IOP Conference Series: Materials Science and Engineering

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To cite this article: D Y Suslov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **552** 012031

IOP Conf. Series: Materials Science and Engineering **552** (2019) 012031 doi:10.1088/1757-899X/552/1/012031

Development and research of low pressure injection burner for biogas combustion

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Abstract. The article is dedicated to the problem of using an alternative energy source – biogas in gas supply systems. A low pressure injection burner with a conical shaped heat diffuser has been designed. A diffuser placed in the burner body provides preheating of the gas-air mixture and allows to increase a flame propagation velocity. A computer simulation of the gas-air mixing process in a body has been made for 3 types of burners: without a diffuser, with a diffuser of 11 mm and 25.5 mm long. As follows from the simulation, 11mm diffuser has no adverse effect on the gas-air mixing process. While an increasing length of the diffuser up to 25.5mm leads to the decreasing cross-section area of a mixing chamber, therefore increasing air-gas mixture rate and methane concentration in the flame holes. Experimental tests have been performed in relation to biogas combustion process for those 3 types of burners. Experimental results proved that placement of 11mm diffuser in a burner body reduces the time for heating water in the tank up to 100°C by 6% (45.41 s). 25.5 mm diffuser reduces the heating time by 1.5% more (11.37 s). Thus, we can make a conclusion that the presence of a diffuser in the burner body increases a flame propagation velocity and a heat rate of the burner.

1. Introduction

One of the promising areas for the development of alternative energy, which is widely used in the European Union (EU) countries, is biogas [1-3]. The difference of biogas from the natural one consists in low methane (40-70%) content and the presence of impurities such as: carbon dioxide (30-40%), hydrogen sulfide (0-2%) and other gases (0-5%). Biogas is produced by biogas units in the process of anaerobic fermentation of organic substances. Energy plants and agricultural wastes are used as an initial substrate for biogas production [4-6]. The amount of produced biogas, as well as methane content depends on the composition of the organic part of the waste containing fats, proteins and carbohydrates [7, 8].

Most of biogas stations apply the produced biogas in cogeneration units or plants to generate electric and thermal energy [8, 9]. One of the promising fields for the use of biogas is its combustion in gas-burning units. A lot of works of our native and foreign scientists are devoted to the study of combustion processes of biogas and other LHV/LCV gases [10-17]. However, given the high content of carbon dioxide in the composition of biogas, the burning of biogas in traditional burners of natural gas will not be effective [16, 17]. Therefore, the design and testing of gas-burning equipment for the combustion of biogas with a high content of carbon dioxide is very relevant today.

2. Materials and Methods

At the present time, gas-burning units and plants are developed in such directions as [18-22]: the use of new materials; the use of devices improving gas-air mixing and the use of elements that provide pre-heating of the gas-air mixture in the burner body. Also biogas is burned with other fuels [23].

Here is the injection low pressure burner for biogas combustion that has been developed recently (Figure 1). The main design elements of the proposed gas burner are: a nozzle, a mixing chamber, exit holes for the gas-air mixture emission, a heat diffuser and primary air regulator.

The novelty of this design lies in the use of a cone-shaped heat diffuser, while the diffuser is connected with the burner cover at a smooth angle with a bend radius equal to the length of this diffuser. This helps to stabilize the gas-air mixture stream flowing inside the gas burner and decreases pressure losses. The application of a diffuser of the original form provides mixture preheating due to the process of heat transfer from the flame through the diffuser to the gas-air mixture itself. Mixture preheating allows to increase the speed of flame propagation and the temperature of combustion. The use of a primary air regulator allows to use biogas of different composition with a high efficiency factor.

