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[1.]N.M. TSYVENKOVA, [1.]A.A. GOLUBENKO,
[1.]S.M. KUKHARETS, [2.]V.R.BILETSKY

THE RESEARCH OF DOWNDRAFT GAS PRODUCER HEAT PRODUCTIVITY ON STRAW

[1.]Mechanics & Agroecosystems Engineering Department, Zhytomyr National Agroecological University, UKRAINE
[2.]Forestry Faculty, Zhytomyr National Agroecological University, UKRAINE

Abstract: A connection between gas producer chamber design parameters and installation exploitation operational modes as well as fuel parameters, was studied. A multi-factor experiment that connects this parameters, was planned and installation tuning characteristics were built based on results. Using these results, under different fuel parameters, allows to gain maximum productivity under given conditions. Some recommended fuel parameters for effective gasification are substantiated also based on experimental data.
Keywords: heat productivity, gas producer, gas composition, tuyer circle diameter, gas blowing mode

1. INTRODUCTION

The gas producing process and its stability depend greatly on technical and operational parameters of gas producer installation and physical and chemical characteristics of straw (Basu, 2013; Higman and van der Burgt, 2008; Knoef, 2012; Kollerov, 1950; Muller et al., 2016). That is why raw material preliminary preparation for gasifying (Golub et al., 2015; Kolerov, 1950; Mezin, 1948) and coordination between gas producer design parameters and gas blowing mode are topical questions (Kolerov, 1950;Mezin, 1941;Los et al., 2014;Tsyvenkova and Golubenko, 2014). That will also allow us to gasify different types of biomass like corn stalks and cobs, sunflower chaff, Miscantus, wood etc. without big changes in design of the gas producer optimized for straw, gaining maximized heat productivity from equipment, depending on raw material.

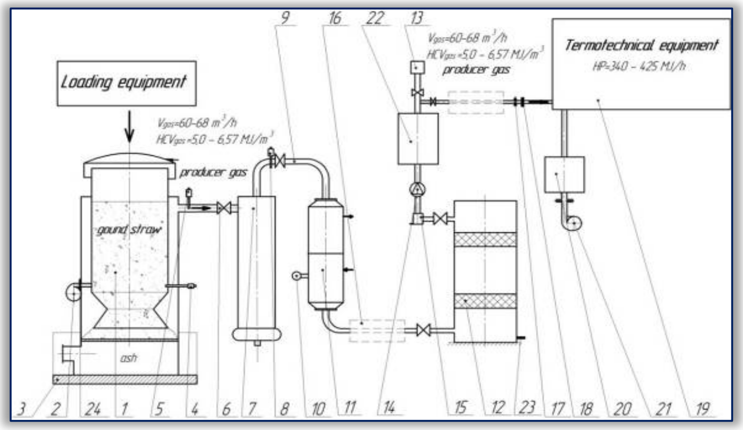
The analysis of written sources dedicated to improvement of the physical and mechanical properties of straw by processing it into pellets, briquettes, and fuel granules shows that this problem is enough explored. But these technological processes are energy cost and expensive (EU energy in figures, 2012; Geletuha and Zheleznaya, 2014; Melnichuk et al., 2011). A new method of straw preliminary preparation for gasifying was proposed – making a poly-fractional mixture from it, which makes its further usage in thermotechnical equipment economically advantageous.

There is a great variety of gas producer designs depending on way of receiving and appointment of producer gas, also by gas producer installation type, by degree of automatization and mechanization, by type of raw material (Mezin, 1948). In books (Basu, 2013; Knoef, 2012; Kolerov, 1950; Mezin, 1948; Pandey, 2015) the main accent was on creating an ideal gas producer design for exact type of raw material and main method of reducing moisture content to the acceptable level when operation of the gas producer will be economically expedient.

It was proposed a design of gas producer chamber where, depending on raw material initial moisture content, one can reduce energy expenditures on gasifying process and increase heat productivity of gas producer by changing tuyer circle diameter and appropriate gas blowing mode (Tsyvenkova and Golubenko, 2014). Also this gas producer can produce energy of any type of biomass which calorific value is close to straw`s, without any extra design changes, only changing position of moving tuyers along its axis. To ensure the effectiveness of this gas producer chamber design, an experiment on defining gas composition and gas producer heat productivity was made.

