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THE STUDY OF BIOMASS MOISTURE CONTENT IMPACT ON THE EFFICIENCY OF A POWER-PRODUCING UNIT WITH A GASIFIERAND THE STIRLING ENGINE

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The aim of this study is to determine the impact of wood chip fuel moisture content on the overall efficiency of the power-producing unit of a mobile chipper consisting of a gasifier, the Stirling engine and a container-dryer. Research of utilization efficiency of heat emissions of the Stirling engine in a container-dryer has been conducted. The container-dryer design for wood chip drying due to thermal emissions of the Stirling engine has been developed. A mathematical model of the autonomous power-producing unit of mobile chipper functioning with wood chip fuel was developed. In addition, the physical experiment was conducted to determine the actual moisture content of wood chips after drying due to thermal emissions of the Stirling engine. According to the results of the experiments we obtained regression equations of the efficiency of power-producing unit dependence on the initial moisture content of biofuels for two cases - with drying in the container-dryer and without drying. Drying of fire wood chips due to utilization of thermal emissions of the Stirling engine in a container-drier of a proposed design improves the efficiency of the power-producing unit. The reduction of the fuel wood relative moisture content from 47.5% to 37.5% increases the efficiency by 7.34%, while moisture reduction from 37.5% to 27.5% results in higher efficiency of only 4.37%, a further reduction in moisture from 27.5% to 17.5% results in higher efficiency of only 2.47%. Thus, the greatest positive effect of drying fire wood chips due to heat recovery of the Stirling engine emissions is observed when using fuel wood with high initial moisture content of more than 30%.

Key words: Drying, Efficiency, Power-producing unit, Gasifier, The Stirling engine, Mathematical model, Moisture content, Wood chip fuel

INTRODUCTION

Studies have shown that with an increase in moisture content of fuel wood the effectiveness of power equipment reduces. This can also be applied to the direct burning of fuel wood, and combustion technology of wood from gasification [05, 12, 19], and to the technology of production of liquid fuels from wood [09]. First of all, this is due to the fact that the high moisture content of fuel leads to the reduction of its' calorific value [8, 19].

In order to reduce the moisture content of fuel wood source its' pre-drying in kilns of various types was used. However, pre-drying of biomass leads to additional costs [07] and, in some cases, increases the cost of energy production [05]. The study [19] proves the unique dependence of calorific value of produced gas from initial moisture content of biomass loaded into the updraft gasifier. The higher the moisture content of biomass is, the lower calorific value of of produced gas. At the same time, the study [05] shows that

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the overall efficiency of the CHP plant consisting of a dryer, a hot-gas air heater, a gasifier, an internal combustion engine and a hot water heater is reduced in proportion to the amount of moisture evaporated from biomass in the dryer. As it's shown in the study [07] this is associated with additional fuel-consumption rate in the hot-gas air heater . However, the same study [05] show that the cost of electrical energy production using a CHP plant decreases with the reduction of biomass moisture content in the dryer. It is also interesting that the study [05] noted a smaller cost of energy produced by using this CHP with rotary dryer and without hot-gas air heater, compared with heat generator dryer, in case of a low dryer capacity. Thus, the relevant question is the efficient use of engine exhaust gases and its cooling air for pre-drying biomass before it enters the gasifier. The aim of this study is to determine the impact of wood chip fuel moisture content on the overall efficiency of the power-producing unit consisting of a gasifier, the Stirling engine and a container-dryer, as well as research the utilization efficiency of heat emissions of the Stirling engine in a container-dryer of self-design project. In this research the power-producing unit with the Stirling engine as it has some advantages in comparison with producer-gas engine with internal combustion is considered. The Stirling engine is less depending to quality of wood gas in comparison with an internal combustion engine. The efficiency of Stirling engine on wood fuel may be higher than an efficiency of internal combustion engine on the same fuel. For proper functioning of an internal combustion engine devices for deep purification of the wood gas are required. Therefore a weight-to-power ratio of producer-gas engine with internal combustion is high. The Stirling engine enable to burn producer-gas without extensive purification.

MATERIALS AND METHODS

Mathematical Modeling

The present study examines the power-producing unit of a mobile chipper [02] shown in Figure 1. The power-producing unit consists of an external combustion engine (the Stirling engine [4, 6, 14, 15]) 4, a biomass gasifier 5 [10], a container-dryer of self-design 6. The container-dryer for drying wood chips using waste-heat of the Stirling engine.

