JUSTIFICATION OF AIR FLOW SPEED IN THE OXIDATION AREA OF A GASIFIER IN CASE OF STRAW PELLETS USING
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ОБҐРУНТУВАННЯ ШВИДКОСТІ РУХУ ПОТОКУ ПОВІТРЯ В ЗОНІ ОКИСЛЕННЯ ГАЗОГЕНЕРАТОРА У ВИПАДКУ ВИКОРИСТАННЯ СОЛОМ'ЯНИХ ГРАНУЛ

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ABSTRACT

On the basis of the Bernoulli equation the dependence for determining the air flow rate in the oxidation zone of the gasifier was obtained. The obtained dependence makes it possible to theoretically establish the average speed and diameter of the air flow depending on the flow length. To check and clarify the obtained dependence for determining the air flow rate in the oxidation zone, the value of the total loss coefficient of the air flow rate in the volume of straw pellets, which are used as fuel for the gasifier, is experimentally established.

АБСТРАКТ

На основі рівняння Бернуллі отримано залежність для визначення швидкості потоку повітря в зоні окислення газогенератора. Отримана залежність дозволяє теоретично встановити середню швидкість та діаметр потоку повітря в залежності від довжини потоку. Для перевірки та уточнення отриманої залежності для визначення швидкості потоку повітря в зоні окислення, експериментально встановлено значення загального коефіцієнту втрат швидкості потоку повітря в об'ємі солом'яних гранул, що використовуються в якості палива для газогенератора.

INTRODUCTION

One of the promising ways to reduce greenhouse gas emissions is the use of biological fuels *(Golub et al, 2017)*. The equipment in which straw is used to produce heat and electricity is widely used *(Barmina et al, 2017)*. However, when burning straw there are difficulties associated with heterogeneity, high humidity, low specific energy and low melting point of ash *(Golub et al, 2018a*). Therefore, to obtain a stable supply of energy to the consumer during the burning of straw, it will be appropriate to use gasifiers (*Sarker et al, 2015; Wu et al, 2017*). The experience of exploitation of gas-producing installations on various biofuel types shows that for the production of gas from straw and straw containing fuels there should be used straight flow gasifiers of the converted gasification process *(Sheth et al, 2009; Basu, 2013; Gai et al, 2014)*. They ensure the stability of the gas formation process, a high degree of decomposition of resins, simplification of technological schemes for cleaning the wood gas from moisture and impurities *(Mysak et al, 2017; Goleb et al., 2018b).*

In scientific studies considerable attention is paid to the theoretical study on the influence of structural *(Susastriawan et al, 2017)* or technological (*Sheth et al, 2009*) parameters of the gasifiers on the quality of the resulting gas. The influence of such parameters as the operating temperature in the oxidation and reduction zones (*Sharma, 2011)*, as well as the humidity of biomass *(Channiwala, Ratnadhariya, 2007) on the qualitative composition of the obtained gas is substantiated*. Analysis of scientific research allows us to conclude that the gasification of biomass is a complex process based on the equations of thermochemical equilibrium, kinetics, heat transfer and mass transfer, which are based on the rate of gasification of biomass. However, the speed of gasification and the efficiency of the gasification process depend on the modes of air supply to the oxidation zone of the gasifier *(Zainal et al, 2001; Melgar et al, 2007; De La Hoz et al,2017).* The experience of gasification of fuels with different straw content shows that insufficient air flow rate can lead to the formation of areas with

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a lack of air in the field of fuel oxidation, which can significantly reduce the efficiency of the gasification process and cause the phenomenon of ash and slag agglomeration (*Sarker et al, 2015; Wu et al, 2017*).

