INVESTIGATION OF TECHNICAL AND TECHNOLOGICAL PARAMETERS OF SYNGAS COMBINED PURIFYING EQUIPMENT

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Abstract. This scientific work is devoted to the investigation of technical and technological parameters of combined cooling and purifying equipment for syngas, produced from lignin, from mechanical impurities and tars. The design of a combined purifier of syngas consisted of wet and dry stages. A scheme of definition of quantity of mechanical impurities and tars in syngas is presented. Wet stage is an irrigated scrubber 0.65 m high with a filtering header in the form of reservoir with bulk filler. Dry stage is a filtering header 0.9 m high with stuffed filler. Dependencies of the integral purification coefficient from fuel moisture content, water consumption and irrigated header type, syngas velocity in scrubber and scrubber cross-section area were found experimentally. Fractional composition of tar and abrasive and disperse composition of dust in syngas were examined before and after purifier. According to the produced data, a combined purifier provides a high grade of refining of syngas – 84.4 % by mechanical impurities and 72 % by tars for wet stage water consumption equal to 15 $L \cdot m^{-3}$. It was defined that optimal water consumption for cooling is 7 $L \cdot m^{-3}$, and for purifying is 11-15 $L \cdot m^{-3}$. Changing the height of the irrigated header does not affect the grade of refining of syngas, and raising syngas velocity in combined purifier deteriorates its purification. The dispersed composition of mechanical impurities proves that the purification coefficient of syngas from ash abrasive particles is more than 99 %. Tar content in syngas after combined purifier is minimal, around 20-30 $mg \cdot m^{-3}$. The presented design of equipment for combined purification of syngas is an alternative to expensive filtering equipment for small business and farms.

Keywords: combined purifier, purification coefficient, scrubber, syngas, mechanical impurities and tars.

Introduction

Gasification is one of efficient and cheap technologies of thermo-chemical conversion of solid biomass fuels to combustible gas, named syngas [1; 2]. However, for reliable operation of heating equipment at syngas, it must be properly cooled and cleaned.

An analysis of scientific papers about the methods of cleaning and cooling gases [3; 4] indicates the existence of many designs of mass transfer apparatus and dust collection equipment, as well as connection diagrams. While, some devices have high energy consumption – bag filters, nozzle units; others are complex in design and operation – column equipment, electrostatic precipitators; also there are low efficiency equipment, such as, foam and mechanical devices. Serial and parallel connection schemes for gas purification systems are widely used in industry [5; 6]. Serial connection eliminates the presence of intermediate flows, which increases the overall efficiency of the system. However, they are multi-staged due to the low efficiency of the individual stages of the system, which is explained by the presence of mechanical impurities that disable absorbing apparatus, especially in syngas [5]. Parallel connection is used for low capability single equipment and when it is necessary to clean large volumes of gas [5-9]. However, these connection diagrams are rarely used for small volume treatment (up to 200 $m^3 \cdot h^{-1}$), due to the high cost and structural complexity, which is typical for the production conditions of small agricultural and farming enterprises.

According to [10; 11], it is recommended to use wet purification technologies and apparatuses for syngas. These methods allow to clean syngas without preliminary preparation. In such units, processes of absorption and purification of gases from abrasive impurities occur simultaneously. The disadvantage of this technology is that the designs of wet-type purifiers, while cleaning syngas with abrasive impurities, often fail due to wet solids sticking together and clogging with tars. The efficiency of gas purification is also reduced, if it has dispersed particles with low wettability.

The use of equipment, operating in the fully developed turbulence mode, is a promising method of intensification of the gas wet purification process [11]. By increasing gas velocity we raise the unit's productivity, as well as gas purification efficiency. It also helps reduce the material consumption of the structure. Units with moving nozzles, vortex units, units with large holes perforated trays, etc. work in this mode [11; 12]. However, such equipment is expensive when used in gas generating units

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with low-productivity gasifiers (up to 100 $m^3 \cdot h^{-1}$). This increases the cost of the unit design. In addition, syngas is difficult to clean because of the physicochemical properties of pollutants and tars, the dispersed composition of mechanical impurities and their concentration [13]. Natural gas cleaning equipment is not suitable for syngas, because it does not meet the required standards of purification.

The works that are devoted to the theory and calculations of processes occurring in scrubbers, when cleaning syngas from biomass, solve the problems of gas cooling, but not its purification. Operational data and recommended parameters for cleaning syngas for stationary gas generating units equipped with scrubbers should be considered contradictory [10-12]. We should state that no studies have been conducted for gas generating equipment with gasifiers, which capacity is up to 100 $m^3 \cdot h^{-1}$.

The aim of this work is to increase the efficiency of the process of purifying and cooling syngas from plant raw materials in scrubbers of gas generating plants with a productivity of up to 100 $m^3 \cdot h^{-1}$.

