Plant Archives Vol. 20, Supplement 2, 2020 pp. 3396-3399 **e-ISSN:2581-6063 (online), ISSN:0972-5210**

INVESTIGATION OF FAST PYROLYSIS OF BIOMASS IN AN ABLATIVE SCREW REACTOR TO OBTAIN PYROLYSIS GAS AND BIO-OIL

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Abstract

In the article, a scheme and technical peculiarities of operation of a modified laboratory fast ablative pyrolysis installation with a screw type reactor are given. The results of the experiments of fast pyrolysis of biomass with the purpose to obtain bio-oil and pyrolysis gas in the ablative reactor are presented. The comparative analysis with foreign similar experimental data was carried out. The process of ablative pyrolysis of biomass was investigated in detail and the measures to further improving of the technology were proposed.
***Keywords*:** Pyrolysis of biomass, bio-oil; pyrolysis gas, experimental data, blative screw reactor.

Introduction

The latest energy policies of the EU-28 and OECD countries are aimed on setting the ambitious targets on development of renewable energy and bioenergy. As for Ukraine, the main feature of energy supply is that approximately half of energy resources (mainly natural gas for heating and industrial purposes) is imported. The price of natural gas has increased significantly over the last 5 years and is expected to grow further. A real alternative to natural gas is the utilization of renewable energy sources, including biomass. There are various commercialized technologies of raw biomass utilization, out of which the most widespread and economically feasible is direct combustion in boilers. Despite its cheapness and comparative simplicity, in some cases the direct biomass combustion is not an appropriate technology for specific industrial sites, for example, if it is not technically feasible to install new biomass boiler or in case of separate energy generation and consumption. In such specific cases, the technologies of biomass gasification and pyrolysis can make sense. Fast pyrolysis is one of the most cost-effective ways to use biomass residues for energy purposes. According to the International Energy Agency, "bio-oil is the cheapest liquid which can be produced from biomass nowadays". Despite many advantages and good prospects, fast pyrolysis technology is not yet as commercial as direct combustion and has some unresolved technical features. There is a number of technical and process organization issues to be addressed and this work is aimed to contribute to this [1-25].

Methodology

The aim of current research is to improve the experimental installation of ablative fast pyrolysis of biomass, which was developed in the Institute of Engineering Thermophysics of NASU and to compare the experimental data with the data of foreign researchers [26, 27].

The results of the laboratory experiments on the mentioned fast pyrolysis installation were presented in the previous scientific work [28]. That installation had a number of design defects, and characteristics of obtained pyrolysis products were quite low. To eliminate the identified defects, the previous design of installation was modified (Fig.1). The main modification consisted in changing of the ablative reactor design dividing it into three separate zones to provide the necessary temperature distribution for different zones, namely:

1) zone of biomass preheating to achieve the necessary temperature;

2) zone of the pyrolysis process;

3) zone of pyrolysis products removal.

Experiments have shown that the installation worked steadily for 180 minutes, and constant yields of bio-oil at the level of about 50% by weight was achieved due to the determination (on the basis of previous test launches) and maintenance of optimal operating conditions of the laboratory installation during operational period.

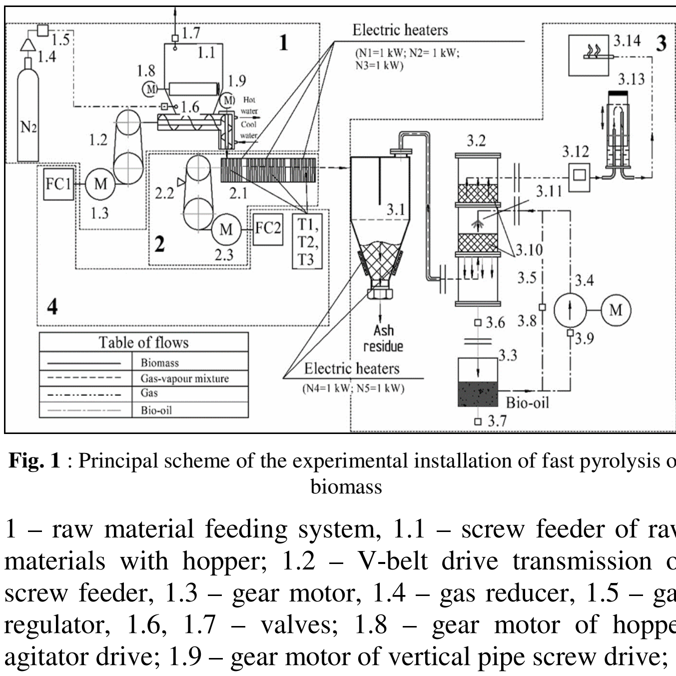

Fig. 1 : Principal scheme of the experimental installation of fast pyrolysis of biomass