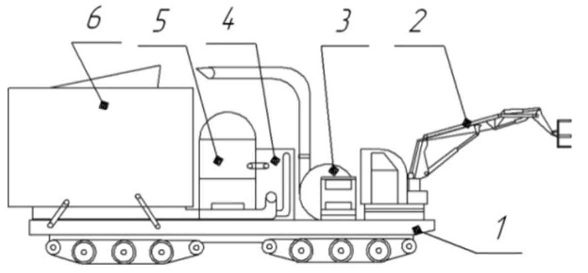

Figure 1: Mobile chipper for production of chips with an autonomous power supply

Mobile wood chipper with an autonomous power supply also has driving chassis 1, hydromanipulator 2 and disk chipper 3. Studies have shown that the efficiency of the production of wood chips with the help of this device is in the range from 86 to 97% and depends on the moisture content of raw wood [01].

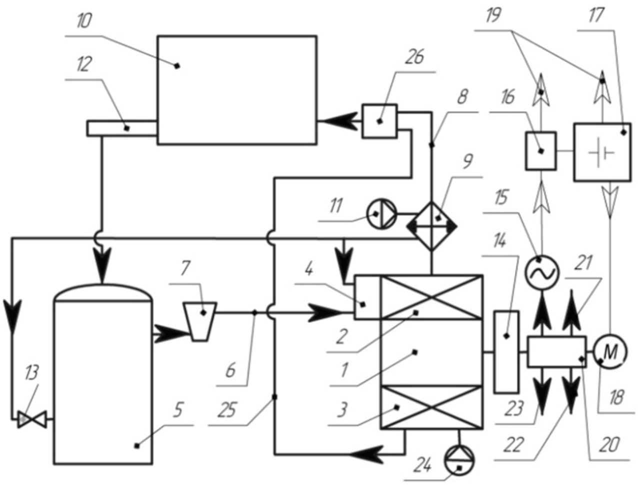

Figure 2: Schematic diagram of the power-producing unit using wood fuel for a mobile chipper

Power-producing unit using wood fuel for the mobile wood chipper consists of the following components: 1 the Stirling engine having a combustion chamber 2 and a cooler 3, a gas-burner 4, a gas generator 5, which is connected to a gas-producer main 6 with a gas burner 4. Also a cyclone 7 for cleaning the producer gas from ash. The main pipe exhaust flue gas 8, in which the flue gases from a combustion chamber 2 through a recuperator 9 are sent to the container-dryer for fuel chips 10 Compressor 11, forcing the air through the heat exchanger 9 in the gas generator 5 and a gas-burner 4. Recuperator 9 serving for the transmission of heat from flue gases to the air. Also it has a screw feeder 12 transporting wood chips from the container-dryer 10 to the gasifier 5, a control valve 13 that regulates the air flow to the gasifier, and a flywheel

14 coupled to the shaft of the Stirling engine 1. Moreover it has the AC power generator 15, a voltage rectifier 16, a storage battery 17, electric DC motor 18 and electrical terminals 19. Also we can see a transfer case 20 which provides transmission of mechanical energy from the flywheel 14 to the electric generator 15, and to the PTO (power take-off) for hydraulic aggregate 21, and then to the PTO for chassis 22, and the PTO for chipper unit 23. Finally, it has a cooling fan 24 of cooler 3, the main pipe for cooling air 25 through which the air from the cooler 3 is sent into the container-dryer 10. At last, it has a mixing heat exchanger 26 where the cooling air from the line 25 and the outgoing flue gases are mixed before the entry into the container-dryer 10 [03]. A mathematical model of the functioning of the power-producing unit, which allows to determine its' efficiency and other parameters depending on the initial moisture content of biofuels was developed. The energy efficiency of the power-producing unit shown in Figure 2 is characterized by an overall efficiency:

$$\eta = \frac{Q_{fuel}}{N_{Stirl}} \cdot 100\% \tag{1}$$

where Q_{fuel} − thermal power released by the combustion of fuels consumed by the installation, kW; N_{stirl} − mechanical power at the shaft of the Stirling engine, kW. Energy balance of this power-producing unit is shown in Figure 3.