Materials and methods

The factors that affect the purifying and cooling of syngas were studied. Those factors are the following: type of irrigated header; spraying density and water consumption; height of the irrigated header; gas velocity in the purifier. Studies were also conducted on the qualitative characteristics of contaminants. In particular, the following characteristics were determined: the dispersed composition of mechanical impurities, their abrasive properties, and the fractional composition of tar.

The study of the syngas purification parameters was carried out at experimental equipment with a downdraft gasifier that was running on plant raw materials [14]. The equipment was improved by incorporating the combined purifier 28 into the base model [14] and is shown in Fig. 1.

The gas, which was delivered to the treating system of the experimental setup, had the following parameters: syngas flow rate – 60-68 $m^3 \cdot h^{-1}$; syngas temperature – 500-60 °C; higher calorific value of gas – 12.2 $MJ \cdot m^{-3}$, moisture content – 60-120 $g \cdot m^{-3}$; content of mechanical impurities – 0.6-1.0 $g \cdot m^{-3}$; tar content is 0.1-0.2 $g \cdot m^{-3}$ [14]. Lignin briquettes were used as fuel for the gasifier. The chemical and technical characteristics of the fuel were the following: the mass fraction of total moisture ranged from 20 % to 30 %; ash content – up to 11.8 %; sulfur content – 0.4 %; LCV – 18.09 $MJ \cdot kg^{-1}$; HCV – 20.91 $MJ \cdot kg^{-1}$.

The combined purifier 28 consisted of a pump 26, wet and dry stages. Its main dimensions were the following: diameter – 0.9 m; height – 2.7 m. The wet stage was an irrigated scrubber 11 with a header that could be stuffed with profiled and random chunks (ceramic rings 50×20×4 mm, charcoal, broken brick 40×70 mm in size). The height of the irrigated scrubber was 0.65 m. The dry stage of a combined purifier 23 contained a filter header (wood, metallic chip) with a total height of 0.9 m.

Water for irrigation of the wet stage was supplied to the sprinkler 12 by four nozzles with holes 4 mm in diameter. The water flow from the nozzles was directed onto steel disks suspended by two rods. After hitting the disks, water was sprayed to the sides and up and also partially flowed down. The untreated gas was fed from the bottom of the purifier and, passed up through the irrigated scrubber 11 and the dry stage of the combined purifier 23, and then was taken out through the gas feeding pipe 27.

Water consumption was measured by the water meter Sensus iPerl Q3 2.5 (DN 15). To measure the temperature inside the purifier, the distant manometric thermometer 6 (TMP-100C) ∅100 mm, with range from 0 to 400 °C, was used. Resistance in different parts of the purifier was measured by a string piezometer. The temperature of the gas at the outlet and the temperature of the water at the inlet and outlet of the purifier were monitored by a XH-B310 ° thermometer. Gas consumption was measured with throttle washers. The calorific value of the gas was controlled by the calorimeter CM6G and calculated by gas analysis. To determine the chemical composition of the gas the chromatograph Agilent 6890N was used.

The level of syngas contamination was determined using the experimental equipment, Fig. 2.

The dispersed composition of the dust or before the purifier was determined by the aspiration method using an AFA-VP-20 filter. It was impossible to collect dust after the purifier, using the specified method, because it was clogging the filter and creating great resistance to gas flow, since the dust was moistened in the wet scrubber. Therefore, after the purifier, a dust sample was taken from the walls of the bent pipe elbow, where the largest amount of entrainment was deposited.