Nevertheless, the establishment of real air flow rates in the working areas of the gasifier is difficult for theoretical research due to the complexity of the interaction, diversity and transience of the processes taking place during the gasification of straw and other biomass types (*Ali et al, 2016; Yan et al, 2018)*. This complexity prevents theoretical models from achieving the necessary accuracy to adequately determine the air flow velocity and the geometric shape of the air flow (*Gu et al, 2018; Mazaheri et al, 2019*). The mathematical models of air movement in the working zones of the gasifier presented in the analysed scientific studies have uncertain boundary conditions. Therefore, it is necessary to accumulate experimental data in the real range of parameters of gas generators and create simple mathematical models that adequately describe the speed of air flow in the oxidation zone of the gasifier.

MATERIALS AND METHODS

To establish the velocity of air flow in the oxidation zone of the gasifier, consider the jet (flow) of air between sections 1-1 and 2-2 (fig. 1) that flows out from the hole of the gasifier tuyere belt (tuyere hole).

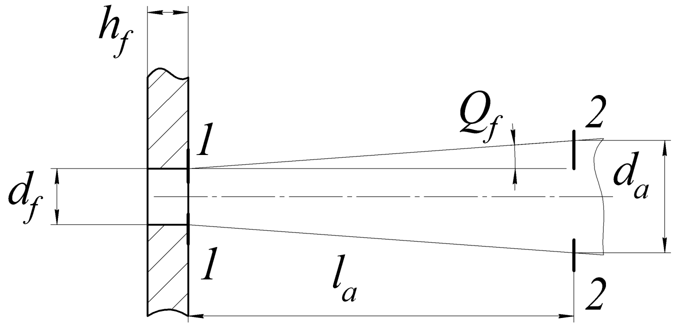

Fig. 1 - Scheme of air flow in the fuel oxidation zone

h_f – tuyere belt depth, m; d_f – the diameter of the flow at the outlet of the tuyere, m; Q_f – polycut expansion of gas stream, deg.; l_a – flow length,m; d_a – diameter of the expanded flow, m

According to Bernoulli's equation *(Dayev, 2018; Yeon, Tu, 2019)* for real flow it can be written:

$$p_1 + \frac{\rho_1 \upsilon_1^2}{2} = p_2 + \frac{\rho_2 \upsilon_2^2}{2} + \Delta p_{1-2}, \tag{1}$$

where:

p_1, p_2 – pressure at the beginning and end of the flow, PA; ρ_1, ρ_2 – air density at the beginning and end of the flow, kg/m^3; υ_1, υ_2 – air flow rate at the beginning and at the end, m/sec; Δp_{1-2} – flow pressure loss, PA.

The equation of gas flow continuity (*Yeon, Tu, 2019)* is as follows:

$$\rho_1 \upsilon_1 \frac{\pi d_f^2}{4} = \rho_2 \upsilon_2 \frac{\pi d_a^2}{4} = const, \tag{2}$$

where:

d_f – the diameter of the flow at the outlet of the tuyere, m; d_a – diameter of the expanded flow, m.

Pressure loss Δp_{1-2} in the air stream consist of two components, the first is pressure loss along the flow length due to friction between the airflow and the side surface elements (particles) of fuel in the fuel oxidation zone of the gasifier and a pressure loss that is similar to the local loss, which delve into the process of interaction of the flow with a frontal (anterior) surface of the fuel particles.

Based on the above, we can write:

$$\Delta p_{1-2} = \frac{\lambda l_a \upsilon_{1-2}^2 \rho_{1-2}}{8 r_{1-2}} + \frac{\xi \upsilon_{1-2}^2 \rho_{1-2}}{2} = \frac{\upsilon_{1-2}^2 \rho_{1-2}}{2} \left(\frac{\lambda l_a}{d_{1-2}} + \xi \right), \tag{3}$$

where:

ρ_{1-2} – average air flow density, kg/m^3; υ_{1-2} – average air flow rate, m/sec; d_{1-2} – average flow diameter, m; l_a – flow length, m; λ – coefficient of pressure loss in the flow, which depends on the area of the lateral surface of the fuel elements; ξ - coefficient of pressure loss in the flow, which depends on the density of the fuel elements in the oxidation zone of the gasifier.

