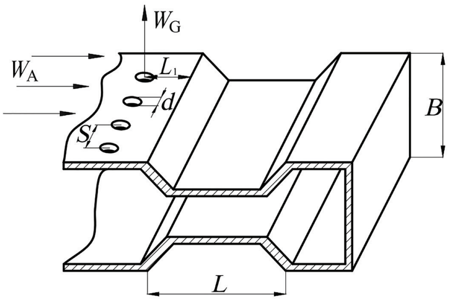


Fig. 2. Schematic of location of JNS on a flat stabilizer: W_A – air velocity, W_G – fuel velocity, L_1 – distance of fuel openings from detachment edge of the niche, S – step of openings location, d – diameters of openings, L – length of niche cavity, B – thickness of stabilizer

4. 2. Thermo-physical characteristics of the examined fuel gases

Combustion stability in the examined system was determined for natural gas and propane-butane mixture, the characteristics of these fuel gases are given in Table 1.

Liquefied gas is a mixture of propane-butane in a volumetric ratio of 50/50 %; natural gas has 98 % of methane in its composition.

Table 1

Thermo-physical characteristics of combustible gases

Property of gas	Unit	Gas		
		Methane	Propane	Butane
Density	kg/m^3	0.717	2.004	2.703
Boundary of flame propagation:				
– lower C_L	% by vol.	5.0	2.2	1.9
– higher C_H	% by vol.	15.0	9.5	8.5
Ignition temperature t_{IGN}	°C	645–850	530–568	490–569
Normal flame propagation rate $U_{n\max}$	cm/s	29–33.8	39	37.9
Stoichiometric coefficient:				
– L_V	m^3/m^3	9.52	23.9	31.0
– L_O	kg/kg	17.23	15.7	15.46
Lower combustion heat Q_H^P	mJ/m^3	35.8	96.0	118.7
Combustion temperature $T_{G\max}$	°C	2040	2155	2118
Ignition energy, Q_{IGN}	mJ	0.48	0.39	0.38

The process of flame stabilization depends on the thermo-physical characteristics of fuel gas, the basic of which include flame propagation rate, concentration ignition boundaries and temperature of mixture ignition. Stability of combustion, flame parameters and emission indicators of an object are determined primarily by the fuel type and then by technical features of PE.

4. 3. Mathematical planning of the experiment

Construction of dependences with consideration of more than 3 factors proved to be almost non-implemented. That is why to solve the tasks, set in the research, it was decided to study the impact of only basic geometrical parameters at fixed mode parameters. Therefore, the central composition plan of the experiment was designed to determine the influence of geometric characteristics of fuel distribution at the boundary of steady combustion. The studied parameters included diameter of the gas openings (d), distance from the detachment edge of the niche of gas openings (L_1), as well as relative step of location (S/d). The basis of the mathematical planning in this method was conduction of the full-factor experiment (FFE), the result of which is linear regressive dependences, which do not make it possible to obtain the adequate mathematical description of the studied flameout phenomenon. That is why, for consideration of inter-factor interactions, it is appropriate to conduct additional measurements at the star points and at the center of the factor space for construction of quadratic term of polynomial. The main purpose of planning is to construct a mathematical model of dependence of total coefficient of air excess (optimization parameter) in starting modes on geometric parameters of fuel distribution in JNS. The results were obtained at starting rate of incident flow of an oxidizer $W_A=5$ m/s and operating air velocity $W_A=15$ m/s. Feedback surface is obtained from the polynomial of the second degree $\alpha_{start}=f(d,L_1,\bar{S})$ for natural gas and propane-butane mixture.

The following values of geometric parameters were accepted as the basic levels of factors during construction of the model: $d=X_1=3$ mm, $L_1=X_2=17.5$ mm, $S/d=X_3=3.45$. $\Delta X_1=1$ mm was accepted by factor X_1, $\Delta X_2=7.5$ mm – by X_2, $\Delta X_3=1.15$ – by factor X_3 (Table 2).