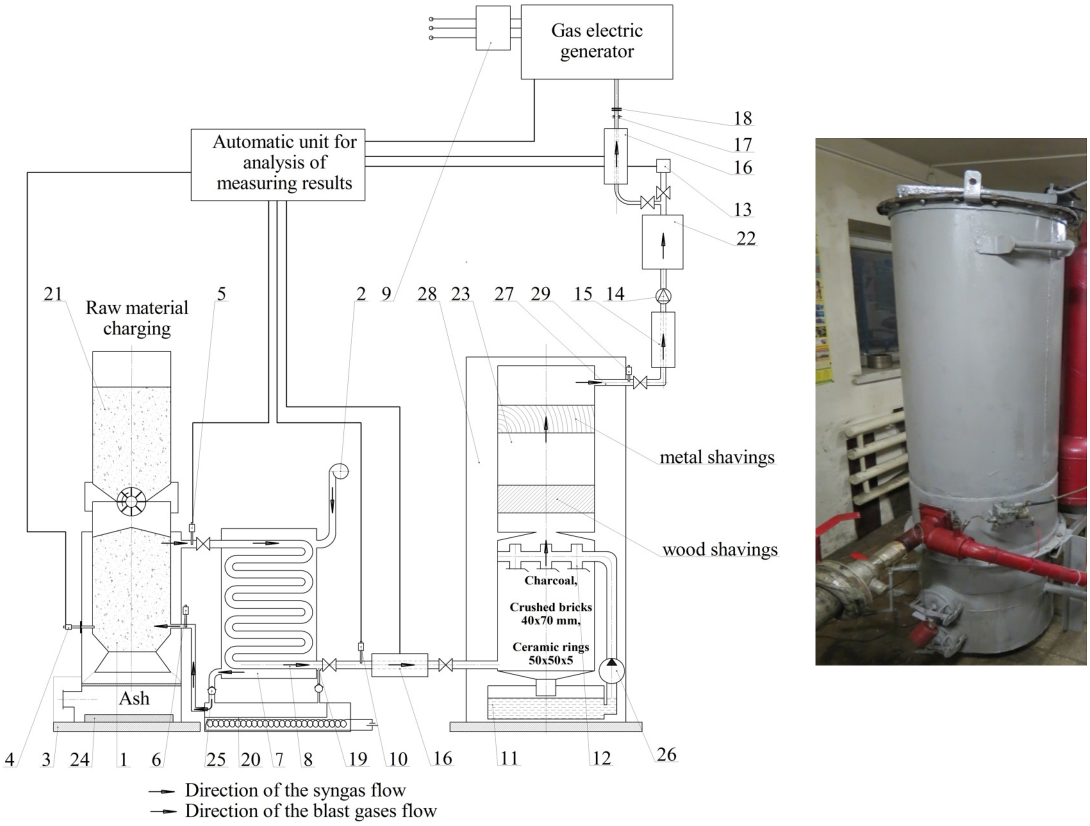

Fig. 1. **Pilot plant for syngas purifying and cooling – diagram (a); photo of general view (b):** 1 – downdraft gasifier; 2 – double stage blower 4 (GHBH 004 34 2R5 3KW); 3 – laboratory scales TVE 500-10 according to DSTU EN 45501; 4 – type C thermocouple; 5, 6, 10 – type K thermocouple; 7 – gas-air recuperator; 8 – gas pipe; 9 – electricity meter; 11 – irrigated scrubber header; 12 – sprinkler; 13 – calorimeter CM6G; 14 – vacuum pump; 15, 16 – gas sampling assembly; 17 – throttle washer for regulation of gas supply; 18 – choke; 19 – pipe with a check valve; 20 – evaporator chamber; 21 – raw bunker; 22 – receiver; 23 – dry stage of a combined purifier; 24 – scales TVE 150-5 according to DSTU EN 45501; 25 – check valve; 26 – pump; 27 – gas feeding pipe; 28 – combined purifier; 29 – mercury thermometer TL-4 according to TC 25-2021.003-88

Fine dust particles skipped further through the system, therefore, the obtained dispersed composition showed an underestimated amount of particles of the finest fractions. This fact was considered in the process of analyzing the harmful effects of power syngas pollution on the wear of the piston group of an internal combustion engine (ICE).

Before the analysis, the dust sample was treated with acetone to remove tarry substances, and then dried at room temperature 18-22 ºC. Dispersion was determined by the sieve methods and mechanical screening in a pneumatic classifier [15]. The sieve method was used to determine the dispersion of fractions with a particle size of 43µm and above. Dust fractions with a dispersion of less than 43µm were determined by mechanical screening in a pneumatic classifier.

The experimental work consisted in determining the gas purification coefficients for both the irrigated nozzle 11 and the total for the combined purifier 28. In this case, the value of the studied factors affecting the purification coefficients changed, while all other factors, also affecting the purification, remained constant. The gasifier operation mode was maintained stable. The gas flow rate during the experiments ranged from 60-68 $m^3 \cdot h^{-1}$, which approximately corresponded to gas consumption by an engine with a power of 22 kW. A stable operating mode of the gasifier provided stability of gas pollution parameters when it enters the purifier, which is necessary for this study.

To establish the dependence of the gas purification coefficient on the water flow rate, water was supplied from the system at a pressure of 0.1-0.2 MPa, and its flow rate varied within 300-1200 $L \cdot h^{-1}$, or 4.5-19 L·m^{-3}. In order to determine the effect of the water sprinkling system on gas purification, the wet stage sprinkling system was designed similarly to the hollow jet scrubber system. The following types of irrigated headers were investigated: profiled chunks – ceramic rings 50×20×4mm; random chunks – charcoal, crushed brick 40×70mm in size. Each type of header was tested at a consumption of 7, 11 and 15 L·m^{-3}.