1 – raw material feeding system, 1.1 – screw feeder of raw materials with hopper; 1.2 – V-belt drive transmission of screw feeder, 1.3 – gear motor, 1.4 – gas reducer, 1.5 – gas regulator, 1.6, 1.7 – valves; 1.8 – gear motor of hopper agitator drive; 1.9 – gear motor of vertical pipe screw drive; 2

– reactor block, 2.1 – reactor with screw, 2.2 – V-belt drive transmission of reactor screw, 2.3 – motor; 3 – system of steam-and-gas cleaning and pyrolysis gases utilization, 3.1 – settling chamber, 3.2 – scrubber, 3.3 – tank for bio-oil collecting, 3.4 – pump, 3.5 – bypass (pump regulation of cooling liquid feed velocity) 3.6 - 3.9 – stop valves, 3.10 – Raschig rings; 3.11 – flow nozzle; 3.12 – pyrolysis gas flowmeter, 3.13 – gasholder, 3.14 – burner for pyrolysis gas combustion; 4 – power supply and control unit.

Analysis of [27, 29, 30] showed that all ablative fast pyrolysis reactors for laboratory tests are quite similar, but the main differences are in the design, automation systems and application of measure devices.

Schematic diagram of the experimental installation, which was developed in the Institute of Engineering Thermophysics NASU, is shown in Fig. 1. There are three electric heaters with 1 kW_{el} capacity each on the external surface of the reactor. A microprocessor temperature controller controls heaters using signals from thermocouples that are fixed on the external surface of the reactor body. The maximum reactor temperature which can provide the heater is 650 ^{o}C. The reactor body is covered with insulating materials to provide as far as possible adiabatic conditions of experiment.

For the experiments different samples of wood sawdust with moisture content of 4% by weight and with particle sizes of 0.5...0.7 mm, 0.5…1.0 mm and 0.5...5 mm and bulk density of 160 kg/m^3, 138 kg/m^3 and 120 kg/m^3 correspondingly were used as raw material. The hopper and the vertical pipe of the feeder were equipped by the agitator and screw, which are driven by gear motors, to avoid hovering of raw material.

The order of experiments was as follows. Samples of biomass of 3…3.5 kg weight were loaded into the hopper, which was sealed to prevent leakage of pyrolysis gas in the opposite direction and to prevent high gas concentration in the laboratory. Before the experiment, nitrogen was injected in the lower pipe of the hopper for 20...25 minutes at a constant flowrate of 0.117 m^3/h for purging of hopper and the path from the reactor to the scrubber of the bio-oil condensation system. The air is forced out from the hopper by nitrogen and taken out through the upper pipe and the burner to the environment. Then diesel oil (3 liters) was measured out and poured into the storage tank with purpose to start condensation process prior to bio-oil obtaining.

After all these manipulations, the electric heaters of the reactor and the settling chamber were turned on and the installation components were heated up to the required operating temperatures in the experiment. Regulation of the reactor temperature was carried out by signals of thermocouples fixed on the external surface of the reactor, taking into account the temperature difference between the outer and inner surfaces, depending on the estimated installation productivity. Temperature fixed by the controller equals to the sum of the required raw material temperature in the reactor and the calculated thermal gradient in the reactor wall. During the experiments, the temperature of the external wall of the reactor was maintained at 550...650 ^{o}C, the settling chamber temperature at 50 ^{o}C while the rate of temperature increase has to be maintained not higher than 2 ^{o}C/hour Simultaneously, the system of temperatures measuring and recording system, which includes multi-gauge and PC, was turned on.

The circulating pump was turned on to supply diesel for the scrubber spraying after installation desired temperatures stabilization.

Drivers of the hopper agitator and screw of vertical pipe feeder were turned on to ensure stable operation of the feeding system. Current frequencies, which are matched to the corresponding screw rotation speed, were set by the frequency converters, which drive the electric motors of the reactor and the feeding screw, on the control panel.

Conditions of the chosen experiments are summarized in Table 1.

Table 1 : Conditions and results of experimental studies of the biomass ablative pyrolysis on the laboratory installation

Characteristic	**Number of experiment**				
	#1	**#2**	**#3**	**#4**	**#5**
Temperature of the reactor external surface [°C]	550	600	550	550	650
Temperature of the settling chamber [°C]	50				
Flow rate of nitrogen for purging [m^3/h]	0.117				
Moving velocity of the raw material particles in the reactor [m/s]	1.0				
Size of raw material particles [mm]	0.5…1	0.5…1	0.5…0.7	0.5…5	0.5…5
Residence time of biomass particles in the reactor [s]	1.0				
Moisture of raw material [%]	4				
Experiment time [min]	180	130	45	120	180
Temperature of cooling liquid [°C]	12	14	10	12	13
Flow rate of cooling liquid [m^3/h]	0.18				
Weight of processed biomass [kg]	2.88	2.57	3.49	2.68	3.13
Weight of carbon residue [kg]	0.7	0.432	1.47	0.998	0.78
Yield of carbon residue [% wt.]	24.3	16.8	42	37	24.9
Weight of bio-oil [kg]	1.408	1.262	1.38	1.18	1.21
Yield of bio-oil [% wt.]	48.9	49.1	39	44	38.6
Density of bio-oil [kg/m^3]	1110	1190	1140	1020	1105
Higher calorific value of bio-oil [MJ/kg]	not determined	13.77	not determined		
Gases yield and losses (on balance) [% wt.]	26.8	34.1	18	19	36.5
Installation productivity of biomass processing [kg/h]	0.96	1.186	4.65	1.338	1.044