On the basis of equations 1-3, the equation of air flow velocity in the section 2-2 is obtained:

$$\upsilon_2 = \sqrt{\left(2p_1 - 2p_2 + \rho_1\upsilon_1^2 - \upsilon_{1-2}^2\rho_{1-2}\left(\frac{\lambda l_a}{d_{1-2}} + \xi\right)\right) / \rho_2} \, . \tag{4}$$

If we assume that the hydrostatic pressure in the air flow and the air density are stable, and the hydrodynamic pressure is formed by the velocity head, and express the total coefficient of the flow rate loss in the form of:

$$k_a = \frac{\lambda l_a}{d_{1-2}} + \xi \, , \tag{5}$$

equation 4 can be written as follows:

$$\upsilon_2^2\left(4 + k_a\right) + 2\upsilon_1 k_a \upsilon_2 + \upsilon_1^2\left(k_a - 4\right) = 0 \, , \tag{6}$$

The solution of this equation is as follows:

$$\upsilon_2 = \frac{\upsilon_1\left(4 - k_a\right)}{4 + k_a} \, . \tag{7}$$

Given that $d_{1-2} = \sqrt{2\upsilon_1 d_f^2 / \left(\upsilon_1 + \upsilon_2\right)}$, the numerical solution of equation (4) allows us to theoretically set the average air flow rate depending on the length of the flow, as well as according to equation (2) continuity of the flow to determine the diameter of the flow. However, to test the theoretical solution, it is necessary to experimentally establish the value of the total coefficient of the flow rate loss and solve the equation (7). For the experimental finding of the coefficient of rate loss of the air flow passing through straw pellets, it was used a pilot plant (fig. 2).