Table 2

Conditions of experiment planning

Characteristic of the plan	Code scale x_i	Natural scale		
		$x_1=d$, mm	$x_2=L_1$, mm	$x_3=\bar{S}$
Zero level	0	3.0	17.5	3.45
Upper level	+1	4.0	25	4.6
Lower level	−1	2.0	10	2.3
Star points	+1.682 −1.682	4.68 1.32	30.1 5.0	5.4 1.5

Coordinates of the star points and other features of designing the plan of the experiment, obtaining regression equations were performed according to [17].

Variable X_1 is the coded variable of value of diameters of gas feeding openings, mm; X_2 is the coded variable of the parameter of distance of gas feeding openings from the detachment edge of the niche cavity, mm; X_3 is the coded variable of relative step of location of openings.

Significance of coefficients b_i was determined from condition $|b_i|>S_{b_i}t$, where t is the value of Student criterion, S_{bi} is the estimations of variances during determining regression coefficients. Verification of adequacy of the derived regressive equations was performed using the Fisher criterion. Results of adequacy evaluation are shown in Table 3.

Reproducibility of the studies was verified by conducting parallel experiments for all points of the plan. Under all the examined conditions (fuel and fuel distribution geometry) for each parameter, calculation value of Cochran criterion (G_p) was compared with the one from table (G). In all situations, at confidence probability P=0.95, we obtained $G_p<G$, that is, experiments should be considered reproducible.

Table 3

Evaluation of adequacy of regressive dependences of starting characteristics of gas distribution in JNS

Fuel	Parameter	S_y^2	S_{AD}^2	F_p	F_{cr}
Natural gas	Ignition, ($W_A=5$ m/s)	0.46	2.88	6.19	6.2
	Die out, ($W_A=15$ m/s)	1.37	7.85	5.72	6.2
Liquefied gas	Ignition, ($W_A=5$ m/s)	2.8	13.67	4.88	6.2
	Die out, ($W_A=15$ m/s)	1.74	9.44	5.41	6.2

5. Results of study of the flameout process in JNS

Fig. 3 shows results of experimental measurements of the boundaries of ignition and «poor» flame die-out in the stabilizer depending on the relative step of location of fuel openings $\bar{S}$.

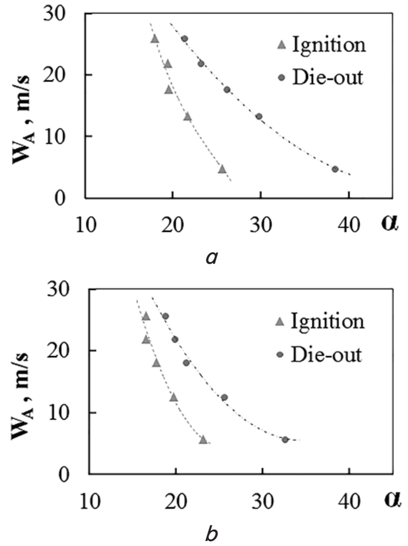


Fig. 3. Boundaries of ignition and poor flame die-out in JNS at $d=4$ mm, $L_1=15$ mm, fuel — natural gas: a — $\bar{S}=2.3$; b — $\bar{S}=4.6$

When analyzing these results, it is necessary to pay attention to the feature that an increase in the distance between gas feeding openings significantly narrows the boundaries of steady combustion, which is basically pronounced in flame die out modes. For all obtained results, characteristic location of the ignition boundary is in the zone of more enriched mixtures in relation to the poor die out boundary. In the case $\bar{S}=2.3$, the biggest difference in consumption for two studied modes is found in the area of $W_A<15$ m/s and makes up 25...33 %. A qualitatively similar pattern is observed for the geometry of fuel distribution at $\bar{S}=4.6$, but with an insignificant increase in quantitative indicators – fuel consumption at starting increases by 20 % in comparison with the mode of flame die-out in the burner. This fact is explained, first of all, by the first volume of the ignition source. During ignition, it is a point spark, which is located in the geometrical center of the niche cavity. During die out, the fuel mixture is ignited due to the next flame, which is limited by the walls of a niche and is significantly larger in volume compared with a spark of the spark-plug.