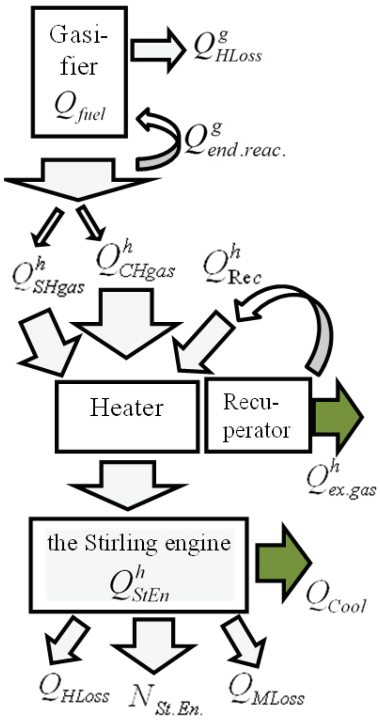

Figure 3: The energy balance of the fuel wood power-producing unit with a gasifier and the Stirling engine

The developed mathematical model of the fuel wood power-producing unit for a mobile chipper is divided into separate blocks. Block №1 The Stirling engine. The Stirling engine is used to produce mechanical energy. In a simulated system we use a gas-fired γ-type Stirling engine the same as STM Power Stirling engine in Lin's research [11]. The thermal energy which is necessary to be supplied into the heater of the Stirling engine by gas fuel combustion can be found with through the use of heat balance method. The heat balance of the heater is represented by the formula:

$$Q^h_{CHgas} + Q^h_{SHgas} + Q^h_{Rec} = \\ = Q^h_{StEn} + Q^h_{Rec} + Q_{HLoss} + Q^h_{ex.gas} \tag{2}$$

where Q^h_{CHgas} − combustion heat of gas fuel in the heater, kW; Q^h_{SHgas} − sensible heat of hot generator gas supplied to the heater; Q^h_{Rec} − recuperation − sensible heat supplied into the heater with hot air; Q^h_{StEn} − thermal heater useful load − the amount of thermal energy supplied from the heater of the Stirling engine into engine cycle; Q_{HLoss} − external heat losses of the Stirling engine; $Q^h_{ex.gas}$ − heat losses of the Stirling engine with the exhaust gas.

The left side of the heat-balance equationis the total amount of heat energy supplied to the heater and in the right side we can see the output part of heat balance. The amount of thermal energy supplied to the heater of the Stirling engine cycle is given by:

$$Q^h_{StEn} = \frac{N_{St.En.}}{\eta_e}, kW \tag{3}$$

where $N_{St.En.}$ − the actual power at the shaft of the Stirling engine (taken equal to the nominal power); η_e - theoretical effective efficiency of the Stirling engine.

The theoretical efficiency of the Stirling engine is given by:

$$\eta_e = \eta_T \cdot \eta_m \cdot \eta_0, \%, \tag{4}$$

where η_T − coefficient of thermal efficiency of the Stirling engine;

η_m − the mechanical efficiency of the Stirling engine which characterizes the frictional losses in the Stirling engine;

η_0 − relative efficiency of the Stirling engine, which takes into account the imperfection of heat exchangers. It is to reliant on the temperature difference in the Stirling engine and can be find on a specific chart [17].

Thus, having found by equation (2) the thermal balance of the Stirling engine heater, it is possible to find the amount of power gas, which must be burned in unit time according to the formula:

$$G^h_{Cgas} = \frac{Q^h_{CHgas}}{Q^0_{\mathrm{LHVgas}}}, kg/\sec \quad (5)$$

where Q^h_{LHVgas} − low heat value of as-received basis of generating gas, kJ/kg. The low heat value of wet producer gas can be found by Mendeleyev's formula on the basis of the known product gas composition.

The amount of heat transferred to the cooling air from the cooler of the Stirling engine can be found by the formula:

$$Q_{Cool} = N_{St.En.} \cdot (1-\eta_e), kW \quad (6)$$

Block №2 Dryer. Power source of heat Q_{drying} needed for the convective drying of wood chips from the initial moisture content W_1 to the desired final moisture content W_2 can be found by the method described in [18].