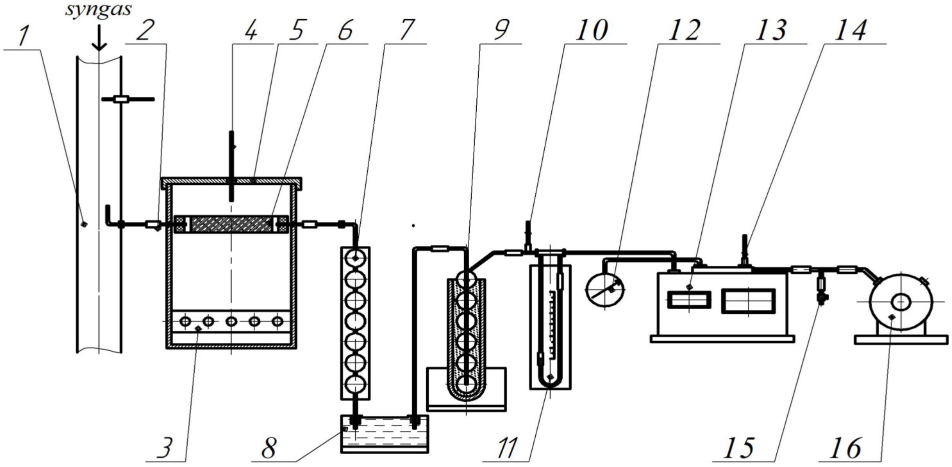

Fig. 2. **Experimental installation for measuring tar and mechanical impurities in syngas:** 1 – pipe with syngas; 2 – syngas sampling pipe; 3 – heating element; 4 – type K thermocouple; 5 – a capacity with thermo insulation; 6 – filtering element; 7 – gas cooler; 8 – reservoir for condensations; 9 – condenser; 10, 14 – thermometer TL-4; 11 – aerometer; 12 – pressure gauge; 13 – gas meter; 15 – regulator; 16 – fan

To study the influence of the gas velocity in the scrubber on its purification coefficient, scrubbers of such cross-sections were made (basic – 0.5 m^2 and reduced section – 0.25 m^2). Thus, it was possible to obtain multiple gas velocities in the purifier without changing the gas flow rate in the gasifier. In these experiments, the height of the header remained unchanged; the water supply was 7, 11 and 15 L·m^{-3}.

Gasifier operating modes, technical and operational syngas parameters are shown in Table 1.

Table 1

Gasifier operating modes, technical and operational syngas parameters

Gasifier mode	**Gas parameters corresponding to the gasification mode**				**Impurities content in gas after gasifier, g·m^{-3}**	
	Moisture content of the fuel W^P, %	Gasifier productivity V^{gas}, m^3·h^{-1}	Gas temperature at the outlet T, ºC	Gas higher calorific value Q^{HCV}, MJ·m^{-3}	Mechanical impurities	Tar
1	20	67	622	12.2	0.823	0.093
2	25	64	548	11.6	0.972	0.109
3	30	66	539	10.4	1.141	0.221

Wood shavings were also used as header filler. Unfortunately, we had to abandon them in the research process, since they created a high aerodynamic resistance in the system due to the high bulk density (320-580 kg·m^{-3} at a humidity of more than 15 %). Shown situation worsened and sometimes stopped the gas flow in the purifier.

In [10; 15], it is indicated that in irrigated scrubber header the efficiency of the header depends on its specific surface, which, in turn, depends on the geometric parameters of the header. But nothing was said about the effect of the surface on the gas cleaning efficiency, which was the reason for conducting the specific research. Headers with a height of 0.65 and 0.9 m were tested in a combined purifier. Headers with a height of 0.65, 1.3 and 1.95 m were tested in a scrubber with a cross section of 0.25m^2. 30 experiments were carried out in each scrubber. The summary tables show the averaged data of 2-5 experiments for each studied factor affecting gas purification.

The change in aerodynamic resistance of the irrigated header, when changing the filler and changing the irrigation modes; the influence of the filler geometric parameters on the length of gas path through the bulk mass; increase in bulk density of filtering irrigated mass during operation, etc. have not been investigated in this work. These simplifications do not affect the results of experimental work, but leave the opportunity for further research using the existing laboratory setup.

For the research, the specific surface of the headers was calculated: 42 $m^2 \cdot m^{-3}$ for a random chunks filler and 88 $m^2 \cdot m^{-3}$ for a shaped chunks filler with a bulk density of 180-230 $kg \cdot m^{-3}$.

Results and discussion

Studies of these types of headers are interesting, because the nature of their surfaces is different, which could affect, if not cooling, then gas cleaning.

As it can be seen from Table 2, the filler made of crushed brick and charcoal did not show a noticeable difference in the gas purification coefficient in the irrigated scrubber, both in terms of mechanical impurities and tar. Gas cleaning was improved due to the increased level of irrigation from 7 to 15 $L \cdot m^{-3}$. For example, with the crushed brick filler, the purification coefficient of the irrigated scrubber by mechanical impurities was 63.8 % at a water consumption of 7.0 $L \cdot m^{-3}$ and increased to 77.4 and 81.7 % at a water consumption of 11 and 15 $L \cdot m^{-3}$ respectively.