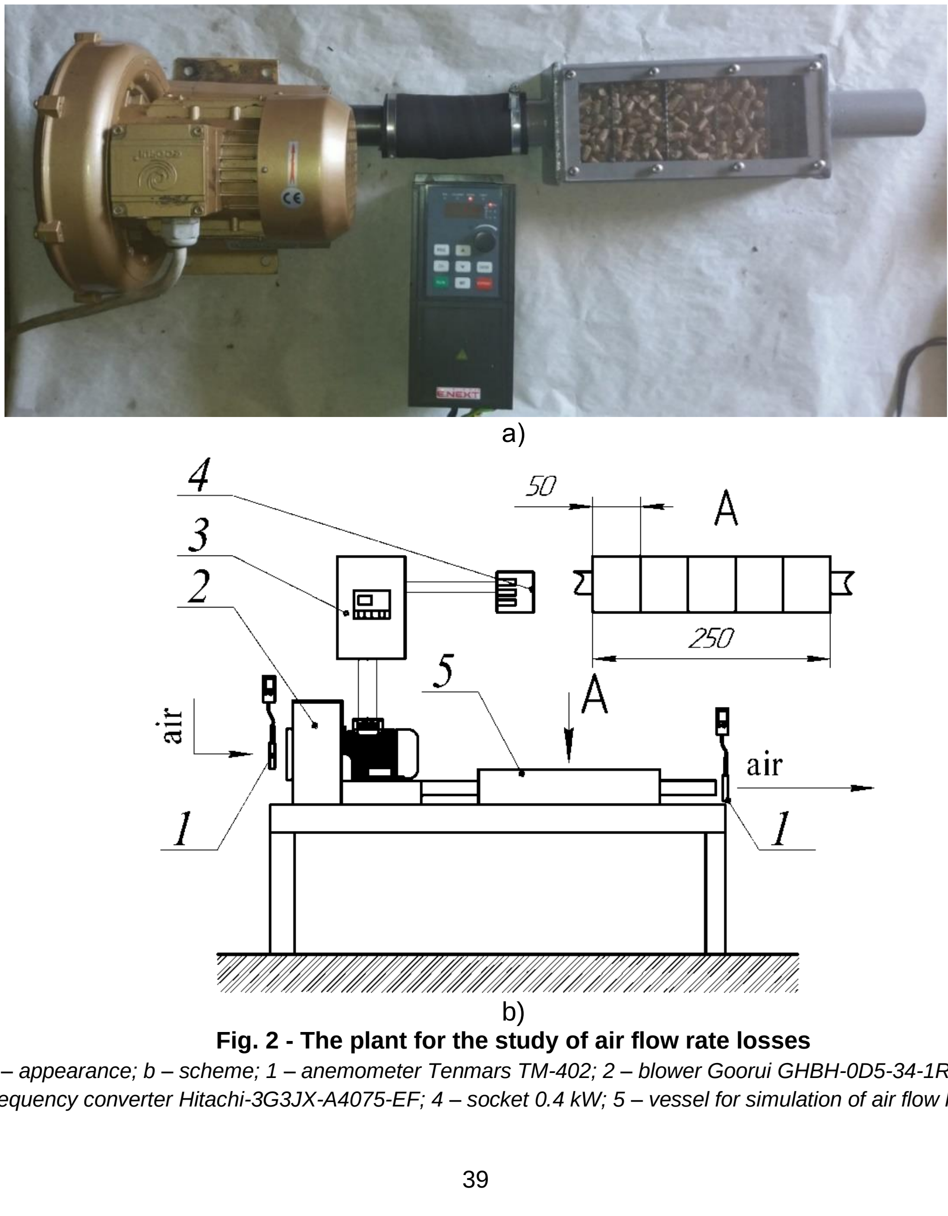

Fig. 2 - The plant for the study of air flow rate losses

a – appearance; b – scheme; 1 – anemometer Tenmars TM-402; 2 – blower Goorui GHBH-0D5-34-1R2; 3 – frequency converter Hitachi-3G3JX-A4075-EF; 4 – socket 0.4 kW; 5 – vessel for simulation of air flow length

The plant consisted of the following main components: a blower *2* and a vessel *5* to simulate the length of the air flow. The air flow rate at the outlet of the blower varied from 6.7 m/sec to 22.2 m/sec. Control of the speed of the blower impeller was carried out using the frequency converter. Vessel *5* was made in the form of a parallelepiped with a width of 100 mm and a height of 80 mm. Inside, the vessel was divided into 5 sections with a length of 50 mm by means of breathable partitions. The inlet and outlet pipes of the vessel were 40 mm in diameter, and were equal to the diameter of the inlet pipe of the blower. During the experiment, each section was consistently unloaded with fuel pellets made of straw. Thus, the length of the air flow in the oxidation zone of the gasifier (from 50 mm to 250 mm) was simulated. Using the anemometer *1*, the air rate at the inlet to the blower *2* and the outlet of vessel *5* was determined. The difference in rates made it possible to establish the pressure drop as a result of energy losses of the air flow and to find, according to the methods that are described in the works (*Baltussen et al, 2018; Berk, 2018*), the k_a loss coefficient.

RESULTS

Experimental studies have allowed to establish the values of the coefficient k_a (table 1) depending on the length of the air flow l_a and the average air flow rate $\upsilon_{1\text{-}2}$.