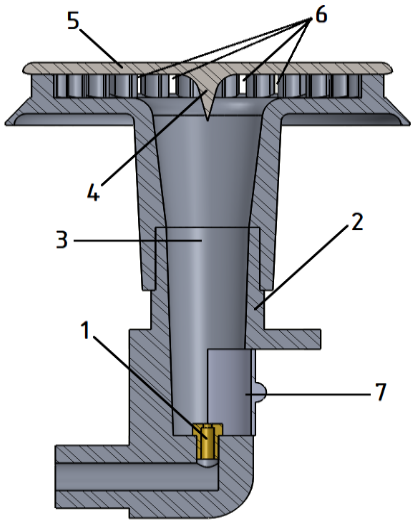


Figure 1. Gas burner: 1 - nozzle, 2 - burner body, 3 - mixing chamber, 4 - pre-heating diffuser, 5 - cover, 6 - holes, 7 - primary air regulator.

2.1. Theoretical research

To describe the gas-air mixture flow in the burner body, we'll use the continuity and Navier –Stokes time-averaged equations (Reynolds equation):

$$\frac{du_j}{dx_j} = 0 \tag{1}$$

$$\rho\frac{\partial u_i}{\partial t} + \rho u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\Pi_{ij} \tag{2}$$

where i,j=1,2,3; $u_1=u_x$; $u_2=u_y$; $u_3=u_z$ – time-averaged velocity vector projections; P – averaged pressure value; Π_{ij} – Reynolds stress tensor.

Reynolds stress tensor arising in the gas-air flow is defined by the expression:

$$\Pi_{ij} = -\rho < u_i' u_j' > \tag{3}$$

where u_i', u_j' – turbulent fluctuations of air-gas velocity projections, <…> – average criterion.

Considering a turbulent combustion of gas-air mixture in a burner body and at the exit of flame holes, we take k-ε model of turbulence.

Reynolds stress tensor of k-ε model is defined by the following expression:

$$\Pi_{ij} = -\rho\left(\frac{2}{3}\kappa\delta_{ij} - \nu_t\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)\right) \tag{4}$$

where κ – turbulent kinetic energy, ε – turbulent energy dissipation rate, v_t – kinetic turbulent viscosity coefficient; δ_{ij} – Kronecker delta.

Mathematical modeling of unconventional fuel has difficulty [24, 25]. To study the process of gas-air environment formation in the body of the developed design burner, we'll use the simulation program complex Solid Works Flow Simulation.

2.2. Experimental research

Experimental studies of the combustion process in the burner were performed on a household gas stove Gefest 3100-07. We used a fast-acting burner with a nominal heat rate of N_{nom} = 3.05 kW, and maximum gas consumption L_{max} = 1076 l/h.

To determine the efficiency and optimal parameters of the diffuser, experiments have been performed using 3 types of burners (figure 2):

– without a diffuser;
– with 11 mm diffuser;
– with 25.5 mm diffuser.

without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

Figure 2. Burner designs.

Experiment procedure:

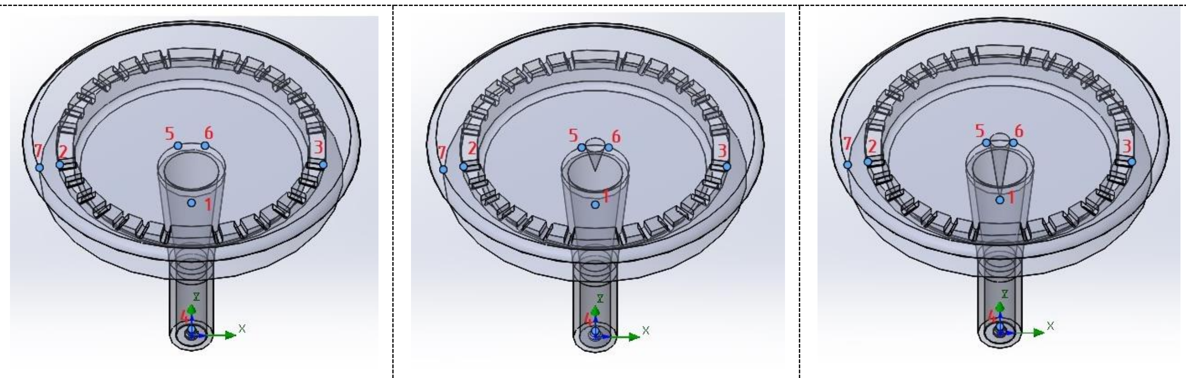
1. Measure the ambient temperature, °C;
2. Measure the temperature of cold water in a tank, °C;
3. Heat the water in a tank using the burner;
4. Measure the time of water heating in a tank 100°C.