Regarding the impact of relative step, the following should be noted. At an increase in the value by 2 times $\overline{S}$ from 2.3 to 4.6, fuel consumption in the starting mode increases on average by 10.2 % within the whole studied range of values of air velocity head, and in the die out mode – by 14.9 %. In terms of reliability of operation of fire-technical equipment in the starting mode and in the process of the maximal possible decrease in FE workload, an increase in step $\overline{S}$ decreases coefficient of regulation K_R of the stabilizer by 15 %, respectively. The largest narrowing of steady combustion boundaries is observed at maximum (starting) velocities of an oxidizer and is almost 1/3 of the steady range of equipment regulation.

It should be stressed that all experimental results for the two studied fuels are similar qualitatively and differ only in their quantitative indicators.

Taking into account the points of the factor space, determined additionally to 9 points of FFE, we obtained the ratios that can be used to estimate the value of total coefficient of air excess in JNS at poor flame die out depending on diameters of gas feeding openings (1.3–4.7 mm), distances from the detachment edge of the niche cavity (5.0–30.0 mm), as well as relative step of openings location (1.5–5.4).

To assess the influence of fuel feed parameters, we presented results of planning of the experiment for determining response function for total coefficient of air excess in the system in the mode of poor flameout and flame ignition mode. Regressive dependences of detachment characteristics are listed below.

Natural gas, ignition mode:

$$\alpha_\Sigma = 98.2 - 12.4d - 2.1L_1 - 17.1\overline{S} + 0.4L_1\overline{S} + 2.6d\overline{S}. \qquad (1)$$

Natural gas, a die-out mode:

$$\alpha_\Sigma = 112.5 - 8.5d - 0.3L_1 - 30.8\overline{S} - 1.73d^2 - \\ - 0.04L_1^2 + 0.6S^2 + 0.4L_1\overline{S} + 4.7d\overline{S}. \qquad (2)$$

Liquefied gas, ignition mode:

$$\alpha_\Sigma = 21.7 - 0.7d - 0.6L_1 - 2.74\overline{S} + 1.1d^2 + \\ + 0.03L_1^2 + 0.73\overline{S}^2 - 0.05L_1\overline{S} + 4.7d\overline{S}. \qquad (3)$$

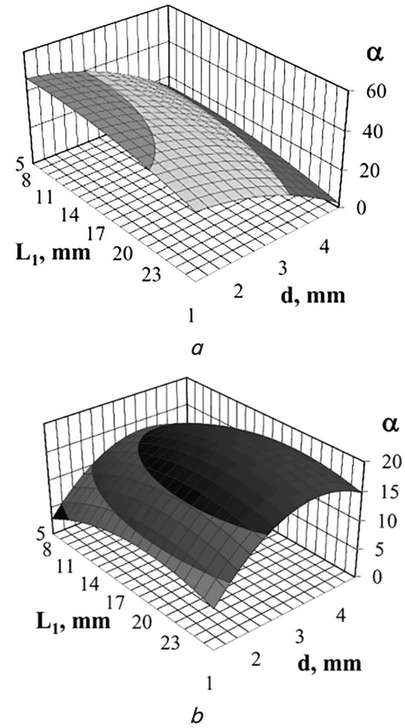
Liquefied gas, a die-out mode

$$\alpha_\Sigma = 45.5 - 6.3d - 0.6L_1 - 4.6\overline{S} + 1.8d\overline{S}. \qquad (4)$$

Preliminary analysis of results with the help of evaluation of coefficients at variables in equations (1) and (3) shows the influence of geometric parameters on starting features of the system with assigned geometry, and expressions (2) and (4) – the range of steady combustion in the system.

Thus, in all presented expressions, an increase in the studied geometric parameters in greater or lesser degree decreases value α_Σ, thereby worsening starting features of the stabilizer (this increases fuel consumption at start). Of all the examined parameters, a change in relative step $\overline{S}$. makes the greatest influence during combustion of natural gas. Firstly, this is explained by a change in fuel concentration in the area of niche cavity, and secondly, by the influence of relative step on hydrodynamics of the circulating flow in the niche cavity.