Table 1

Results of experimental studies of air flow losses

Air flow length, mm	Air rate at the inlet to the air-blower, m/sec	Air rate at the outlet of the air-blower, m/sec	Air flow rate losses, m/sec	Air flow pressure loss, PA	Average air flow rate, m/sec	Flow rate loss coefficient
50	22.2	17.5	4.7	3.3	19.9	0.056
50	18.7	15.0	3.7	2.1	16.9	0.048
50	15.8	13.0	2.8	1.2	14.4	0.038
50	10.8	9.6	1.2	0.2	10.2	0.014
100	21.5	15.5	6.0	5.4	18.5	0.105
100	18.5	13.5	5.0	3.8	16.0	0.098
100	13.2	10.1	3.2	1.5	11.6	0.073
100	9.3	7.5	1.8	0.5	8.4	0.046
150	21.0	14.2	6.8	6.9	17.6	0.149
150	15.5	10.7	4.8	3.5	13.1	0.134
150	12.4	8.8	3.6	1.9	10.6	0.115
150	8.1	6.1	2.0	0.6	7.1	0.079
200	20.5	13.0	7.5	8.4	16.8	0.200
200	17.1	11.0	6.2	5.7	14.0	0.192
200	14.1	9.2	4.9	3.6	11.7	0.177
200	7.2	5.0	2.2	0.7	6.1	0.130
250	20.0	12.0	8.0	9.6	16.0	0.250
250	16.6	10.1	6.6	6.4	13.3	0.242
250	13.6	8.4	5.2	4.1	11.0	0.227
250	6.7	4.3	2.4	0.9	5.5	0.190

The analysis of the data in table 1 allowed us to obtain an empirical equation of the dependence of the k_a coefficient on the air flow length l_a and the average air flow rate $\upsilon_{1\text{-}2}$, which is valid for the values of the air flow length more than 50 mm and the average air flow rate more than 6.7 m/sec.

$$k_a = -0.3412 + 0.002 l_a + 0.0337 \upsilon_{1-2} - 0.0008 \upsilon_{1-2}^2 \, . \tag{8}$$

The dependence 8 is graphically shown in fig. 3.

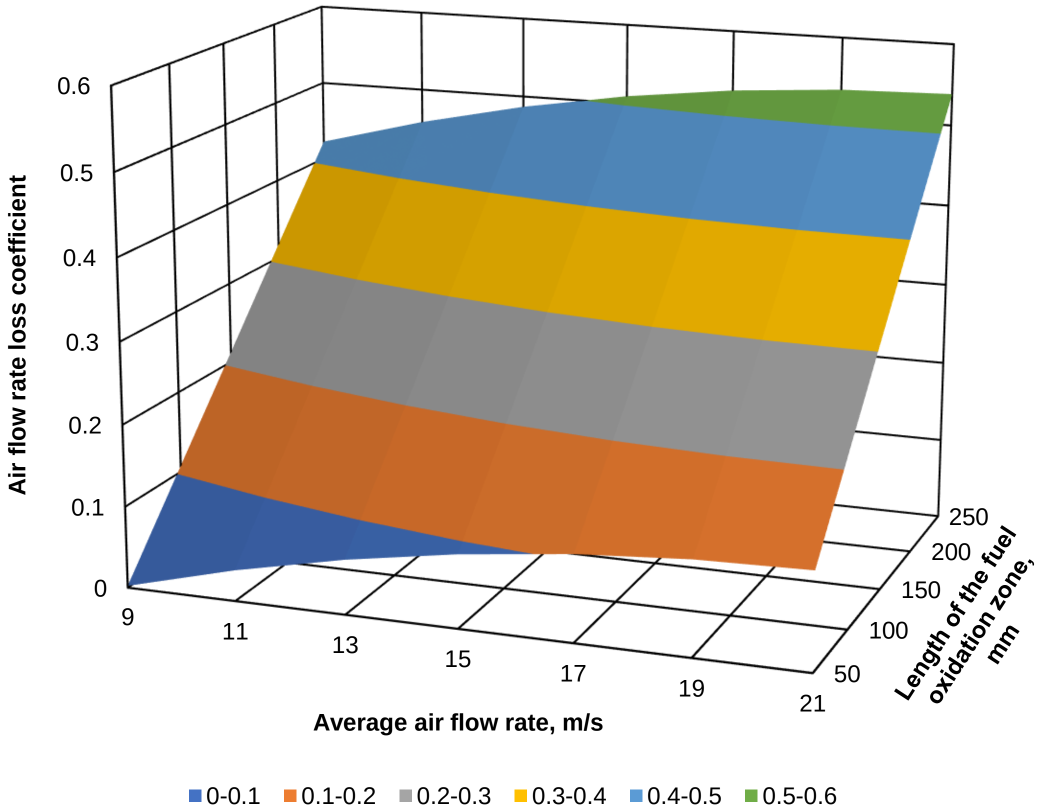

Fig. 3 - Dependence of the air flow rate loss coefficient on the length of the fuel oxidation zone and the average air flow rate