The burner efficiency has been defined by the time spent on water heating in the tank up to 100 °C. The initial water temperature was 14°C. Finally, in order to get precise and reliable results of the experiment, we performed 3 different tests.

3. Results and Discussion

3.1. Theoretical research

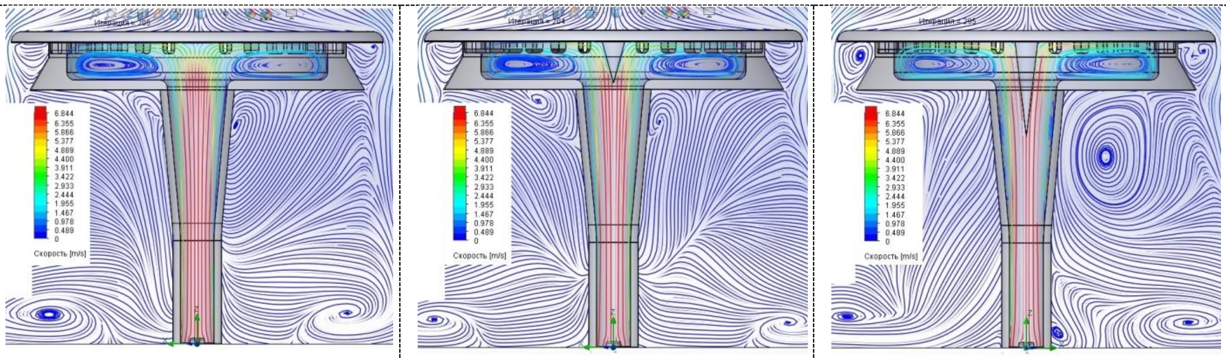
The results of computer simulation provide visual pictures methane concentration and gas-air mixture velocity distribution in the burner body and at the exit of flame holes. Moreover, the concentration and gas-air mixture velocity have been measured on 7 different parts of the burner (figure 3).



without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

Figure 3. Points of measurement of concentrations and velocity of the gas-air mixture.

Simulation results of gas-air mixture velocity distribution in the body are given in figure.4.



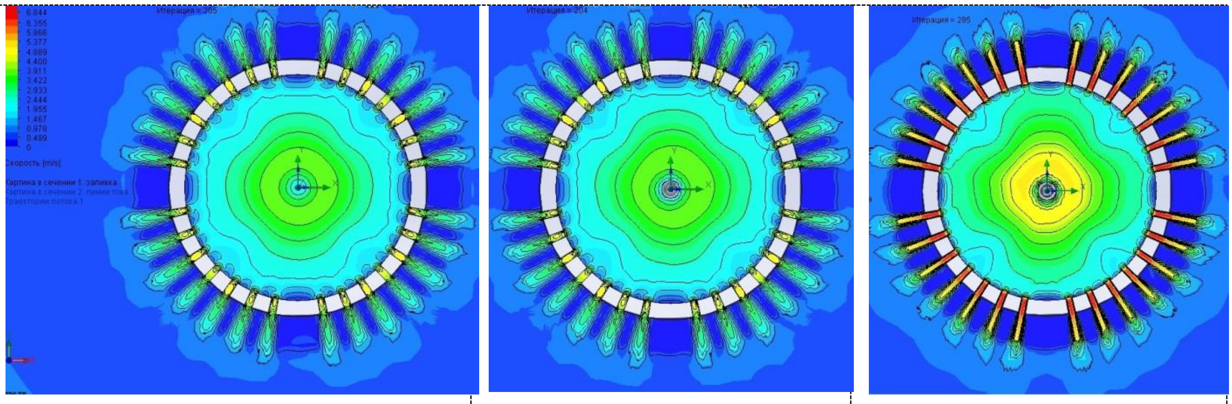
without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

Figure 4. The velocity distribution of the gas-air mixture in the burner body.