When selecting optimal fuel distribution parameters, it is advisable to conduct a reciprocal analysis of all examined factors by the results of planning (Fig. 4).



a

b

Fig. 4. Dependence of total coefficient of air excess air on the basic parameters of fuel distribution at the boundary of «poor» flameout, height of air channel H_{Ch} = 72 mm: *a* – $\overline{S}$ = 2.3; *b* – $\overline{S}$ = 4.6; fuel is natural gas

Based on the results of the studied flameout processes under these conditions, it is possible to argue about the possibility of improvement of coefficient of regulation of the system in case of adequate selection of the studied parameters. In the range of the studied geometric characteristics, the most acceptable combination for natural gas is the geometry with the least values of parameters (taking into account the results of measurements at the star points). As regards the propane-butane mixture, for improvement of the start, it is necessary to select values of parameters d and $\overline{S}$ from the range of the studied values, vice versa, towards increasing, due to much greater caloric and significant difference of thermophysical characteristics. Maximization of the derived dependences (1)–(4) will make it possible to obtain the regions of optimal values of fuel distribution parameters, which can be used in the design of universal JNT-based PE. The results obtained are given in Table 4.

Table 4

Regions of optimal values of fuel distribution parameters of BD of JNT

Fuel distribution parameter	Designation of parameter	Region of optimal values for natural gas	Region of optimal values for liquefied gas
Diameter of openings	d	1.3...2.0 mm	4.5...5.0 mm
Step of location	$\overline{S}$	1.5...1.7	4.3...4.8
Distance from niche	L_1	5.0...7.0 mm	5.0...7.0 mm

The results showed a definite relationship between «starting» characteristics and «disruption» qualities of the system, so the die out mode was selected for consideration in subsequent analysis. It is also important to note the fact that the use of liquefied gas on the burners for natural gas requires correction of the fuel distribution system. It is explained by impossibility of providing stoichiometric fuel concentration in the volume of the mixture in the area of flame stabilization at the application of fuel feed geometry for natural gas. In fact, improvement of starting modes for more caloric fuel requires smaller gas concentrations, which is achieved at least by an increased step of gas feed openings in comparison with gas feed of burners for natural gas.

From the results of solution of an optimization problem, it was determined that the combination of factors for natural gas is the fuel feed geometry with the least values of parameters in the studied range is: $d=1.3$ mm, $L=5$ mm, $\overline{S}=1.5$. When it comes to the propane-butane mixture, an increase in step and in distance L_1 improves the start of the burner for propane due to approximation to stoichiometric concentration of fuel in the flame stabilizer area.

As Fig. 5 shows, for liquefied gas at relative step $\overline{S}=4.6$ when using large diameters, it is appropriate to move the value of distance L_1 towards increasing (10...30 mm), which is illustrated by an increase in characteristics of flameout (dotted line in Fig. 5, *a, b*). The influence L_1 for smaller values of diameters ($d<3.0$ mm) is insignificant.

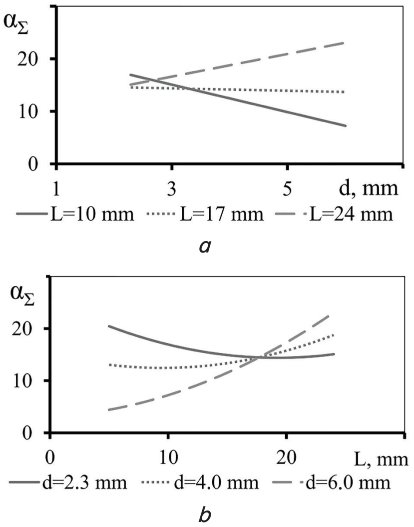


Fig. 5. Characteristic of poor flameout for liquefied gas at $\overline{S}=4.6$: *a* — dependence on diameter, *b* — dependence on parameter of distance L_1

When designing BD, the principle of modularity of burners is used, when a single pylon of flame, the operation characteristics of which fully determine the main characteristics of burners, is considered as an independent fuel cell. Thermal capacity of the device is «collected» by the appropriate number of single modules and is a uniform grade of flame stabilizers. The length of the stabilizers is selected in accordance with the design features of the facility, and the air pipe of pylons must be placed in the existing opening of the «embrasure», where the regular burner is located.

