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THE DETERMINATION OF THE FEATURES OF THE PROCESS OF MIXTURE FORMATION OF HYDROGEN BURNER

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The use of hydrogen fuel as an alternative source of individual heat supply is a rather promising direction in the development of thermal energy. However, due to the physical properties of hydrogen and the peculiarities of its combustion, several problems arise for the practical use of hydrogen heat generators. Such problems include ensuring flare stability and large emissions of thermal nitrogen oxides (NO_X). For stable operation of the hydrogen burner, safe operation, and reduction of nitrogen oxide emissions when burning hydrogen, first, it is necessary to ensure high-quality pre-mixing with air.

This work presents the first stage of research into the operation of a hydrogen burner for heat production in the Flow Simulation module of the SolidWorks software environment. For volume flow rates of air and hydrogen corresponding to capacities of 1, 1.5 and 2 kW and air excess coefficient α=1.6. The given design makes it possible to ensure uniform mixture formation (the volume fraction of hydrogen is approximately 18.5 % at the outlet cross-section of the burner and the speed at the outlet of the burner is 5.4, 8.1, and 10.8 m/s, respectively. The burner is a nozzle with a short premixing chamber First, hydrogen is supplied for mixing into the air flow through symmetrically located holes. After that, a vortex is created, which ensures high-quality mixing of gases with a short length of the burner, as well as a uniform distribution of velocity at the exit.

The obtained results allow to proceed to the next stage – the study of hydrogen combustion processes in the combustion chamber of the contact heat generator, which would ensure the formation of a stable flame and low NO_X emissions. In addition, this design can be used in the development of hydrogen burners for heating boilers to meet the needs of private homes and small businesses

Keywords: hydrogen fuel, hydrogen burner, burner consumption, mixture formation, heat production, nitrogen oxides

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1. Introduction

The aggravation of global environmental problems brings to the fore the issue of wider use of alternative energy sources in various industries. Among them, the importance of environmental issues of heat supply systems is growing.

All over the world, today, the state of heat-generating capacities requires a number of measures to modernize and introduce new technologies in this field. In addition to the problem of significant wear and tear, moral and technical obsolescence, and non-compliance with modern environmental standards, a large part of boiler houses and CHPs was also damaged or destroyed as a result of hostilities. The use of hydrogen as a heat source makes it possible to simultaneously ensure both environmental friendliness and decentralization of heat production. This also corresponds to the goals defined in the Energy Strategy of Ukraine until 2050 [1].

In this context, hydrogen is a unique energy carrier that has three times the heat of combustion compared to natural gas, is easy to store and transport, and the only product of hydrogen combustion is water. Thus, the development of hydrogen technologies can provide significant development in the energy industry [2].

However, the higher adiabatic temperature of hydrogen combustion leads to a significant increase in the emission of nitrogen oxides, which are formed from the air. Hydrogen has a higher burning rate, in addition, pure hydrogen leads to stronger corrosion, so equipment designed for burning natural gas is not suitable for using hydrogen fuel. At the same time, an important issue is uniform preliminary mixture formation, which would make it possible to create a stable flame and ensure complete combustion of the fuel mixture in the combustion chamber [3].

Thus, effective use of hydrogen as a fuel requires research and implementation of new technologies that would ensure highly efficient operation of the equipment.

2. Literature review and problem statement

The main part of research on combustion processes concerns the determination of the correlation between the combustion temperature and the formation of thermal NO_X. The work [4] gives the results of kinetic studies on the effect of temperature on the combustion process and the burning rate in a hydrogen burner with premixing. The dependence of the combustion temperature on the coefficient of excess air and preheating of air and hydrogen is shown. These results are necessary to ensure the stability of the torch. The issue of uniform and stable mixing remained unresolved. With the increase in the use of hydrogen as a source of thermal energy, the importance of this issue will grow.