Table 2

Results of the study of the syngas purification coefficient in the irrigated scrubber

Gasifier mode	Impurity content in syngas, $g \cdot m^{-3}$		Type of wet header filler	Water consumption 7.0 $L \cdot m^{-3}$				Water consumption 11.0 $L \cdot m^{-3}$				Water consumption 15.0 $L \cdot m^{-3}$			
				Impurities in syngas after scrubber, $g \cdot m^{-3}$		purification coefficient, %		Impurities in syngas after scrubber, $g \cdot m^{-3}$		purification coefficient, %		Impurities in syngas after scrubber, $g \cdot m^{-3}$		purification coefficient, %	
	mechanical impurities	tar		mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar
1	0.823	0.093	Charcoal	0.288	0.039	65.0	58.1	0.174	0.032	78.9	65.6	0.146	0.027	82.3	71.0
2	0.972	0.109	Charcoal	0.431	0.051	55.7	53.2	0.219	0.042	77.5	61.5	0.191	0.035	80.3	67.9
3	1.141	0.221	Charcoal	0.562	0.105	50.7	52.5	0.264	0.088	76.9	60.2	0.249	0.073	78.2	67.0
1	0.823	0.093	Crushed brick	0.298	0.045	63.8	51.6	0.186	0.034	77.4	63.4	0.151	0.028	81.7	69.9
2	0.972	0.109	Crushed brick	0.446	0.054	54.1	50.5	0.228	0.051	76.5	53.2	0.202	0.038	79.2	65.1
3	1.141	0.221	Crushed brick	0.578	0.111	49.3	49.8	0.284	0.092	75.1	58.4	0.243	0.078	78.7	64.7
1	0.823	0.093	Ceramic rings	0.237	0.034	71.2	63.4	0.142	0.031	82.7	66.7	0.128	0.026	84.4	72.0
2	0.972	0.109	Ceramic rings	0.398	0.041	59.1	62.4	0.202	0.037	79.2	66.1	0.173	0.031	82.2	71.6
3	1.141	0.221	Ceramic rings	0.418	0.088	63.4	60.2	0.236	0.078	79.3	64.7	0.236	0.069	79.3	68.8

In the case of the charcoal filler, the increase in the level of irrigation from 7 to 15 $L \cdot m^{-3}$ for the first operation mode of the gasifier, lead to the increase of the purification coefficients from 65.0 (for mechanical impurities) and 58.1 % (for tars) to 82.3 and 71.0 % (for 15 $L \cdot m^{-3}$). The purification coefficients for the tar are practically the same for both chunk fillers. This trend is observed in all operating modes of the gasifier. It is important to note that irrigated scrubbers are suitable for cleaning syngas from tars only when the tar is cracked as completely as possible in the gasifier.

The ceramic ring filler showed a higher level of gas purification from both mechanical impurities and tars. The mechanical impurities purification coefficient for the irrigated header was 71.2 % and 63.4 % for tars in the first operation mode of the gasifier for water consumption of 7 $L \cdot m^{-3}$. The purification coefficient for mechanical impurities increased to 82.7 % and 84.4 % and for tars – up to 66.7 and 72.0 % for water consumption of 11 and 15 $L \cdot m^{-3}$ respectively.

Table 2 shows that in the context of syngas purification it is rational to work in the range of water consumption 11-15 $L \cdot m^{-3}$, which, in this case, should be considered optimal. The lack of water (less than 11 $L \cdot m^{-3}$) does not provide the desired degree of mechanical impurities gas purification. The mechanical impurities purification coefficient increases only by 6 %, if the water consumption is above 15 $L \cdot m^{-3}$ (the total mechanical impurities purification coefficient is 93 % for water consumption of 20 $L \cdot m^{-3}$ compared to 86 % for water consumption of 15 $L \cdot m^{-3}$). This is ineffective compared to the cost of providing the system with additional water. The same tendency is observed in the tar purification coefficient.

It is enough to use up to 7 $L \cdot m^{-3}$ of water for syngas cooling. That water consumption is enough for cooling the gas to a temperature of 15-17 ºC (water temperature 10 ºC at an inlet) and 25-26 ºC (water temperature 20 ºC at an inlet). However, when the initial water temperature is 20 ºC and the irrigation water consumption is 7 $L \cdot m^{-3}$, the temperature of the purified producer gas can reach 50 ºC. This can negatively affect the operation of the controllers of the specific heating equipment.

The results of the study of the syngas purification efficiency in the dry stage are shown in Table 3. The purification was carried out in a dry header after an irrigated scrubber with a water consumption of 11 $L \cdot m^{-3}$. The table shows the average data of five measurements with a wet header filled with ceramic rings 50×20×4 mm. The choice of this type of wet header was made due to the fact that it has the highest degree of purification.