2. MATERIAL AND METHOD

Experiments on heat productivity of a downdraft gas producer working on straw where made on gas producer installation of ZhNAEU (figure 1) with laboratory measuring equipment of ZhNAEU and Institute of Gas NAS of Ukraine according to the accepted methods and branch standards.



a)


b)

Figure 1. Basic scheme (a) and general view (b) of the experimental installation where V_{gas} is gas producer productivity by gas, HCV_{gas} is higher calorific value of producer gas.

The installation consists of gas producer 1, electric air blower 2 with control, weights 3 for continuous registration of fuel consumption during operational cycle, thermocouples 4,5 and 8, for measuring fuel temperature in reaction zone, gas on the exit from gas producer and gas on the exit from cyclone scrubber 7 and on exit from cooler respectively, module of gas sample selection 16, module of fine purification 12, with condensate drain tube 23, moisture extractor 15 for separation water steam from gas. Since whole system has essential aerodynamical resistance and also for imitating consumer there is a vacuum pump 14 on the exit line. For levelling gas composition before feeding a furnace there is a receiver 22. Calorimeter 13 for on-line measuring and registering producer gas calorific value. For regulating gas supply installed throttling washer 17, and valve 18 for shutting off gas pipe.

A ground wheat straw was used as fuel for gas producer. On its base there were made a poly-fractional mixture: cylindrical stems ~ 35 mm long with nubs, wall thickness 0.5 – 1.1 mm; cylindrical even stems 25 – 35 mm long, wall thickness 0.2 – 0.3 mm, outer diameter 2 – 4 mm; squished stems 25 – 40 mm long, wall thickness 0.3 – 0.5 mm; bigger splintered stems 10 – 30 mm long, wall thickness 0.15 – 0.25 mm; small splintered stems ~ 8 mm long, wall thickness 0.15 mm; all other fractions content in all less than 3 %. Chemical composition of straw by dry mass N=0.52 %, C=44.43 %, H=5.86 %, O=44.43 %, S=0.11 %, cinder content 6.5%.

Finding connection between variable factors (D_t, V_{air}, W^P) and dependent (HP) ones, determination of the type of that connection and definition of the mathematical equation for expressing this connection is possible only by making a multifactor experiment.

Exploration of the operating modes of gas producer in laboratory consisted of such steps: loading a ground straw with predetermined, according to the plan, moisture content into the gas producer bunker; tuning the air blower 2 and moving tuyers to the initial position, when tuyer circle diameter D_t equals the tuyer belt diameter D_{Ch}; tuning calorimeter 13 and installing gas sample selection module 16; making the experiments, and result analyzing.

Air blower 2 productivity and tuyer circle diameter were changed during the experiment; control measurements of calorific value were registered by calorimeter 13. Gas sampling selection module consists of glass bulb 500 ml with two valves. Producer gas sampling was made by free-flow method. Producer gas chemical composition was determined with laboratory installation consisting of two channel chromatograph “Agilent 6890 N”, bulb with the carrier-gas – argon, manometer and a PC for logging. Calorific value of producer gas was calculated by gas chemical composition according to GOST 22667-83, and gas composition – by chromatography according to ISO 6974-1:2007.

Factor variation intervals are: air supply for gasifying process V_{air} 34, 40 and 46 m^3/h; straw moisture content W^P – 10, 20 and 30 %; parameter D_t – 272, 306, 340 mm. Factors encoding: $D_t=X_1$, $W^P=X_2$, $V_{air}=X_3$. Variation levels of abovementioned factors are given in table 1. To reduce the number of experiments and obtain the regression equation, the mathematical method of the experiment planning based on Box-Behnken quadric plan (Melnikov et al., 1980) was used.

Table 1. Variable factors & limits of their variation for definition of technological parameters of gasifying process

Factor variation level	Tuyer circle diameter D_t, mm	Straw moisture content W^P, %	Air supply for gasifying V_{air}, m^3/h.
Upper level (+)	340	30	46
Middle level (0)	306	20	40
Lower level (–)	272	10	34

Planning stage included the following steps: factor encoding, scheduling, randomization tests, implementation plan of the experiment, testing of reproducibility of the experiments, calculation of regression coefficients, assessment of the significance of regression coefficients and adequacy of the test model. The experiment consisted of 15 tests at threefold repetition in each of them.