Figure 4 shows that gas velocities in the central part of the burner body (point 1) without a diffuser and with a diffuser of L = 11 mm have similar values - 14.15 m/s and 14.18 m/s, respectively. And in the burner with a diffuser of L = 25.5 mm, we observe a significant speed increase (20,82 m/s).

The gas velocity at the bottom of the diffuser (points 5, 6) in the burner without the diffuser is 3.10 m/s, in the burner with the diffuser of 11 mm the speed is reduced to 2.54 m/s. And in the burner with a diffuser of 25.5 mm the speed increases to 3.45 m/s.

Simulation results of gas-air mixture velocity distribution in flame holes are given in figure 5.



without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

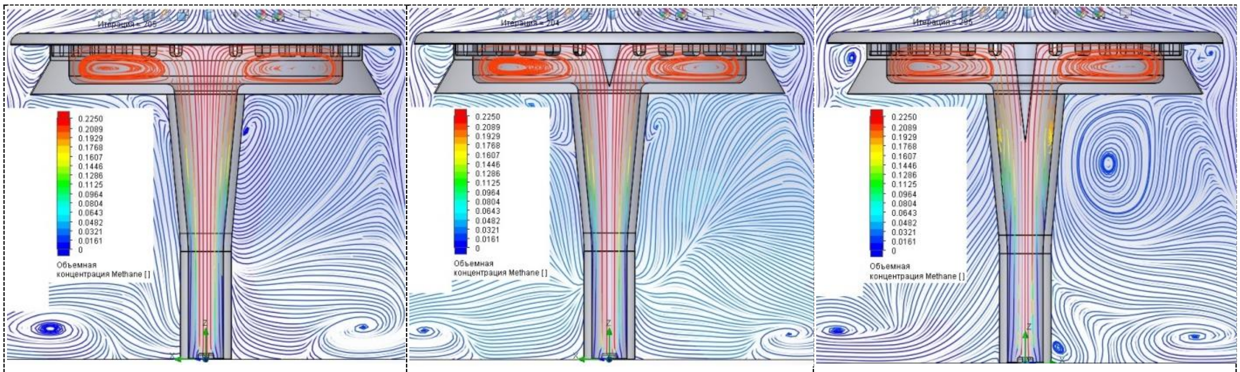
Figure 5. The velocity distribution of the gas-air mixture in the holes.

Figure 5 shows that gas-air mixture velocities at the exit from the flame holes (points 2, 3) in the burner without a diffuser and in a burner with a diffuser of L = 11 mm have similar values - 3.617 m/s and 3.620 m/s, respectively. Moreover, the speed of the mixture in the burner with a diffuser of L = 25.5 mm increases to 6.710 m/s.

Gas-air mixture velocities at a certain distance from the flame holes (point 7) in the burner without a diffuser and in the burner with a diffuser of L = 11 mm have similar values – 2.828 m/s and 2.834 m/s, respectively. The mixture speed in the burner with the diffuser of L = 25.5 mm increases as well (5.580 m/s).

The increased gas-air mixture velocity in the burner body with the diffuser of L = 25.5 mm is explained by the fact that the top of the diffuser is located in the mixing chamber leading to the reduction of cross-sectional area of the mixing chamber. Thus, the 11 mm diffuser does not affect the speed of the gas-air mixture in the burner body and at the flame holes. Reducing the cross-sectional area at a stable consumption rate increases the mixture flow rate. Thus, the diffuser length 11 mm does not affect the speed of the gas-air mixture in the burner body and at the flame holes.

Simulation results of methane concentration distribution in the burner body are given in figure 6.