Table 3

Results of the syngas purification coefficient in a dry stage

Gasifier mode	**Content of impurities in syngas before the purifier, $g \cdot m^{-3}$**		**Impurity content in syngas after the purifier, $g \cdot m^{-3}$**		**Purification coefficient, %**	
	mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar
1	0.152	0.079	0.117	0.054	23	31.6
2	0.218	0.061	0.17	0.045	22	26.2
3	0.35	0.041	0.29	0.031	17.1	24.4

According to Tables 2, 3, the most mechanical impurities and tars are captured by a wet scrubber with an irrigated header (about 90-95 %). Changes in the resistance of the cleaner headers were also recorded. It was up to 10Pa for the irrigated header, and up to 500Pa for a dry header. The dependence of the resistance of the system on the type of headers used and the irrigation modes has not been investigated in detail. The total resistance of the system was about 670Pa.

Next, it is important to consider the effect of water flow on syngas purification. According to Table 2, the increase of the water consumption on irrigation causes the increases of the quality of purification of syngas. It is important to study to what extent this water consumption will continue to affect the process. The upper limit of irrigation density is flooding [15]. The lower border of the liquid spray rate of the header is the amount of fluid that covers the entire surface of the irrigated header. It was experimentally found by determining the heat transfer coefficient, which increased with increasing water supply up to a certain point. Irrigation density corresponds to the cessation of the growth of the transmission coefficient. This, as well as its slight decrease, indicates coverage of the entire header surface with liquid and is the minimum or lower limit of irrigation. The lower limit of irrigation according to [15] is equal to the product of the irrigation coefficient and the specific surface of the header. However, this reliance is valid when the scrubber functions as a cooler.

According to calculations, the minimum irrigation density for a chunk filler with a chunk size of 40×70 mm is 5-10 $m^3 \cdot (m^2 \cdot h)^{-1}$, and for ceramic rings 50×20×4 it is 10.5-21 $m^3 \cdot (m^2 \cdot h)^{-1}$. For a scrubber ∅ 0.9 m with a chunk filler, the water consumption should be 3-6 $m^3 \cdot h^{-1}$, and for ceramic rings – 6-13 $m^3 \cdot h^{-1}$. Irrigation rates per 1 m^3 syngas are 5-20 $L \cdot m^{-3}$ [15]. In the existing water system of the developed combined purifier, the water consumption varied within 4.5-19 $L \cdot m^{-3}$. Thus, the existing irrigation norms corresponded only to the second condition – water consumption per 1 m^3. At the same time, to obtain the lower limit of irrigation according to the norms of irrigation density per cross-section area unit of the scrubber was possible only for the chunk filler.

As a result, considering the wet stage of the cleaner as a header scrubber, we obtained a large cross-sectional area with a low gas velocity of 0.1 m·s^{-1} (with acceptable values of this parameter above 1 m·s^{-1}). The combined purifier developed at the Zhytomyr National Agroecological University, even under such operating conditions, provided a sufficiently high efficiency of purifying syngas from mechanical impurities and tars. This is because the sprinkling system for the wet stage of the purifier was designed similarly to the sprinkling system for hollow jet scrubbers. In this regard, the density of irrigation had a minimal effect on the degree of purification of syngas.

A number of studies have been carried out to determine the influence of water consumption for irrigation on the degree of cooling and purification of syngas. Tests were conducted for this sprinkling system with a water consumption of 4.5-19 L·m^{-3} or 1 to 4 m^3·h^{-1}. Ceramic rings were used as irrigated filler. The results of the study of the dependence of the degree of purification of syngas on the water consumption of the irrigated header are shown in Table 4.

Table 4

Influence of water consumption on the syngas purification coefficient

Gasifier mode	**Water consumption, L·m^{-3}**	**Gas impurities content, g·m^{-3}**						**Purification coefficient, %**			
		Before purifier		After wet stage		After dry stage		On mechanical impurities		By tar	
		mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar	for wet stage	total	for wet stage	total
1	7	0.823	0.093	0.237	0.034	0.190	0.028	71.20	76.96	63.44	70.39
2	7	0.972	0.109	0.398	0.041	0.318	0.032	59.05	67,24	62.39	71.04
3	7	1.141	0.221	0.418	0.088	0.334	0.063	63.37	70.69	60.18	71.73
1	11	0.823	0.093	0.142	0.031	0.114	0.025	82.75	86.20	66.67	73.67
2	11	0.972	0.109	0.202	0.037	0.162	0.028	79.22	83.37	66.06	74.54
3	11	1.141	0.221	0.236	0.078	0.189	0.055	79,32	83.45	64.71	75.05
1	15	0.823	0.093	0.128	0.026	0.102	0.021	84.45	87.56	72.04	77.63
2	15	0.972	0.109	0.173	0.031	0.138	0.024	82.20	85.76	71.56	78.39
3	15	1.141	0.221	0.236	0.069	0.189	0.050	79.32	83.45	68.78	77.52