An option to overcome the relevant difficulties may be to determine the internal mechanisms that can affect the spread of the flame when burning hydrogen. Such a study is given in [5], which describes a diffusion mechanism that can be a destabilizing factor. It is shown how this effect increases in burners

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with premixing of a lean fuel mixture (α=1.6). But there is no solution for torch stabilization. There are various concepts for flame stabilization by premixing, including swirlers and porous media burners. Most of the studies concern the stabilization of the torch, where hydrogen is mixed with natural gas or other gaseous fuel [6, 7]. The available results show very close ranges of operating conditions for all combustors to ensure low NO_X emissions (<1 ppm). NO_x emissions increase with higher air excess ratios and heat loads. The combustion process with different hydrogen content in a mixture with other gaseous fuel is shown, but there is practically no research on mixture formation and flame stabilization when burning pure hydrogen. In [8], one of the concepts of a burner with low NO_X emissions based on partial premixing is presented. It is shown that this process occurs due to the creation of vortices in front of the outlet of the burner, which ensures a uniform gas flow rate and volume distribution of gases in the mixture. However, this study does not reveal the issue of using hydrogen, as the proposed burner model works for natural gas with up to 30% hydrogen and coke gas. Studies of hydrogen combustion in burners with premixing, given in [9], showed that the addition of hydrogen leads to an increase in the share of NO_X in emissions. Thus, the lowest values of NO_X emissions were 26 ppm for methane and 66 ppm for hydrogen when using dry air [10]. The disadvantage of these studies is that they examine burners that are designed to use natural gas. When burning hydrogen or natural gas with a large proportion of hydrogen, the combustion temperature will be significantly higher than when burning natural gas.

Numerical and experimental studies of hydrogen burners [11, 12] indicate various ways of formation of NO_X during combustion. Despite the extensive coverage of chemical reactions, the influence of the distribution of hydrogen and air before combustion is not given in the process. This issue is covered in the study [13], which shows the design of a hydrogen jet burner for a wide range of air excess ratios. However, for mixing flows in jet burners, a relatively long device length is required. A design with a short burner premixing chamber is shown in [14]. It defines that the use of flow bodies creates a vortex inside the chamber of the burner device. Thanks to this, mixing takes place in a relatively short area. However, it only briefly examines the process of mixing hydrogen and air and their effect on further combustion. The reason for this is that combustion processes play the main role in the formation of nitrogen oxides. However, much less attention is paid to mixing processes and the design of the burner device itself, which also significantly affect the stability of the flame and fuel combustion.

This allows to state that it is expedient to conduct a study dedicated to determining the peculiarities of the mixture formation process in a hydrogen burner.

3. The aim and objectives of the study

The aim of the study is to determine the features of the mixture formation process in the chamber of the burner device to ensure high-quality pre-mixing of hydrogen with air. This will make it possible to ensure a stable combustion process and reduce the NO_X formation during the combustion process.

To achieve the aim, the following research objectives were set:

– to determine the consumption indicators of the burner in the range of thermal capacities from 1 to 2 kW and the coefficient of excess air α=1.6 to set the initial conditions for modeling the mixture formation process in the burner;

– to investigate in the software environment the process of mixture formation based on the volumetric distribution of hydrogen and air in the pre-mixing chamber at different consumption of the fuel mixture.

4. Materials and methods of the study

4. 1. The object and hypothesis of the study

The object of the study is the process of air and hydrogen mixture formation in the burner chamber.

The research hypothesis is as follows: ensuring high-quality mixture formation directly depends on the design of the pre-mixing chamber of the burner and its consumption characteristics.

The coefficient of excess air is accepted taking into account [4], as the one that ensures complete combustion of hydrogen, but at the same time the mixture is not stable at the pre-mixing stage and the study will show the least favorable version of the process.

The main assumption is that the proposed design of the burner ensures swirling of flows and, as a result, high-quality mixture formation with a short length of the mixing region.

For simplicity, the humidity of the air supplied to the burner was not taken into account at this stage of the study.

4. 2. The method of calculating the consumption characteristics of the burner

The mass flow of hydrogen m_{H2} is determined from the thermal power of the burner device:

$$m_{H2} = Q / LHV, \quad (1)$$

where LHV – the lower heat of hydrogen combustion.