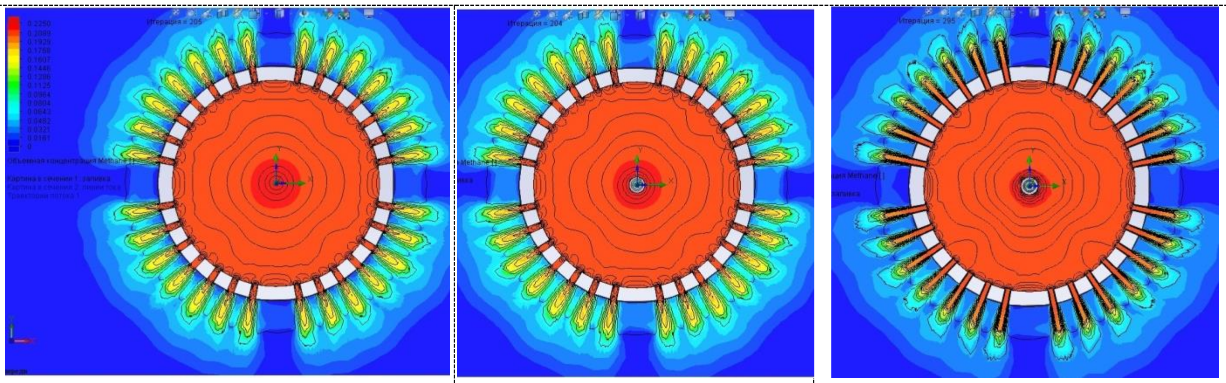
without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

Figure 6. The distribution of methane concentration in the burner body.

Figure 6 shows that methane concentrations in the central part of the body (point 1) in the burner without a diffuser and in the burner with 11 mm diffusor have the same values – 26.5%, and in the burner with 25.5 mm diffuser the methane concentration increases to 31.2%.

The methane concentration at the bottom of the diffusor (points 5, 6) in the burner without the diffuser and in the burner with 11 mm diffuser have almost the same values – 21.6% and 21.7%, respectively. And in a burner with 25.5 mm diffuser, the concentration of methane slightly increases to 22.1%.

Simulation results of methane concentration distribution at the flame holes are given in figure 7.



without diffuser | with diffuser L= 11 mm | with diffuser L= 25.5 mm

Figure 7. The distribution of methane concentration in the holes.

Figure 7 shows that methane concentrations at the outlet of the flame holes (points 2, 3) in the burner without a diffuser and in the burner with 11 mm diffuser have similar values - 20.5% and 20.7%, respectively. At the same time, the methane concentration in the burner with 25.5 mm diffuser slightly increases to 21%.

The methane concentration at some distance from the flame holes (point 7) in the burner without a diffuser is 17.4%. In a burner with 11mm diffuser, the concentration rises to 17.8%, and in a burner with 25.5 mm diffuser it rises to 20.2%.

The increase in methane concentration in burners with diffusers explained by the increase in the gas flow rate leading to a decrease in the amount of primary air.

According to the results of computer simulation, it can be concluded that 11 mm diffuser does not affect the distribution of methane concentration and the velocity of the gas-air mixture at the outlet of the flame holes. The 25.5 mm diffuser results in an increased gas-air mixture velocity and methane concentration.

3.2. Experimental research

The experimental results of the combustion process in the injection burner are given in table 1 and in figure 8.

Table 1. The results of experimental studies of the combustion process.

The burner design	Time, sec at °C									
	14	20	30	40	50	60	70	80	90	100
Burner without diffuser	0,00	64.94	132.30	201.75	271.67	344.04	419,88	499.89	603.62	762.97
Burner with a diffuser L=11 mm	0,00	74.43	142.10	208.73	276.03	346.27	419,45	499.58	596.03	717.56
Burner with a diffuser L=25.5 mm	0,00	69.57	135.56	196.98	265.68	332.32	403,61	477.69	571.54	706.19