If we compare the dependence of the average air flow rate on its length calculated by numerical method according to equation (4) (theoretical values) and the dependence calculated by equation (7) using the empirical coefficient of loss of air flow rate k_a (experimental values), we can observe almost complete identity of the obtained theoretical and experimental values of the average air flow rate (fig. 4).

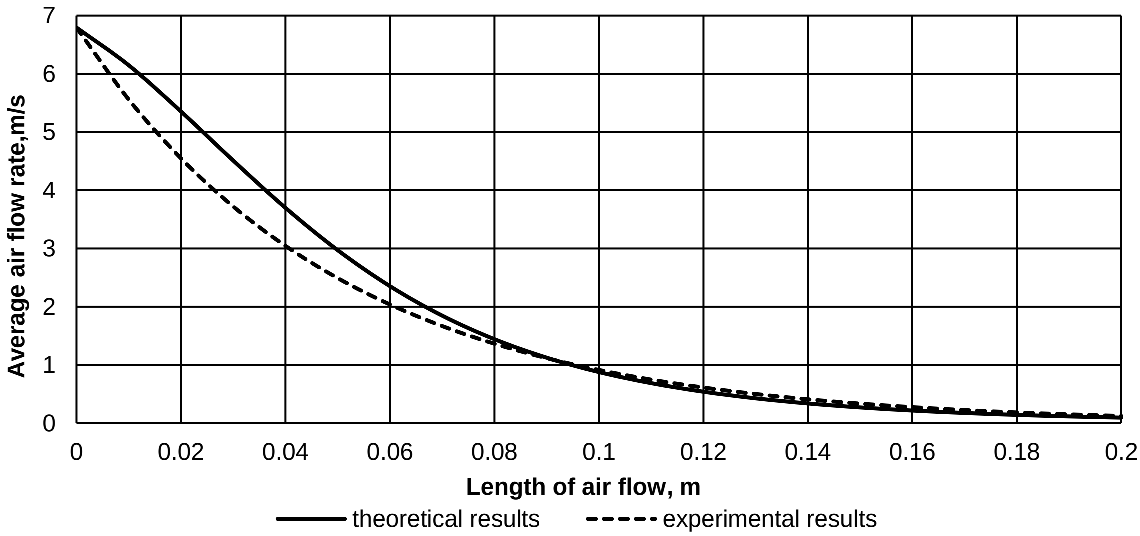

Fig. 4 - Comparison of the dependence of the average air flow rate on its length calculated by the numerical method (theoretical values at loss coefficients λ=0,08, ξ=0,2) and calculated using the empirical loss coefficient k_a (experimental values). The air supply to tuyere belt 0.012 m ^{3}/sec, the diameter of the tuyere holes – 0.01 m, the number of holes – 24

We assume that the effective air flow rate in the oxidation zone of the gasifier can be estimated by the Reynolds similarity criterion (*Berk, 2018; West, Photiou, 2018)* and must conform to turbulent regime movement (Re>2000). Such air movement in the oxidation zone in the gasifier provides fuel oxidation without forming low-temperature areas with a lack of air. In particular, the air supply to the tuyere belt of 0.012 m^3/sec, the diameter of the tuyere holes of 0.01 m, the number of holes of 24, the effective air movement is terminated at a distance of 0.2 m from tuyere belt, as the Reynolds criterion takes on values smaller than 2000 (Fig. 5). The air flow regime becomes laminar, low-temperature areas appear, the efficiency of the fuel oxidation process decreases, the quality of the gasifier deteriorates.