Volume flow rate of hydrogen V_{H2}:

$$V_{H2} = m_{H2} / \rho_{H2}, \quad (2)$$

where ρ_{H2} – hydrogen density at t=20 °C.

$$V_{air} = L_{V0} V_{H2} \alpha, \quad (3)$$

where L_{V0} – the stoichiometric ratio of volumes of hydrogen to air, α – the coefficient of excess air, α=1.6 is taken;

$$L_{V0} = V_{air}^{0} / V_{H2}. \quad (4)$$

The stoichiometric volume of air is found from the equation of the hydrogen combustion reaction:

$$2H_2 + O_2 = 2H_2O. \quad (5)$$

The volume content of oxygen in air is 0.2095 [15], so the ratio of molar volumes will be determined as:

$$L_M = \frac{M_{air}}{M_{H2}}. \quad (6).$$

The stoichiometric ratio of volumes of hydrogen to air:

$$L_{V0} = L_M \cdot \frac{29}{2} \cdot \frac{\rho_{H2}}{\rho_{air}}, \quad (7)$$

where ρ=1.29 kg/m^3 – dry air density.

The average speed of the fuel mixture at the exit from the burner:

$$w = \frac{V_{mix}}{F_{out}}, \quad (8)$$

where $V_{mi}x$ – the volumetric flow rate of the mixture, F_{out} – the cross-sectional area of the burner nozzle.

4. 2. The method of determining the nature of the preliminary mixture formation in the chamber of the burner device

The study is conducted in the Flow Simulation module of the SolidWorks software environment (USA, France). A drawing of the burner model with dimensions is shown in Fig. 1.

A three-dimensional model of the burner device was simulated according to the dimensions in Fig. 1. The general appearance of the model is shown in Fig. 2.

When modeling the process, pre-calculated flow characteristics of air and hydrogen were set as boundary conditions. An example of information about the performed calculation is shown in Fig. 3.

In numerical form, the data were obtained using the XY plot functions, the Cut Plot function was used to visualize the process.

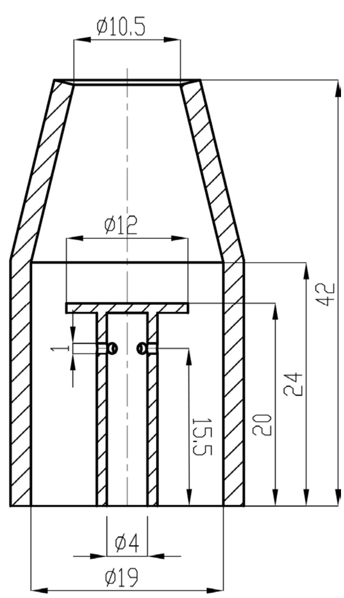


Fig. 1. Dimensions of the simulated burner device

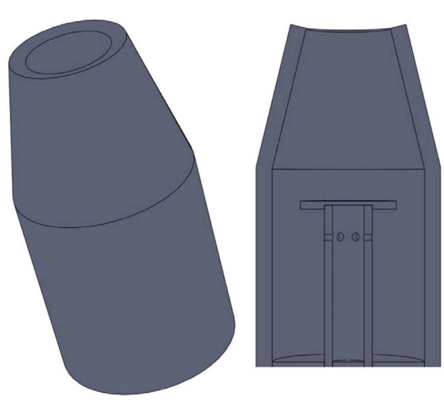
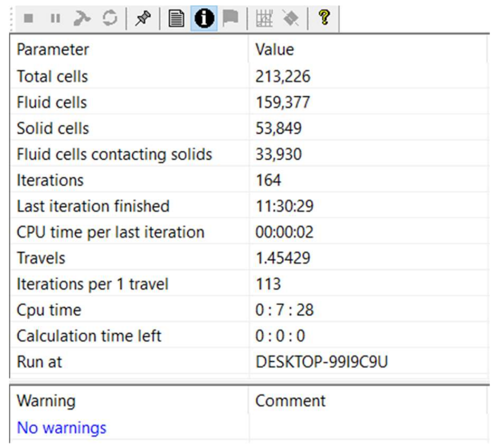