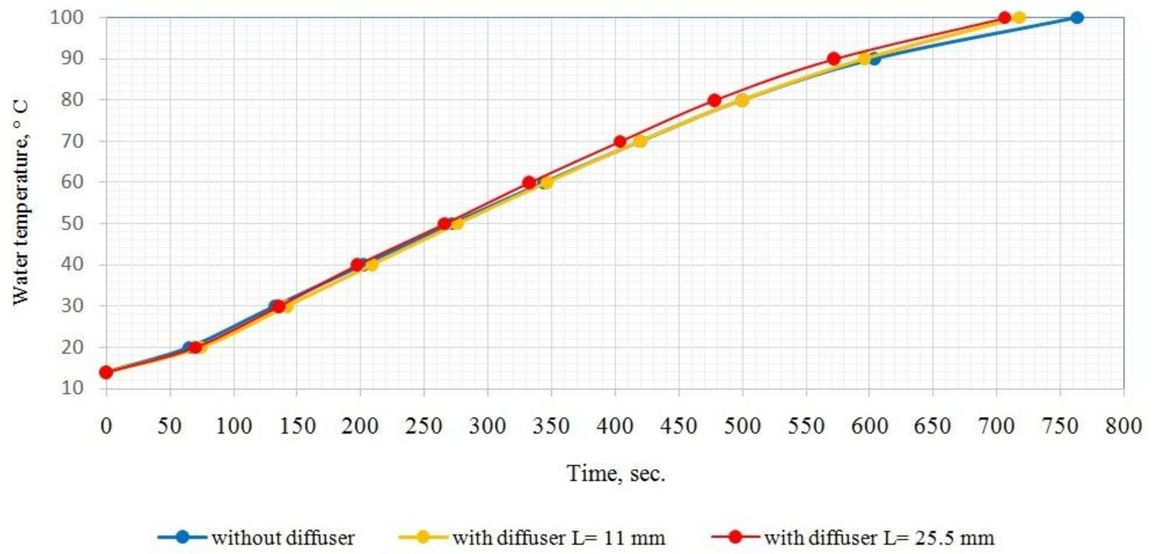


Figure 8. Graph of water temperature versus time.

At the beginning of the experiment, the water in the tank on the burner without a diffuser (132.3) is heated most quickly to a temperature of 30°C. This is explained by the fact that the part of the heat at the initial stage of the process in burners with diffusers is spent on heating this diffuser and, therefore, less heat is transferred to the water tank.

The water in the tank on a burner with the diffusor of L = 25.5 mm (403.61 s) is heated up to 70°C by 16 s faster than on a burner without a diffuser (419.88 s) and with a diffuser of L = 11 mm (419.45 s).

The water in the tank on a burner with the diffuser of L = 25.5 mm (706.19 s) is heated faster to a temperature of 100°C. The water on a burner with a diffusor L = 11 mm is heated in 717.56 s, on a burner without a diffusor – in 762.97 seconds.

Thus, 11 mm long diffuser in the burner body reduces the heating time of the water in the tank by 45.41 seconds or 6%. At the same time, an increase in the length of the diffuser to 25.5 mm shortens the heating time by 11.37 seconds or 1.5% more.

The experiment results prove that the presence of a heat diffuser in the burner allows to increase the flame propagation velocity due to a preheating of gas-air mixture in the burner body.

4. Conclusion

Here is the injection low pressure burner with a cone diffuser that has been developed recently. The theoretical studies of gas-air mixing process in the body proved by experimental tests have been performed for 3 types of burners: without a diffuser, with a diffuser of 11 mm and 25.5 mm long.

As a result of computer simulation, it has been established that the presence of a diffuser with a length of L = 11 mm has no any adverse effect on the distribution of methane and gas-air mixture velocity in the burner body and at the exit of the flame holes. An increased length L = 25.5 mm of a diffuser leads to the decreasing cross-section area of a mixing chamber, therefore increasing air-gas mixture rate (or speed) and methane concentration. Increasing the speed of the gas-air mixture can lead to disruption of the combustion process and flame lift-off.

Experimental results show that the presence of 11 mm diffuser in the burner body reduces the time for heating water in the tank to a temperature of 100°C by 6% (45.41 s). At the same time, 25.5 mm diffuser reduces the heating time by an additional 1.5% (11.37 s).

It can be concluded that the optimal solution to increase the efficiency and stability of the gas combustion process is to install an 11mm long diffuser in the burner body. This allows to increase flame propagation velocity and heat rate of the burner.

5. Acknowledgments
The reported study was funded by RFBR according to the research project № 18-38-00351.

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