Heat content of drying agent $Q_{Dry.AG}$, i.e. amount of heat emissions of the Stirling engine, which can be used for convective drying of chips equals the sum of the stack gases heat content $Q^h_{ex.gas}$, and calorific content of the engine cooling system Q_{Cool} :

$$Q_{Dry.Ag.} = Q^h_{ex.gas} + Q_{Cool}, \ kW \quad (7)$$

The average theoretical relative moisture content of wood chips after drying in the container due to waste heat:

$$W_2^{theor} = W_1 - (W_1 - W_2)\frac{Q_{Dry.Ag.}}{Q_{drying}}, \% \quad (8)$$

Block №3 Gasifier unit. In a simulated system we use updraft fixed bed gasifier (the same as in Lin's research [11]) in which the chips are loaded from the container with the help of a screw feeder. Producer-gas from gasifier is combusted in the heater of the Stirling engine. The model analysis of the gasifier is based on the design methods methods for gasifiers which are presented in the works of Tokarev G.G., Ravich M.B., and Zainal Z.A. [13, 16, 19].

The purpose of the calculation is Q_{fuel} determination. For this we need to calculate the consumption of solid fuel G_{fuel} for getting a predetermined amount of producer-gas G^h_{Cgas}.

On the basis of the product gas composition we can determine the specific net calorific value of its labor supply Q^0_{LHVgas} . The product gas composition can be found using the equilibrium modeling, as proposed in Zainal's work [19]. Thus, according to the equations of carbon, hydrogen and oxygen balance of the chemical reactions occurring in the updraft gasifier it is possible to simulate the product gas composition depending on the moisture content of wood biomass.

According to [19] the general equation of the wood gasification reaction can be expressed by the formula:

$$CH_{1.44}O_{0.66} + wH_2O + mO_2 + 3.7mN_2 = x_1H_2 + \\ + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2,$$

where w − water content in wood kmol; m − oxygen content per 1 kmol of timber; x_1, x_2, x_3, x_4, x_5 − factors characterizing product gas composition. Also Zainal (Table 6, page 1513) [19] experimentally determined coefficients x_1, x_2, x_3 of wood gasification in the gasifier of the inverted type (x_1=0,575; x_2=0,798; x_3=0,176).

From the carbon balance equation we can find x_5 coefficient by the formula:

$$x_5 = 1 - x_2 - x_3,$$

From the following equation hydrogen balance factor x_4 can be found by the formula:

$$x_4 = w + 0.72 - x_1 - 2x_5,$$

The specific consumption of wood chips in the gasifier to produce 1 kg of the producer-gas is obtained from the carbon balance of gasification reaction [16]:

$$g_{fuel} = \frac{C_{fuel}}{C_{Cgas}}, \mathrm{kg/kg}$$

where C_{fuel} − carbon content in the solid fuel, $C_{C\text{-}gas}$ − carbon content in the producer-gas. Then the mass flow of wood chips per unit time is equal to:

$$G_{fuel} = G^h_{Cgas} \cdot g_{fuel}, \mathrm{Kg/\sec} \quad (9)$$

Thus, the desired value of heat power of the solid fuel combustion is:

$$Q_{fuel} = G_{щ} \cdot Q^0_{\mathrm{LHVwood}} \ \mathrm{kW}, \quad (10)$$

where $Q^0_{LHVwood}$− low heating value on as-received basis of thesolid fuel supplied to the gasifier, kJ/kg.

Experiment

Physical experiment was conducted to determine the actual moisture content of wood chips dried in the container-drier due to heat emissions of the Stirling engine. To this end model of container-dryer was created in a scale of 1:15, which is shown in Figure 4.