The purification coefficient for mechanical impurities and tar increases with increasing water consumption. This can be seen in the shown series of experiments. The ratio of the coefficient values for the irrigated scrubber and the total coefficient for mechanical impurities and tars remains the same as in the previous series of experiments. This means that the purification coefficient for mechanical impurities is higher than for tar, and the irrigated scrubber captures 90-95 % of impurities. The purification coefficient for mechanical impurities for the irrigated scrubber and the total with an increase in water consumption from 7 to 11 L·m^{-3} increases from 71.2 and 76.96 % to 82.75 and 86.2 %. But then with further increase in water consumption to 15 L·m^{-3} – only up to 84.45 and 87.56 %. The purification coefficient for the tar increases from 63.44 and 70.39 to 66.67 and 73.67 and then to 72.04 and 77.63 % respectively. Thus, in the context of gas purification, it is more expedient to work in the range of water consumption 11-15 L·m^{-3}, which should be considered optimal.

As for water consumption above 7.0 L·m^{-3}, they were excessive in terms of gas cooling. Calculation of the total heat balance of the purifier shows that the effect of using water as a cooling agent, at water consumption above 7.0 L·m^{-3}, drops sharply. The relative ratio of water use drops to 87 % for water consumption of 9.5 L·m^{-3}, and for 14 L·m^{-3} and above – to 80 and 75 %.

The volumetric heat transfer coefficients for the irrigated scrubber are in the range 1.186-2.098 MJ·(m^3·h· ºC)$^{-1}$, and their value fluctuations in the indicated range are explained by the different initial moisture content of syngas before the scrubber, which varied within 38-133 g·m^{-3}. The value of the surface heat transfer coefficients for the irrigated scrubber was 0.0131-0.0246 $MJ\cdot(m^2\cdot h\cdot {}^{\circ}C)^{-1}$, which is lower than the acceptable values of this parameter for irrigated scrubbers 0,038-0,063 $MJ\cdot(m^2\cdot h\cdot {}^{\circ}C)^{-1}$ at gas velocities in a scrubber from 1 $m\cdot s^{-1}$ and above.

A number of studies have been carried out to determine the dependence of the purity of syngas on the gas velocity and the method of supplying water to the combined purifier. For this purpose, an experimental scrubber with a cross section of 0.25 $L\cdot m^2$ was manufactured. At the same time, the height of the existing scrubber with an irrigated header filled with ceramic rings 50×20×4 mm did not change. The syngas velocity in the purifier increased 2 times. According to Table 5, the amount of mechanical impurities and tars in the purified syngas increased almost twice for the maximum possible consumption of irrigating water in the purifier that equals to 20$L\cdot m^{-3}$. At the same time, the syngas purification coefficient for both stages of irrigation did not differ.

If we compare the obtained data with the previous results (Table 2), then the purification coefficient of the ceramic ring filled header at the same water consumption of 15 $L\cdot m^{-3}$ and fuel moisture content of 20 % decreased: for mechanical impurities – from 84.4 % to 67.9 %; for tar – from 72.0 % to 53.81 %. This is due to the fact that a decrease in the cross section of the combined purifier by half reduces the volume of the wet stage of the purifier by the same amount. As a result, the water spraying area is halved. Accordingly, the gas purification process got worse.

Subsequent experiments were carried out with a cleaner of the same cross section (0.25 m^2), but with an irrigated scrubber height of 1.3 m and 1.95 m at a gas velocity of 0.2 $m\cdot s^{-1}$. The results are presented in Table 5. According to Table 5, an increase of the height and specific volume of the header did not practically improve the level of gas purification compared with the experiments presented in Table 2. Thus, the header height does not matter with water jet sprinkling. This was confirmed by a decrease of the irrigated header height from 0.65 to 0.5 m in an existing cleaner while diameter stayed ∅0.9 m. The grade of purification almost did not change.

Table 5

Syngas purification coefficient in a scrubber with a cross-section of 0.25 m^2

Fuel moisture content, %	**Water consumption, $L\cdot m^3$**	**Gas impurities content, $g\cdot m^{-3}$**						**Gas purification coefficient, %**			
		Before purifier		After wet stage		After dry stage		On mechanical impurities		By tar	
		mechanical impurities	tar	mechanical impurities	tar	mechanical impurities	tar	for wet stage	total	for wet stage	total
Height of the irrigated header 1.3 m											
20	15	0.84	0.092	0.321	0.063	0.283	0.049	61.8	66.3	31.5	46.7
25	20	0.92	0.108	0.35	0.058	0.291	0.046	62.0	68.4	46.3	57.4
Height of the irrigated header 1.95 m											
20	15	0.86	0.089	0.311	0.059	0.278	0.045	63.8	67.7	33.7	49.4
25	20	0.9	0.116	0.326	0.056	0.284	0.042	63.8	68.4	51.7	63.8

The dry stage catches only 5-10 % of the total amount of entrainment coming from the gasifier. Its purification coefficient is 13-40 % if we consider impurities content after wet stage to be 100 %. The gas velocity in the dry scrubber should not exceed 0.2 $m\cdot s^{-1}$, since its increase leads to an increase in the aerodynamic resistance of the system and the gas purification coefficient decreases as well.