Fig. 2. Appearance of the burner device model



Parameter	Value
Total cells	213,226
Fluid cells	159,377
Solid cells	53,849
Fluid cells contacting solids	33,930
Iterations	164
Last iteration finished	11:30:29
CPU time per last iteration	00:00:02
Travels	1.45429
Iterations per 1 travel	113
Cpu time	0:7:28
Calculation time left	0:0:0
Run at	DESKTOP-99I9C9U

Warning	Comment
No warnings	

Fig. 3. Information about the calculation in the SolidWorks software environment

5. Results of the study of hydrogen fuel mixture formation in the burner device

5. 1. Consumption indicators of the burner device

The calculation of hydrogen and air consumption is performed for thermal power in the range from 1 to 2 kW. This range was chosen for the following reasons. Because at lower power, the local flow rate can be lower than the burning rate of the fuel mixture, and at higher power, there is a large aerodynamic resistance in the hydrogen supply tube.

The results of the calculations are shown in the Table 1.

Table 1

Consumption indicators of the burner

Thermal capacity Q, kW	Volume flow of hydrogen V_{H2}, 10^{-4} m^3/s	Volume flow of air V_{air}, 10^{-4} m^3/s	Volume flow of gas mixture V, 10^{-4} m^3/s	Area of the outlet nozzle of the burner F, 10^{-5} m^2	Average velocity of the gas mixture w, m/s
1	0.928	3.593	4.52116	8.655	5.22
1.1	1.021	3.952	4.97327	8.655	5.75
1.2	1.114	4.312	5.42539	8.655	6.27
1.3	1.206	4.671	5.87751	8.655	6.79
1.4	1.299	5.03	6.32962	8.655	7.31
1.5	1.392	5.39	6.78174	8.655	7.84
1.6	1.485	5.749	7.23385	8.655	8.36
1.7	1.578	6.108	7.68597	8.655	8.88
1.8	1.67	6.468	8.13808	8.655	9.4
1.9	1.763	6.827	8.5902	8.655	9.93
2	1.856	7.186	9.04232	8.655	10.45

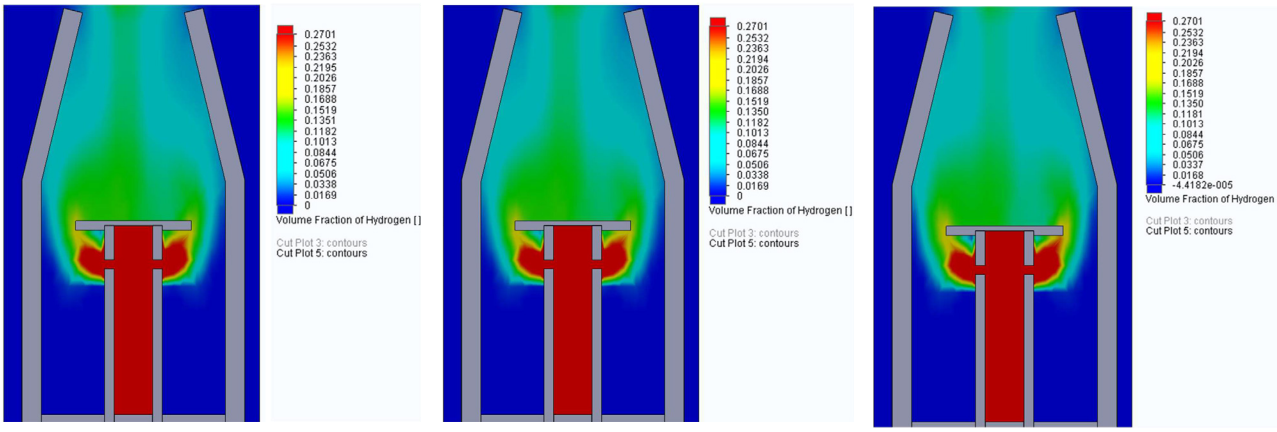
After determining all the values of the consumption parameters of the burner, you can proceed to the study of the mixture formation process.