3. RESULTS

As a result of laboratory experiments and statistical computation a heat productivity data array was got, given in table 2.

Table 2. Planning matrix of a multifactor experiment for determining gas producer heat productivity HP

№	Experiment planning method				Experiments results				Model adequacy check		
	X_0	X_1	X_2	X_3	HP_1	HP_2	HP_3	HP_{med}	$HP_{med.com}$	$(HP_{med} - HP_{med.com})$	$(HP_{med} - HP_{med.com})^2$
1	+	+	+	0	377.73	376.58	377.21	377.17	374.96	2.21	4.87
2	+	+	–	0	421.60	422.89	421.09	421.86	416.75	5.11	26.10
3	+	–	+	0	303.02	302.09	301.97	302.36	307.47	–5.11	26.10
4	+	–	–	0	337.88	338.00	337.97	337.95	340.16	–2.21	4.87
5	+	0	0	0	384.44	385.56	382.62	384.21	385.38	–1.17	1.37
6	+	+	0	+	345.26	344.93	343.10	344.43	345.93	–1.50	2.26
7	+	+	0	–	301.22	301.14	299.88	300.75	306.68	–5.93	35.12
8	+	–	0	+	275.42	275.10	275.01	275.18	273.89	1.29	1.67
9	+	–	0	–	241.31	240.82	240.18	240.77	234.63	6.14	37.68
10	+	0	0	0	385.18	386.65	384.94	385.59	385.38	0.21	0.04
11	+	0	+	+	298.73	297.69	297.56	297.99	296.85	1.15	1.31
12	+	0	+	–	260.45	260.52	260.25	260.41	257.59	2.82	7.97
13	+	0	–	+	333.34	332.93	333.17	333.15	334.08	–0.93	0.87
14	+	0	–	–	291.53	292.01	291.83	291.79	294.83	–3.04	9.21
15	+	0	0	0	387.94	384.79	386.30	386.34	385.38	0.96	0.92

Regression coefficients: $b_0=384.16$; $b_1=35.99$; $b_2=-18.35$; $b_3=19.63$; $b_{12}=-2.28$; $b_{13}=2.32$; $b_{23}=-0.95$; $b_{11}=-14.94$; $b_{22}=-9.39$; $b_{33}=-78.94$.

Experiment results were processed using the software "Statistica". Homogeneity of variances was tested by the Cochrane criterion. Since $G^{com}=0{,}176<G^{tabl}(0{,}05;\ 15;2)=0{,}4$ the process is reproduced. When determining of confidence intervals for regression coefficients, the Student test was used, tabulated value of which level was at a 5 % and the number of degrees of freedom of experiment variance reproducibility f1=2 was t=4.3 (Melnikov et al., 1980). The significance of regression coefficients was tested according to the established confidence intervals and covariance. As a result, the regression equation acquired the form:

$$HP=384.16 + 35.99\cdot X_1 - 18.35\cdot X_2 + 19.63\cdot X_3 - 2.28\cdot X_1\cdot X_2 + 2.32\cdot X_1\cdot X_3 - 0.95\cdot X_2\cdot X_3 - 14.94\cdot X_1^2 - 9.39\cdot X_2^2 - 78.94\cdot X_3^2 \quad (1)$$

where: X_1 - encoded value of tuyer circle diameter; X_2 - encoded value of the moisture of ground straw; X_3 - encoded value of the air supply for gasifying.