Results and Discussion

Obtained experimental data showed that the average bio-oil yield for chosen experiments is 44% (Table 2). The moisture content of obtained bio-oil is 47.2% (Table 3), which is a relatively high indicator compared with data from University of Florence. At the same time other scientific sources [29,31] shows that the bio-oil yield from dry and low-ash biomass can be up to 65% by weight. Water is always formed during the pyrolysis process from the biomass elements even if dry biomass is used, and the total yield of liquid products from dry and low-ash biomass can reach even 75%. The natural moisture content of raw material also obviously effect on H_2O content in bio-oil. In case of very high moisture content (over 30%), bio-oil is separated in two phases with different properties [28, 29, 31].

Comparison of basic characteristics of bio-oils, which were obtained on the experimental installations of the Institute of Engineering Thermophysics and the University of Florence with the same pyrolysis technology, are shown in the Table 2 [27]. It could be seen that characteristics of the obtained bio-oil do not differ significantly from the main characteristics of bio-oil obtained by foreign researchers, which may indirectly confirm that pyrolysis process on the presented installation is properly organized.

Table 2: Characteristics of bio-oil from IET and Florence University installations

Item name	Analysis result of IET	Analysis result of Florence University
Weight fraction of moisture [%]	47.2	20…30
Weight fraction of sulfur [%]	0.028	0.02…0.05
High heat value [MJ/kg]	16.03	16.6…19.4
Low heat value on as-fired fuel basis [MJ/kg]	13.77	13…18

The share of combustible gases is about 80% of all volume of the pyrolysis gas obtained during the experiment. Due to the high content of CO_2, H_2, CH_4, that is more than 50% (see Table 3) of the all gases volume, so the caloric value of pyrolysis gas is high enough. Pyrolysis gas can be used, for example, for the reactor heating instead of electricity.

Table 3: Component analysis of the pyrolysis gas of experiment #2

Component	H_2	CO	CH_4	CO_2	C_2H_4	C_2H_6	C_3H_6	C_3H_8	iC_4H_{10}	H_2O	N_2	Total	Low calorific value, [MJ/m^3]
[% wt.]	9.51	34.03	11.65	24.35	1.43	1.38	0.19	0.71	0.55	1.72	14.19	100	12.67

Neccesity of Further Modifications

A series of experiments showed that the design of the screw needed further upgrading with the purpose of efficient conducting of sawdust pyrolysis process. It is likely that wood particle is not completely decomposed during passing through the reactor. At the same time, the existence time of tar vapors is sufficiently high and, as a result, they are affected by secondary reactions. This explains the smaller proportion of bio-oil yield and its high moisture content in comparison with respective foreign data.

Particles of raw material pass the reactor with almost the same speed. In the first zone of the reactor, particles are heated to the required temperature for pyrolysis decomposition, in the second zone they are broken down on gas-vapor mixture. The obtained pyrolysis products remain in this state longer than necessary to prevent secondary reactions before they are removed from the reactor. According to the data from thermocouples fixed on the reactor body, there was a temperature drop on 50...100 ^{0}C at the reactor inlet during the loading of fresh raw materials depending on productivity of the feeding system. Based on this fact we made an assumption, that if the zone, in which there was the temperature drop, is extended on almost one-third of the reactor length, the bio-oil yield will increase.

It is expected that biomass after passing 1/3 of the reactor length does not absorb heat from the reactor body and, therefore, is heated enough to the required pyrolysis process temperature and can overheat due to the work of transporting in the reactor.

Conclusions

1) The different approaches to technical realization of pyrolysis technologies have been analyzed and compared aimed on the development of own concept of pyrolysis;
2) The own pyrolysis laboratory installation was constructed and tuned on the basis of series of test experiments to determine the optimal regimes of operation with respect to maximizing of bio-oil yield;
3) The first samples of bio-oil were obtained with the average yield of 44%; the pyrolysis gas (≈10 wt%) and biochar (≈15 wt%) could be in future usefully utilized for own needs of the installation;
4) The assumptions for future modification of the installation aimed on increasing of the bio-oil yield has been made.

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