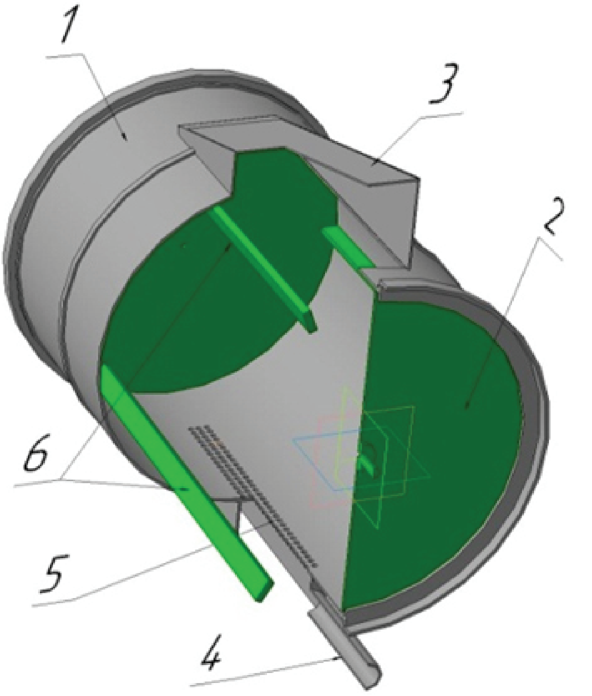

Figure 4: The container-dryer of mobile chipper

Container-dryer consist of cylinder 1 with movable sidewalls 2. Chips fed into the container-dryer through the upper feed opening 3. The flow of hot gases from the Stirling engine is sent into the tube 4 and uniformly distributed through the holes 5. Therefore, chips in the container-dryer are constantly blown by hot gases coming from below through the holes 5. The chips during the drying process in a container-dryer are constantly mixed using blades 6 attached to the rotating side walls 2. The experimental model of a container-dryer is a model of the dryer 10 shown in schematic diagram Figure 2.

The structural scheme of the experiment is shown in Figure 5. In the course of the experiment chips of certain moisture content were loaded into the model of a container-dryer and hot air was supplied from below.

Rotating speed of agitating blades was 1.5 rpm. Adjustable parameters such as consumption of chips, flow, temperature and moisture content of hot air corresponded to the actual conditions. The drying of chips was equal to the time of filling of the container-dryer. After drying the moisture content of wood chips was measured in accordance with the standard EN 14774-2: 2009.

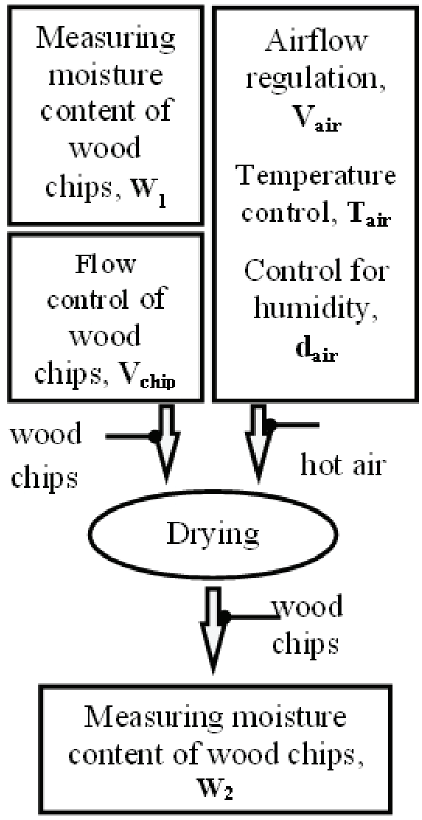

Figure 5: Schematic course of experiment

Further computing experiment was conducted by the mathematical model of the power-producing unit shown in Figure 2. The purpose of the experiment was to determine the overall efficiency of the power-producing unit depending on the moisture content of biofuel entering the gasifier.

THE RESULTS OF THE STUDY AND DISCUSSION

The experimental data of chips drying in a container-drier is presented in Table 1. For parameters Vchip − volumetric flow of wood chips in a container-dryer and Vair – volumetric flow of hot air in a container-dryer scale transfer factor is equal to 3033. The value Vchip corresponds to the performance of mobile chipper shown in Figure 1 with the Stirling engine capacity of 200 kW.

Table 1: Experimental data of chips drying

W_1, %	V_{chip}, ml/sec	V_{air}, l/sec	T_{air}, °C	d_{air}, g/kg	W_2, %
47,50	18,00	1,72	128,38	37,42	43,00
45,00	17,84	1,70	121,47	36,40	40,70
42,50	17,68	1,68	116,22	35,41	38,30
40,00	17,52	1,66	112,10	34,47	36,10
37,50	17,36	1,65	108,81	33,56	33,40
35,00	17,20	1,64	106,11	32,70	31,30
32,50	17,04	1,63	103,87	31,87	29,00
30,00	16,88	1,63	101,99	31,09	26,80
27,50	16,91	1,62	100,38	30,34	24,70
25,00	16,93	1,62	99,00	29,63	22,50
22,50	16,95	1,61	97,81	28,95	20,10
20,00	16,98	1,61	96,78	28,32	18,00
17,50	16,99	1,61	95,92	27,75	16,00
15,00	17,01	1,60	95,26	27,29	14,20

The value Vair, as well as the value of Tair − the temperature of the drying agent and dair − the moisture content of the drying agent within the parameters of the power-producing unit correspond to the Stirling engine capacity of 200 kW.