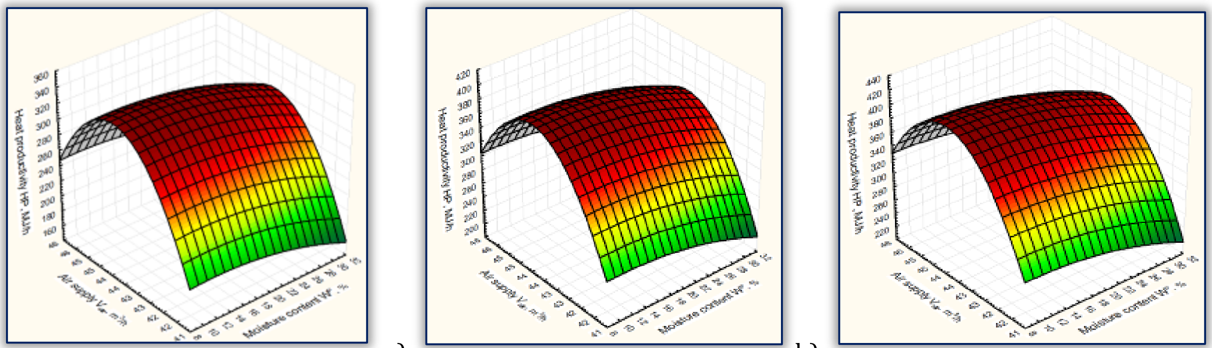
Adequacy test of hypotheses of obtained regression equation was performed by the Fisher criterion. The estimated value of this criterion in the dispersion of inadequacy $S^2_{inadeq}=1.17$ and dispersion $S_y^2=2.33$ reproducibility of the experiment was: $F^{com}=0.5$. Tabular value of Fisher's exact test adopted by the 5 % of significance, according to (Melnikov et al., 1980), was: $F^{tabl}(0.05;\ f_1;\ f_2)=19.38$, where $f_2=8$ variance inadequacy degrees of freedom f1=2 – variance experiment reproducibility degrees of freedom. Since, $F^{com}=0.5<F^{tabl}(0.05;\ f_1;\ f_2)=19.38$, the hypothesis by the adequacy of the regression equation is confirmed.

Final regression equation of the factors in the species acquired the form:

$$HP = 384.16 + 35.99\cdot D_t - 18.35\cdot W^P + 19.63\cdot V_{air} - 9.39\cdot(W^P)^2 - 78.94\cdot V_{air}^2 \quad (2)$$

where: D_t – tuyer circle diameter, W^P – moisture content of a ground straw, V_{air} – air supply for gasifying.

Graphical representations of the abovementioned equation are given on figures 2-4.



a) b) c)

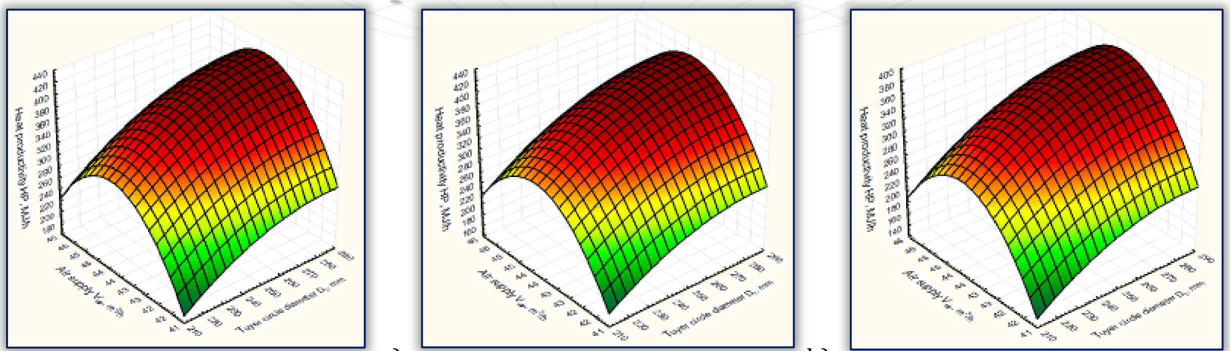
Figure 2. Gas producer heat productivity HP against straw moisture content W^p and air supply V_{air}
a) - D_t=272 mm, b) - D_t=306 mm, c) - D_t=340 mm

As we can see from figure 2 unless air supply V_{air} is rising from 34 m³/h till 41 m³/h gas producer heat productivity HP is also rising. Raising trend is present in all three cases (a), b), c)). However maximum numbers are reached between 39 – 42 m³/h of air supply. These limits were accepted as rational gas blowing mode for this gas producer working on ground straw with moisture content 10 – 30 %.