5. 2. The process of mixture formation in the SolidWorks Flow Simulation software environment

5. 2. 1. Volume distribution of gases in the burner

The volume distribution of the components of the fuel mixture is an important characteristic that affects the stability of the flame and the quality of combustion of the fuel mixture. Fig. 4 shows the volume distributions of hydrogen and air in the burner at gas flows corresponding to heat capacities of 1, 1.5, and 2 kW, respectively.

Distribution in Fig. 4 is necessary used for process analysis in the next section.



a *b* *c*

Fig. 4. Volume distributions of hydrogen and air in the burner at different gas flows corresponding to the power: *a* – 1 kW; *b* – 1.5 kW; *c* – 2 kW

5. 2. 2. Velocity distribution in the burner

Just like the volumetric distribution of gas mixture components, uniform flow rate plays an important role in ensuring stable combustion.

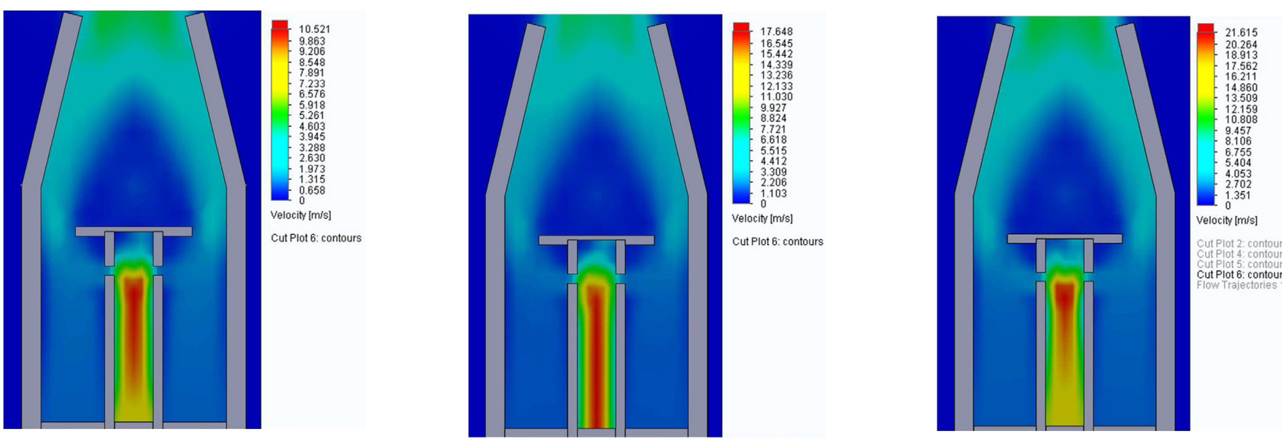
Fig. 5 shows the distribution of gas flow velocities in the burner at gas flows corresponding to heat capacities of 1, 1.5, and 2 kW, respectively.

Fig. 6 shows the trajectories of gas flows, which show the nature of gas mixing in the burner.

Table 2 shows the numerical values of flow velocities along the burner axis for three variants of hydrogen and air consumption, calculated in the software environment.

On the basis of the obtained data, graphs of flow velocities along the axis of the burner at the consumption of hydrogen and air corresponding to thermal capacities of 1, 1.5 and 2 kW were constructed (Fig. 7–9).

The given graphs are built on the key points determined by the SolidWorks software environment.



a *b* *c*

Fig. 5. Distribution of gas flow velocities in the burner at gas consumptions corresponding to thermal capacities: *a* – 1 kW; *b* – 1.5 kW; *c* – 2 kW

Table 2

Numerical values of flow velocities along the burner axis at different hydrogen and air flows

Length, m	Velocity, m/s		
	1 kW	1.5 kW	2 kW
1	2	3	4
0.001	7.39	11.09	14.78
0.0013	7.48	11.22	14.96
0.0016	7.50	11.25	15.00
0.0030	7.75	11.62	15.50
0.0042	7.98	11.97	15.97
0.0056	8.20	12.30	16.40
0.0091	8.64	12.97	17.29
0.0103	8.80	13.20	17.60
0.0108	8.87	13.30	17.74