Thus, when designing burners, the value of diameter of fuel openings, which is determined according to the technological conditions of FE, should be selected as the first geometric parameter of fuel feed (Table 5).

Table 5

Basic recommendations concerning selection of geometric fuel distribution parameters, fuel is natural gas

d, mm	Capacity, GCal	Application
0.5–2	Without limitations	Combustion chambers of GTU
2–4	Up to 15	Boilers, furnaces, drying chambers
4–6.5	15...100	Boilers

Regarding the step selection, it should be noted that, firstly, it must take into account, hydrodynamics of interaction of fuel jets with the air flow, and secondly, provide the appropriate concentration of the mixture in the area of stabilization, so working values of stepes steps for two of studied gases are in the range of 3.0...6.0. The values of parameter L_1 allow regulating the fuel mixing degree, so it is recommended to select larger values at larger diameters in the recommended range (quadrant 2 of the diagram) (Fig. 6).

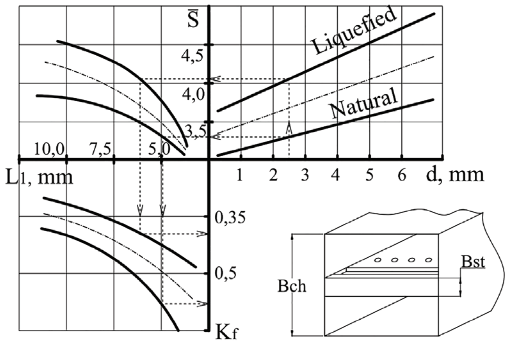


Fig. 6. Nomogram for calculation of burner device of JNS, fuel — natural gas, air channel of square intersection, coefficient of cluttering $K_f=B_{st}/B_{ch}$, selection of L_1 by the scale for natural gas

Parameter of relative cluttering of the air channel by stabilizers K_f during selection for larger diameters is shifted towards a decrease in the possible range of variation, for provision of the necessary air flow. Its selection is based on the stoichiometric ratio gas/air. Recommendations for selection of K_f are presented in the technique for calculation of the industrial gas burner equipment [20].

6. Discussion of results of research and recommendations for selection of parameters of fuel distribution of burners

As it can be seen from the above materials, the universality of the accepted structure regarding the arrangement of burners can be also proved at the transition from natural gas to combustion of alternative fuels. It is necessary to take into account the features of hydrodynamics of the flow of fuel and an oxidizer in the system in order to enable fuel combustion stability. As the studies showed, ensuring combustion stability for two different fuels can be achieved by common geometry of fuel distribution.

The results of optimization are interpreted in a certain way in the technique for PE designing. It is necessary to shift from the optimal area of a relative step of openings $\overline{S}$, associated with peculiarities of organization of hydrodynamic structure of the flow, because it plays a decisive role in the studied devices. Thus, working relative step for natural gas is $\bar{S} = 2.0...4.0$, and stoichiometric factor equals to 9.5, which is by nearly 3 times smaller compared with liquefied gas. At first glance, the logical adjustments $\bar{S}$ for liquefied natural gas to values 6...12 turns out to be a rather incorrect measure, and the maximal working value is not more than $\bar{S} = 6.0$. This is explained by the features of behavior the jets' system in the incident flow of an oxidizer. Thus, at step $\bar{S} > 6.0$, fuel jets propagate in the flow independently without interaction of boundary layers, which violates the common vortex structure of the combustion mixture, worsening the process of flame stabilization. Similar findings can be interpreted to less caloric gases, stoichiometric ratio of which approach the values of 1:1...4.0 (fuel:air). Specifically, a decrease in relative step up to values $\bar{S} < 2.0$ leads to fuel jet joining, which actually make a one dense jet. Such a pattern makes high-quality mixture formation in the modes of maximum consumption impossible due to worsening of fuel penetration in the oxidizer flow. That is why regardless of combusted gas, the operation value is the value of parameter $\bar{S} = 2.0...6.0$, which contributes to formation of a stable vortex structure in a wide range of change in velocities of fuel and an oxidizer. Stoichiometric ratio on a burner is ensured by variation of cluttering the air channel by stabilizer K_f.