The phenomenon of rising productivity is explained by fact that when air supply to the chamber working zone is rising, the amount of oxygen rises, which promotes intensification of fuel carbon oxidizing reaction. Since oxidizing reaction is endothermic, significant heat is released in active zone, which is needed for creating CO – one of the main combustible components of the producer gas. This, in turn, leads to rising of producer gas calorific value, and, consequently, gas producer heat productivity.

But further rising of air supply to more than 42 m³/h gas producer heat productivity lowers, since extra air, while going through fuel layer in reaction zone, cooling it, promoting creation more CO_2 instead CO by blowing out fuel carbon with gas, which is taken away from gas producer.

In figure 3 is seen that expanding tuyer circle diameter D_t from 272 to 340 mm makes gas producer heat productivity rise due to better conditions for aerodynamical processes in gasification chamber. However excessive expanding of the D_t leads to instability of the gas producing process. The phenomenon of gasification zone localization and appearance of zones where fuel is not burning in the middle of gasification chamber are observed. Tars content in gas rises as a result. For a ground straw with moisture content W^p=30 % under normal conditions tars content was close to 3 g/m³, moisture – 0.2 kg/m³.



a) b) c)

Figure 3. Gas producer heat productivity HP against tuyer circle diameter D_t and air supply V_{air}
a) - W^p=10 %, b) - W^p=20 %, c) - W^p=30 %

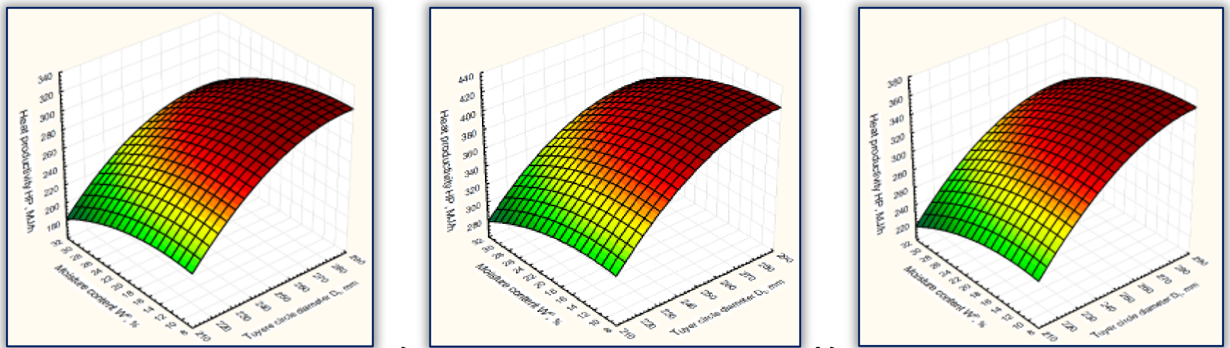
The other requirement which limits expanding or restricting D_t is providing proper D_t to d_g (gas producer diameter) ratio that is needed for creating favorable conditions for tars cracking process.

Restricting tuyer circle diameter D_t while air supply V_{air} and moisture content W^P are constant will lead to localization of combustion zone in the middle of gasification chamber and creating zones where fuel is not burned alongside the walls of gasification chamber, followed by lowering temperature in reaction zone and consequently to the gas producer heat productivity HP reducing.

Therefore, changing regulated parameter, like tuyer circle diameter D_t, we can tune gas producer heat productivity depending on straw initial moisture content W^P, while air supply V_{air} is constant.

Most preliminary preparation activities of raw material before using it in any thermotechnical equipment, converge to reducing moisture content to the level when technological process and equipment, that is used, are economically reasonable. For example, in our case lower limit of moisture