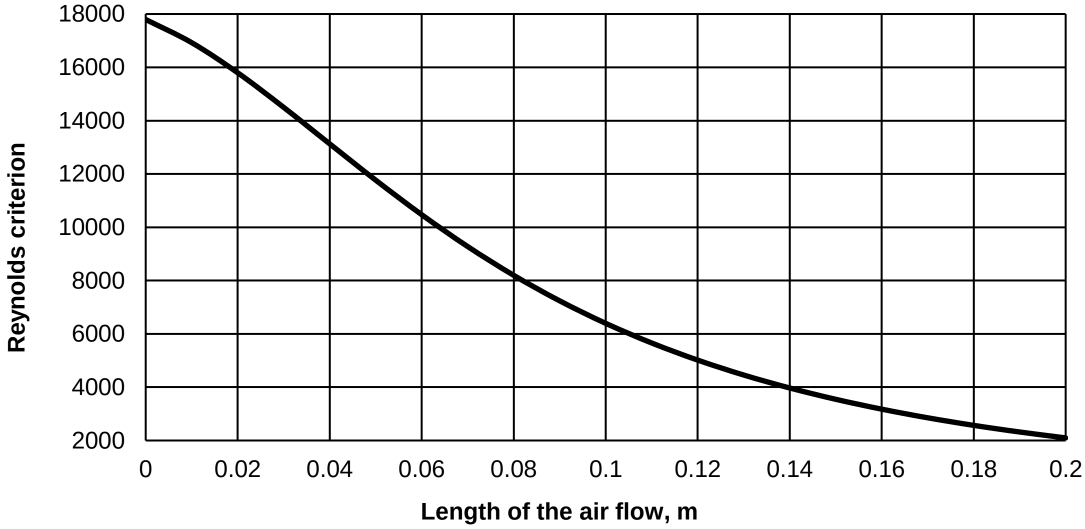

Fig. 5 - The dependence of the Reynolds criterion on the length of the air flow (air supply to the tuyere belt 0.012 m ^{3}/sec, the diameter of the tuyere holes – 0.01 m, the number of holes – 24)

The flow diameter determined according to equation (2) and reflected in fig.6, in our opinion, will correspond to the effective height of the oxidation zone of the gasifier.