Figure 6 represents a dependency graph of chips moisture reduction during their drying in the container-dryer from initial wetness. Individual points on the graph show the results of an experimental study of the container-dryer layout.

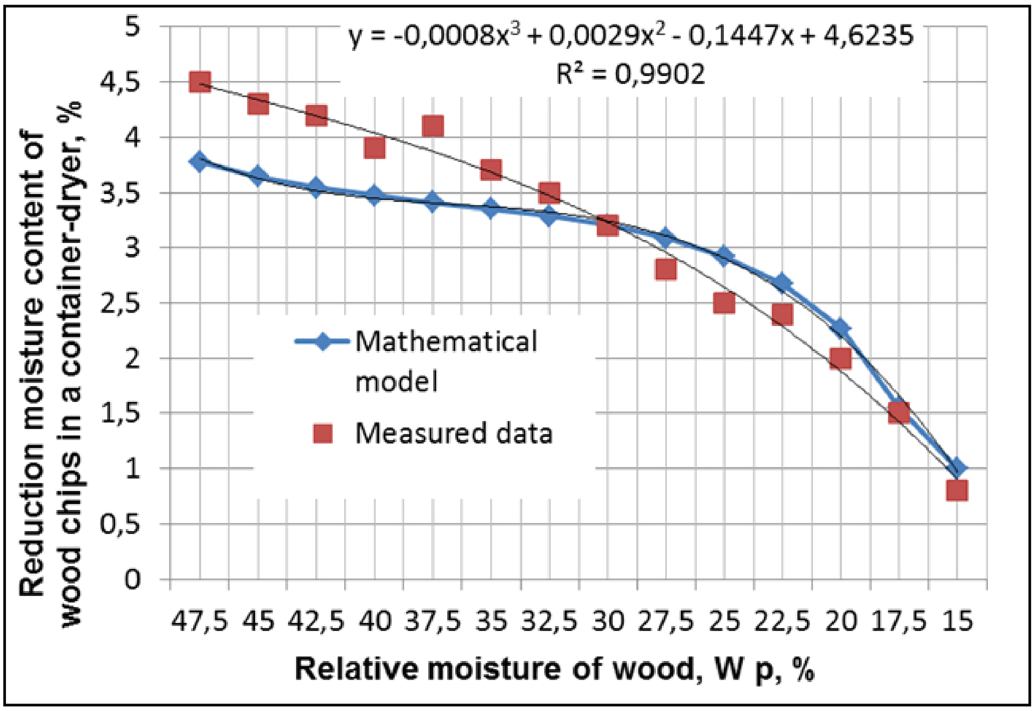

Figure 6: Reduction in moisture content of wood chips in a container-dryer

Regression equation of reducing moisture content in the container-dryer from the initial moisture of biofuel was been obtained by the experimental data:

$$(W_1 - W_2) = -0,0008W_1^3 + 0,0029W_1^2 - 0,1447W_1 + 4,6235 \quad (11)$$
$$R^2 = 0,9902$$

As the result of computational experiment indicators of the power-producing unit of mobile chipper performance efficiency were identified by a mathematical model. And also, we found the regularities of the fuel wood moisture supplied to the gas generator influencing the efficiency of the power-generating unit.