content in straw is 8 %. This moisture is enough for formation of such combustible gas component as H_2 and its drying expenditures are relatively low.
In order to find the upper limit of moisture content next experiment was made. Ground straw with moisture content of 40 % was used as fuel for gas producer. Gas producer bunker was additionally equipped with condenser device, and grating design provides a rocking grating with blades inside another circular grating. Nonetheless satisfactory technological parameters of gas producer operation were not provided. Within the first hour of operation on straw with moisture content 40 % and ash content 6.5 % dry gas output reached v_d=1.4 m^3/kg with calorific value Q_L^{pg}=3.6 MJ/m^3 instead of v_d=2.14 m^3/kg and Q_L^{pg}=6.14 MJ/m^3 when working on straw with moisture content 8 %. Fuel layer resistance rised from 8 Pa to 25 Pa because of intensive slag production, and gas producer heat productivity reduced from 394 MJ/h till 151 MJ/h till the end of fifth operational hour. Gas producing stability was broken. Starting from 3rd hour of operation was necessary to move rocking grating with blades periodically. Comparing our experimental data with data from (mezin I.S. 4) about producing gas from straw briquettes and peat (ash content 12 % moisture content 15 % with cinder melting point 1300 ^{0}C), results show that slag producing from ground straw with moisture content 40 % is a bit more (1.24 kg/h) than straw briquettes (1.13 kg/h) and less than peat (3.14 kg/h). Nonetheless, straw slag, compared to slag from peat has a viscous structure because of low softening temperature, and covers fuel surface, reducing its gas permeability. Slag when mixed with fuel reduces the possibility of its pushing down into the lower part of chamber thus stopping operation. In this case using the poly-fractional composition from ground straw is much better than straw briquettes, since it has greater reaction surface and is more gas permeable when slaging. Therefore using ground straw with moisture content more than 30 % is inappropriate because of big heat productivity loses.
Analysing fuel moisture content influence on gas producer operational characteristics, we can see that gas producer firing time is about 20 min when moisture content is 8 % and 45 min when 30 %, because of energy expenses on straw drying directly in gas producer bunker. Lower calorific value of a dry producer gas from 30 % moisture straw is Q_L^{pg}=5.43 MJ/m^3, that is 1.2 times lower than from 8 % moisture straw – 6.14 MJ/m^3, and quantity of producer gas from one kilogram of ground straw reduced by 1.3 times to 1.65 m^3/kg.
Graphical representation (figure 4) shows nature of the change of gas producer thermal mode depending on rising moisture content in fuel. Rising moisture content from 8 to 30% leads to rising heat expenses on evaporating moisture from fuel by almost 15%, and its further rising leads to reaction zone temperature sharp reducing, and gas producing process instability. So, moisture content interval of 8 – 30% is rational, and all technological process of straw preparation for gas producing should provide limiting moisture content to the above mentioned limits.



a) b) c)

Figure 4. Gas producer heat productivity HP against tuyer circle diameter D_t and straw moisture content W^P
a) - V_{air}=34 m^3/h, b) - V_{air}=40 m^3/h, c) - V_{air}=46 m^3/h

However, analysis of fig.4 shows that moisture content in fuel influences heat productivity lesser than D_t. Maximum productivity of the gas producer depends more on the current position of moving tuyers in the gas producer active zone.

4. CONCLUSIONS

Summing all, we can say that:

≡ gas producer heat productivity rises by 30 – 35 % while air supply is rising from 34 to 41 m^3/h, and drops again while air supply is rising further. So, between 39 and 42 m^3/h gas producer heat productivity is maximized and is between 340 and 425 MJ/h for straw moisture content 8 %;

- ≡ while rising D_t from 272 to 340 mm heat productivity rises by 22 – 24 % with the fixed moisture content and V_{air}=34 – 46 m^3/h;
- ≡ while rising W^p from 10 to 30 % gas producer heat productivity drops by 12 – 15 % with V_{air}=34 – 46 m^3/h.
- ≡ We should note that within moisture content 8 to 30 %, air supply 39 – 42 m^3/h and tuyer circle diameter between 272 – 340 mm high calorific value of dry producer gas was reached 5.0 – 6.6 MJ/m^3, and maximum gas producer productivity of 425 MJ/h was reached at V_{air}=40 m^3/h, D_t=340 mm and W^p=8 %.

Based on experimental results analysis we can do a conclusion that making a gas producer chamber with the variable tuyer circle diameter (with the tuyer that can moved along its axis during gas producer operation) is a real and effective design feature, providing appropriate gas blowing mode to fit moisture content that will let us gaining high heat productivity numbers.

Further research will be aimed to study the influence of fine-grained vegetal waste distribution irregularity of the fire surface on fuel combustion completeness, hence gas producer productivity.

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