The gas velocity in a dry scrubber is recommended to not exceed 0.1 $m^3\cdot h^{-1}$ for a purifier ∅0.9 m and productivity by gas of 60-68 $m^3\cdot h^{-1}$, based on the conditions of optimal terms for replacing the header filler. The dry scrubber performs the functions of both additional gas purification and catching residual moisture that comes with gas from the wet stage.

In order to obtain data on the abrasive properties of impurities for a downdraft gasifier operating on lignin, their disperse composition has been studied.

Considering that dust could not be completely detared; the conglomeration of its particles was recorded, which significantly affected the experimental error. The dispersed composition of dust was: particle size of 50-60µm – 53 %, 40-50µm – 13 %; 30-40µm – 11 %; 20-30µm – 6 %; 10-20µm – 4 %; 5-10µm – 8 %; 2.5-5µm – 5 %.

To estimate abrasive properties of mechanical impurities indirectly, their ash content was defined. Considering that ash content, as well as its qualitative characteristic determines the wear of the engine, to a great extent, under operating conditions.

The experimental data indicate that the dust collected in the water tank of the irrigated scrubber has ash content twice as large as the dust carried away from the gasifier (64 % compared to 33 %). The ash content of the dust passed through the scrubber is 7 %. The foregoing indicates the ability of the purification system to capture the ash portion to a greater extent. This indicates that the purification coefficient of gas for the ash component is higher than 99 %, taking into account the quantitative content of pollution.

Dust, which consists of 93 % carbon soot particles, being fine dispersed in small amounts in the gas, must be completely burned in the cylinders of internal combustion engines, leaving just 6 % ash residues. Syngas pollution standards for mechanical impurities are 20-30 $mg \cdot m^{-3}$ and while gas being fed, for example, to ICE [8], they are not justified without taking into account their abrasive characteristics.

The study of the fractional composition of the tars and their physical-mechanical parameters during gasification of lignin showed that the initial boiling temperature of tar is 210 ºC. Around 28.2 % of the tar evaporates between 310-335 ºC. Above 335 ºC, the tar stops distilling, foams and is transformed into hard brittle pitch (30.7 %). Gases are released during the decomposition of the tar at a temperature of 270 ºC. This indicates that the tar belongs to the category of high boiling polymerized oxidized compounds, which is a consequence of its transit through the high temperature zone (1200-1500 ºC in the oxidation zone of the gasifier).

The tar condenses in the gas distribution system and mechanisms, disabling them and forming soot in the internal combustion engine cylinders. These are the negative properties of tar. Therefore, studies focused on reducing the level of tars in the syngas are necessary to ensure the normal operation, reliability and durability of the equipment running on it.

For the gasifier shown in Fig. 1, the tar content in the syngas can reach about 20-30 $mg \cdot m^{-3}$ that is not enough to disable the heating equipment running on it. Such low tar content in the gas was achieved by two factors: a high degree of cracking of the tars that was provided by the new design of the gasification chamber [16] and good results in purifying gas from residual tars were achieved using a combined purifier.

Conclusions

The experimental study of the purification coefficient of syngas from mechanical impurities and tars has led to the following conclusions:

1. Three types of irrigated header fillers were tested – charcoal, crushed brick with a piece size of 40×70 mm and ceramic rings with a size of 50×20×4 mm. They did not show a significant difference in the quality of syngas purification from mechanical impurities and tars. That is why we consider crushed brick as an acceptable substitute for them, as an affordable material, in the absence of charcoal and ceramic rings.
2. The optimum water consumption for cooling syngas is 7 $L \cdot m^{-3}$, and for gas purification 11-15 $L \cdot m^{-3}$. Changing the irrigated scrubber height from 0.65 to 1.3 and 1.95 does not affect the grade of syngas purification. Increasing the syngas velocity in the combined purifier reduces its purification grade.
3. The dispersed content of mechanical impurities indicates that the combined purifier does not perform a complete fine purification of syngas. However, it removes abrasive ash particles by 99 %. After the purifier, 93 % of mechanical impurities are carbon soot particles, which have insignificant abrasiveness and are mostly burned in the engine cylinders.
4. When tar, which is contained in the syngas, enters the engine with gas, it negatively affects its operation. A high degree of tar cracking was provided by the design of the gasifier. The amount of

tar in syngas, after the combined purifier, does not exceed 20-30 $mg \cdot m^{-3}$. Such a small amount does not affect normal operation of both the engine and controllers.

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