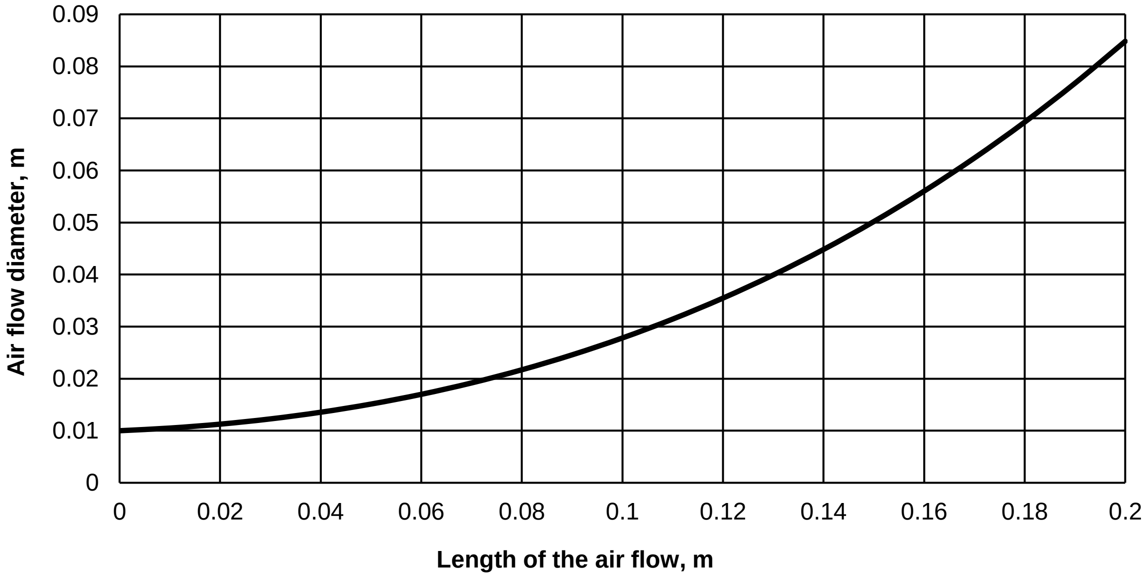

Fig. 5 - Dependence of the air flow diameter on its length (loss coefficients λ=0,08, ξ=0,2, the air supply to tuyere belt - 0.012 m^3/sec, the diameter of the tuyere holes – 0.01 m, the number of holes – 24)

Thus, when air is supplied to the tuyere belt of 0.012 m^3/sec, the diameter of the tuyere holes – 0.01 m, the number of holes – 24, the effective length of the flow l_a in the fuel oxidation zone in the gasifier will be 0.2 m, height h_a of the fuel oxidation zone will be 0.085 m. If the air supply to the tuyere belt of the gasifier is changed, the effective flow length changes accordingly.

For example, when air is supplied to the tuyere belt of 0.006 m^3/sec, the diameter of the tuyere holes of 0.01 m, the number of holes of 24, the effective length of the oxidation zone l_a in the gasifier will be 0.15 m, and the height h_a of the fuel oxidation zone – 0.05 m.

As a result of the analysis of theoretical and experimental studies, the influence of the air flow rate from the tuyere hole on the air flow length (linear length of the oxidation zone of the gasifier) was determined:

$$l_a = 0.089 ln(\upsilon_1) + 0.0394 \tag{9}$$

as well as the influence of the air flow rate from the tuyere hole on the air flow diameter (the effective height of the oxidation zone of the gasifier):

$$h_a = (0.0144\upsilon_1 - 0.0036) + h_f \tag{10}$$

where:

h_f – tuyere hole height, m

With the help of equations 9 and 10, it is possible to calculate the geometric parameters of the oxidation zone in the gas generator, which ensure the oxidation of the fuel without the formation of low-temperature regions with a lack of air.

CONCLUSIONS

The dependence of the air flow rate in the oxidation zone (gas generator), obtained on the basis of the Bernoulli equation allows us to theoretically set the average air flow rate depending on the flow length, as well as according to the continuity equation to determine the air flow diameter. To verify and clarify the theoretical equation, the value of the total loss coefficient of the flow rate in the volume of straw pellets, which are used as fuel for the gas generator, is experimentally established.

The effective air flow rate in the oxidation zone of the gasifier can be estimated by the Reynolds similarity criterion and must correspond to the turbulent regime (Re>2000). Such air movement in the oxidation zone of the gasifier provides fuel oxidation without forming low-temperature areas with a lack of air. In particular, the air supply to the tuyere belt of 0.012 m^3/sec, the diameter of the tuyere holes of 0.01 m, and the number of holes of 24, the efficient air movement stops at a distance of 0.2 m from the tuyere belt, since the Reynolds criterion acquires values less than 2000. The air flow regime becomes laminar, low-temperature areas appear, the efficiency of the fuel oxidation process decreases, the quality of the gasifier deteriorates.

In terms of air supply to the tuyere belt of 0.012 m^3/sec, the diameter of the tuyere holes of 0.01 m, the number of holes of 24, the efficient length of the flow in the fuel oxidation zone of the gasifier will be 0.2 m, the height of the fuel oxidation zone will be of 0.085 m. These geometric parameters of the oxidation zone in the gasifier provide straw pellets oxidation without the formation of low-temperature areas with lack of air.

When changing the air supply to the tuyere belt of the gasifier, the effective length of the air flow changes. Thus, when air is supplied to the tuyere belt of 0.006 m^3/sec, the diameter of the tuyere holes of 0.01 m, the number of holes of 24, the effective length of the oxidation zone l_a in the gasifier is 0.15 m, and the height of the fuel oxidation zone is 0.050 m.

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