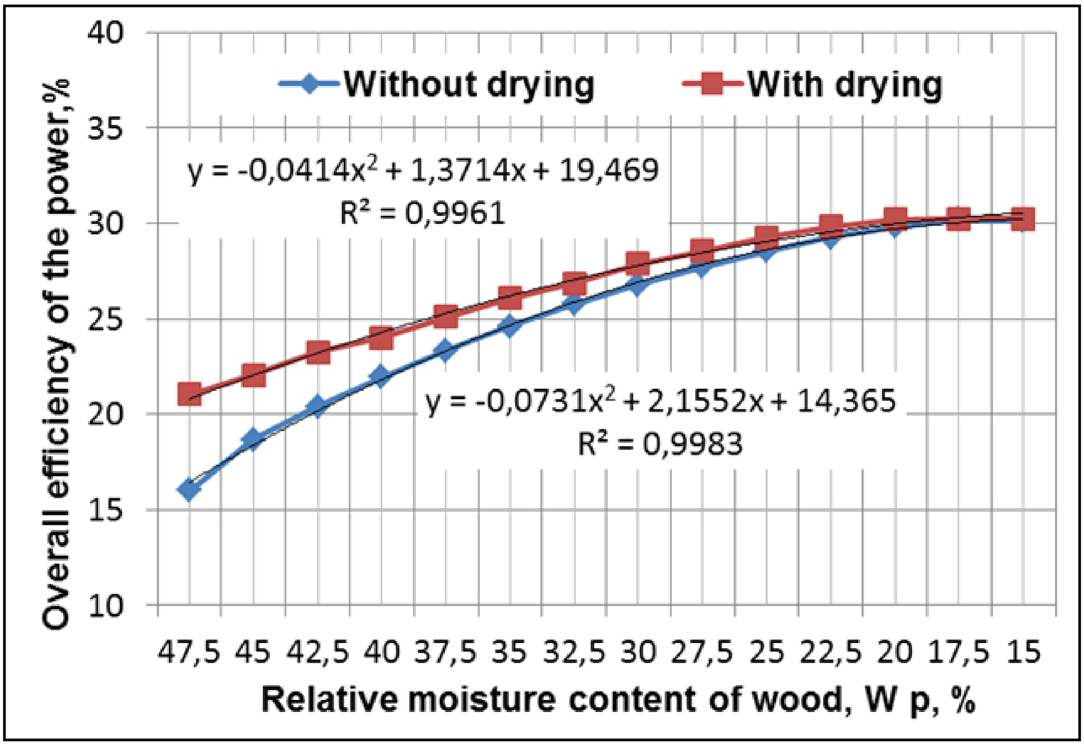

Figure 7: The total efficiency of the power-generating unit of mobile chipper

Figure 7 shows a dependency graph of the efficiency of the power-producing unit of autonomous mobile chipper, calculated according to the Formula (1) from the initial moisture content of wood chips.

As it can be seen from the graph in Figure 7, the dependence of the efficiency of the power-generating unit from the initial moisture content of biomass is not linear, the efficiency increases with a decrease in moisture content and decreases sharply with increase in relative moisture content of fuel wood above 45%. Reducing the relative moisture content of fuel wood from 47.5% to 37.5% increases the efficiency by 7.34%; moisture reduction from 37.5% to 27.5% results in higher efficiency of only 4.37%, and a further reduction in moisture from 27.5% to 17.5% results in higher efficiency of only 2.47%.

Thus, the greatest beneficial effect is observed at lowering relative moisture content from green-wood chips to the moisture content of about 30%.Thus, regression equation of dependence on the moisture content of biofuel efficiency of the power-generating unit without utilization of thermal emissions:

$$\eta = -0{,}0731W_1^2 + 2{,}1552W_1 + 14{,}365 \quad (12)$$

$$R^2 = 0{,}\ 9983$$

And regression equation of dependence on the initial moisture content of biofuel efficiency of the power-generating unit with wood chips drying due to the utilization of thermal emissions of the Stirling engine in a container-drier:

$$\eta = -0{,}0414W_1^2 + 1{,}3714W_1 + 19{,}469 \quad (13)$$

$$R^2 = 0{,}\ 9961$$

CONCLUSIONS

Drying of wood chip fuel due to utilization of thermal emissions of the Stirling engine in a container-drier of a proposed design improves the efficiency of the power-producing unit. A particularly positive impact of drying on the overall efficiency of the unit is observed at a high initial moisture content of biomass. The experimental data confirm the performance of the container of the proposed design. On the basis of the experimental data we obtained the equation (10) of regression dependence of lowering moisture content of wood chips in a container-dryer from the initial moisture content of biofuel. As a result of experiments we got the equations (11, 12) of regression dependence of the efficiency of the power-producing unit from the initial moisture content of biofuel for two cases − with drying in the container-dryer and without drying. The results of the study are consistent with previous results of theoretical and experimental studies.

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