Continuation of Table 2

1	2	3	4
0.0110	8.90	13.35	17.80
0.0121	9.18	13.77	18.36
0.0135	9.64	14.46	19.29
0.0145	9.93	14.90	19.86
0.0156	8.62	12.93	17.24
0.0168	4.72	7.08	9.44
0.0173	3.34	5.01	6.68
0.0175	2.66	4.00	5.33
0.0177	2.02	3.03	4.04
0.0180	1.44	2.16	2.88
0.0182	1.31	1.96	2.62
0.0184	1.22	1.82	2.43
0.0187	1.17	1.75	2.34
0.0189	1.18	1.76	2.35
0.0191	1.23	1.85	2.46
0.0203	1.19	1.79	0.94
0.0215	0.47	0.71	2.49
0.0238	1.24	1.87	2.57
0.0262	1.28	1.92	1.31
0.0285	0.66	0.98	0.23
0.0300	0.11	0.17	0.06
0.0303	0.03	0.05	0.23
0.0306	0.11	0.17	5.86
0.0379	2.93	4.40	7.83
0.0402	3.92	5.88	9.49
0.0425	4.75	7.12	2.49

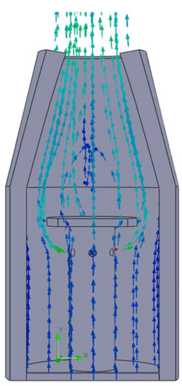


Fig. 6. Trajectories of gas movement in the chamber of the burner device

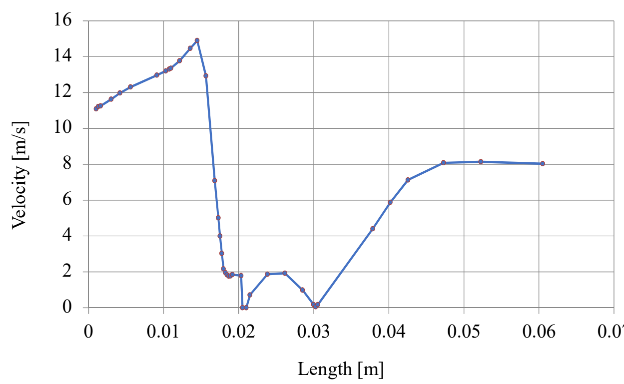


Fig. 8. Flow rate along the burner axis at the consumption of hydrogen and air corresponding to the power of 1.5 kW

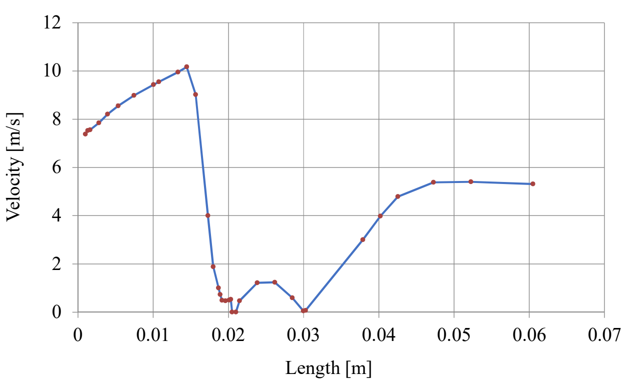


Fig. 7. Flow rate along the burner axis at the consumption of hydrogen and air corresponding to the power of 1 kW

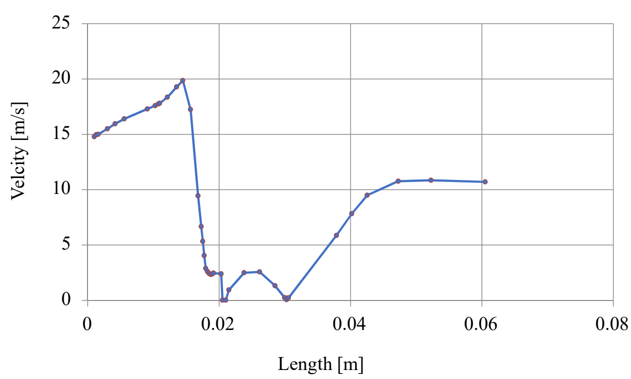


Fig. 9. Flow rate along the burner axis at the consumption of hydrogen and air corresponding to the power of 2 kW

6. Discussion of the results of the mixture formation process of the hydrogen burner device

The consumption indicators of the burner device show that, in general, the mixture formation process took place uniformly.