The influence of diameter and parameter of the distance should be considered jointly. An increase in diameter leads to an increase in the depth of penetration of a jet into the flow of an oxidizer and determines permissible boundaries of cluttering of the channel by stabilizers. Parameter of distance L_1 makes it possible to regulate the mechanism of combustion, and at an increase in the distance from the detachment edge, changes the diffusive flame toward the kinetic one. When using increased diameters (5...7.0 mm), it is expedient to distance the jets deep into the channel. This measure makes it possible to shift diffusivity of the process towards micro-diffusive fuel combustion, which is a necessary condition for organization of steady combustion with sufficiently high heat intensity of the working volume.

Presented results are an important step regarding determining the prospects for application of already acknowledged FE structure, which runs on natural gas. Provided recommendations offer an opportunity to adapt FE to combustion of both studied gases and greatly increase reliability of FE operation, due to reserving natural gas with the liquefied mixture of propane-butane.

The main disadvantage of the obtained results is limitation in terms of the experiment in the number of the studied influencing factors. Such a situation did not allow determining the influence of flow rate of incident air, or comprehensively explore fuel combustion depth and conduct gas analysis together with the starting characteristics. In addition, there is a certain disagreement of results of optimization regarding improvement of starting with working modes at nominal costs.

It is an obvious fact that the next stage of the research should include selection of the structure of a stabilizer of the burner, which would allow using gases with caloricity of 1–4 Kcal/m^3. Given the results obtained, it is possible to make the assumption that it will not be possible to solve the set task fully only by correction of fuel distribution. In this case, it is necessary to optimize mode parameters of the burner in addition to its geometric parameters.

Subsequent development of the research should be the search for possibilities of combustion of liquid fuel (diesel, fuel oil) in addition to the studied gases. The implementation of this requirement demands complication of the fuel distribution structure and a considerable number of research experiments with further testing on an actual site.

7. Conclusions

1. Research into the «start» and «flameout» mode in the JNS revealed that starting fuel consumption in higher by 1.05...2.5 times larger and are determined by the geometric and mode parameters of the system. This difference is minimized at air velocity W_A>20 m/s, and reaches the maximum values at W_A<10 m/s. It was determined that for natural gas, $G_{IGN}/G_{DIE-OUT}$ is by 5...15 % less compared to this indicator for liquefied gas. Thus, to ensure reliability and starting safety of the equipment, it is recommended to ignite the combustible mixture in the burner at the minimal air velocity. To ensure the maximal depth of unloading of the unit, it is recommended to select parameters of the stabilizer in accordance with the given recommendations.

2. It was determined that the use of the full-factor experiment (FFE) for construction of regressive equations, which would adequately describe the flameout process in the examined system, obviously, is not sufficient due to non-linearity of the studied process. That is why construction of regressive dependences is limited only by three influential factors and in addition to 8 points of the experiment plan, we also selected the results in the star points and the center of the factor space. All in all, this makes it possible to construct the central orthogonal composition plan of the second order, and eventually to get an adequate mathematical model of the examined phenomenon.

3. Optimal parameters of fuel distribution for JNS-based burners were determined. The crucial influence of relative step $\bar{S}$ on the operation process of FE was established; the recommended values for double-burner device are 3...4.5. Selection of distance L_1 should be carried out as close as possible to the detachment edge of the niche regardless of conditions, implemented within the values of 5...10 mm. The working ranges of values of diameters of fuel distributing openings are within 1.0...7.0 mm and are selected according to technological conditions of FE.

4. Based on the conducted studies, recommendations on improvement of the technique for designing gas burner equipment of JNT for a wide range of FE were developed. The results obtained allowed development of the foundations for designing the double-burner FE with the possibility of using natural and liquefied gases. The achieved indicators regarding the expansion of the regulation range at the level of 5...100 % of the nominal value positively characterize the research technology in comparison with modern analogues. Low fuel pressure for a start (up to 1 mm of water column) makes it possible to ensure minimal fuel consumption, which provides a «mild» temperature mode and absence of explosively hazardous gas pollution of the furnace space.

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