As can be seen from Fig. 4, hydrogen enters the burner chamber perpendicular to the air flow through the holes in the tube. Then it gradually mixes with air, and at the same time, the process takes place in a very short section of the movement of gas flows. This design ensures uniform distribution of gases in the mixture due to the mixing of hydrogen and air flows. At the same time, with an increase in gas flow rate, even a more even distribution of gas at the outlet of the burner device can be observed.

The nature of the flow corresponds to the initial assumption, as well as the experimental data given in [14], which indicates the adequacy of the modeling of the process in the burner, which clearly demonstrates the nature of the process in the premixing chamber of the burner.

The peculiarity of the study is that we consider a burner for working with hydrogen fuel from the very beginning. In comparison with [11, 12], the distribution of hydrogen in the pre-mixing chamber and the consumption indicators of the mixture of hydrogen and air are given. In this way, the prerequisites for further fuel combustion are provided. In contrast to [13], preliminary mixing is ensured with a short length of the burner chamber (42 mm). This becomes possible due to the swirling of hydrogen and air flows, which is ensured by the installation of a local constriction. Therefore, in the process of flowing around, better mixing is achieved, compared to burners in which mixing of air and gas occurs during parallel movement of flows. Unlike [14], the mechanism of mixing air and hydrogen related to the design of the burner was described.

From Fig. 4–7, it can be seen that the distribution of flow velocities after mixing hydrogen and air stabilizes and is within the average value of the velocity at the exit from the burner. At the same time, these values are greater than the maximum burning speed of hydrogen, which is 3.2 m/s, so the operation of such a burner is also safe when used in heat-generating equipment.

As can be seen from Fig. 6 and graphs in Fig. 7–9, around the local narrowing, the vorticity of the flows first occurs. Further, after flowing around, the already mixed flows are accelerated with the narrowing of the burner chamber itself and at a distance of approximately 12 mm from the exit, they merge into one flow. In this flow, the hydrogen content is greatest in the center and decreases evenly towards the periphery.

The limitations are the limits of hydrogen and air consumption, which correspond to capacities from 1 to 2 kW and the dimensions of the burner itself. Accordingly, with higher hydrogen consumption and larger dimensions of the burner itself, other features may be detected that cannot be determined in this work. In addition, at lower values of the excess air coefficient (including $\alpha<1$) it is possible to achieve both a better mixing result and lower NO_X emissions.

The disadvantage of the study is the lack of simulation of the combustion process, as this function is not provided in the SolidWorks software environment. This does not make it possible to fully assess the quality of hydrogen combustion in this burner, since the mixture formation process is only a component of the combustion process.

Therefore, in further studies of the burner, it is planned to additionally conduct an analysis of the combustion process of the air-hydrogen mixture in the relevant software products using the data obtained in this work, including at larger capacities and equipment sizes. The results obtained in this way can be used in the development of environmentally friendly heating systems and hot water supply for private buildings or small enterprises. And when using more powerful equipment – in the process of replacing and reconstructing boiler room equipment.

7. Conclusions

1. The consumption parameters of the burner are determined to set the initial conditions for modeling the mixture formation process in the burner. The values of hydrogen and air consumption are calculated to provide thermal power from 1 to 2 kW at the coefficient of excess air equal to =1.6, as well as the average gas flow velocities at the exit from the burner. With the obtained values, stable and safe operation of the burner device is achieved.

2. The analysis of the process of mixing air and hydrogen in the burner chamber based on modeling in the SolidWorks software environment shows that this burner design provides uniform and stable mixture formation at different gas consumption parameters. This is explained by the swirling of the hydrogen and air flows due to the perpendicular mixing of the flows and the local narrowing of the premixing chamber. Therefore, with a length of the burner mixing chamber of only 42 mm, it is possible to obtain a high-quality fuel mixture at different values of air and gas consumption.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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