THEORETICAL STUDY OF ENERGY-EFFICIENT STRAW DRYING BASED ON SENSIBLE HEAT RECOVERY FROM POST-PRESSED BRIQUETTES

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Abstract. The article discusses the problem of high energy consumption in the process of drying chopped straw in technological lines for the production of solid biofuel. It is shown that traditional drying methods using external heat sources (gas, solid fuel and electric heat generators) account for a significant share of the cost of production and are accompanied by additional environmental burdens. The feasibility of using internal heat resources of production, in particular the sensible heat of Pini Kay post-press briquettes, which temperature at the press outlet reaches 150–220 °C, is justified. The aim of the study is to justify and develop an energy-efficient system for drying crushed straw by recovering the sensible heat of hot briquettes without burning them, using a heat exchange recuperator with separate channels for material and air flows. The research is theoretical in nature and is based on analytical modelling of the heat balance of the drying process, calculations of mass and energy balances, and assessment of the potential for heat energy recovery. The work calculates the heat demand for reducing the moisture content of straw from 16% to 12% at a mass flow rate of 1000 $kg \cdot h^{-1}$ and determines the heat potential of post-press briquettes when cooled from 170 °C to 70 °C. It is shown that the sensible heat of the briquettes is about 153.6 $MJ \cdot h^{-1}$ and almost completely (99.3%) covers the heat demand of the drying process, which is 154.7 $MJ \cdot h^{-1}$. The results obtained indicate the fundamental possibility of implementing an energy-closed drying system without the use of external heat sources.

Keywords: solid biofuel, heat recovery, Pini Kay fuel briquettes, thermal balance, heat exchange, energy balance.

Introduction

In the context of the global strategy for decarbonisation of the energy sector and transition to renewable energy sources, bioenergy is considered one of the key areas of sustainable development of the agro-industrial complex. Agricultural biomass, in particular cereal straw, plays a special role in this process, as it is characterised by significant production volumes, availability, renewability and relatively high calorific value [1-3]. According to international experts, the potential for energy use of agricultural waste could replace up to 10-15% of fossil fuels in the final energy consumption structure [4; 5].

One of the most effective ways to use straw for energy is to process it into solid biofuel in the form of fuel briquettes or pellets. The briquetting process increases the bulk density of the material, improves transportation and storage conditions, and ensures stable physical and mechanical characteristics of the fuel [6-8]. At the same time, numerous studies show that the quality of finished briquettes significantly depends on the moisture content of the raw material: with increased moisture content, the heat of combustion decreases, the strength of the briquettes deteriorates, and the energy costs of pressing increase [1; 6].

To ensure the necessary performance characteristics of biofuel, the moisture content of crushed straw before briquetting should generally be reduced to 10-12% [4; 9]. The drying process is one of the most energy-intensive stages of the technological line and can account for up to 30-40% of the total energy consumption for biofuel production [4]. Traditionally, external heat sources are used for drying – gas, solid fuel or electric heat generators, which are characterised by high energy consumption, complexity of operation and additional environmental loads in the form of combustion product emissions [4; 9; 10].

In this regard, modern scientific research is actively developing the direction of improving the energy efficiency of biomass drying processes through the use of secondary heat resources and the integration of thermal processes within a single technological system [9-11]. In particular, the concept of sensible heat recovery, which is based on returning part of the thermal energy from hot flows directly to the technological needs of drying, is considered promising [4; 11].

Of particular interest in this context is the Pini Kay fuel briquette production technology, in which the temperature of the product leaving the press can reach 150-220 °C [12-14]. As shown in [12; 13], the post-press heat of briquettes has significant energy potential, but in most industrial schemes it is not utilised and is dissipated into the environment. Existing briquette cooling systems are generally focused

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only on ensuring fire safety and packaging capabilities, without performing the functions of targeted thermal utilisation [13; 14].

At the same time, individual scientific works and patent developments [12-14] demonstrate the fundamental possibility of integrating briquette cooling and biomass drying processes into a single energy-closed system.

Unlike most existing studies, which mainly focus on experimental investigations of drying processes or on heat recovery from exhaust air flows, the present study provides a quantitative theoretical assessment of the possibility of using the sensible heat of post-pressed briquettes as the primary energy source for drying. The novelty of the work lies in the development of an analytical model based on mass and energy balances, which makes it possible to determine the degree of coverage of the heat demand of the drying process by internal heat resources. In contrast to previous studies, where the utilisation of post-press heat is considered qualitatively or fragmentarily, this study demonstrates that the sensible heat of briquettes can almost completely cover the thermal requirements of straw drying under given conditions.

Thus, there is scientific and practical interest in developing an energy-efficient system for drying chopped straw based on the recovery of sensible heat from Pini Kay-type post-press briquettes, ensuring controlled heat transfer, separation of heat carrier and material flows, and the possibility of integration into existing biofuel production lines. The implementation of such systems is in line with current trends in the development of resource-efficient technologies, the principles of the circular economy and the concept of sustainable energy development.

Materials and methods

The research materials are crushed cereal straw with an initial moisture content of 16% and Pini Kay fuel briquettes obtained by screw pressing. Straw was used as raw material for drying, and post-press briquettes were used as a source of sensible heat for heat energy recovery. The temperature of the briquettes at the press outlet was 170 °C, and the mass flow rate of straw was 1000 kg·h^{-1}.

The main object of modelling is the system of heat recovery from post-press briquettes with separation of briquette and heat carrier flows, implemented in the form of a recuperator with two insulated channels separated by a heat-conducting metal wall (Fig. 1).

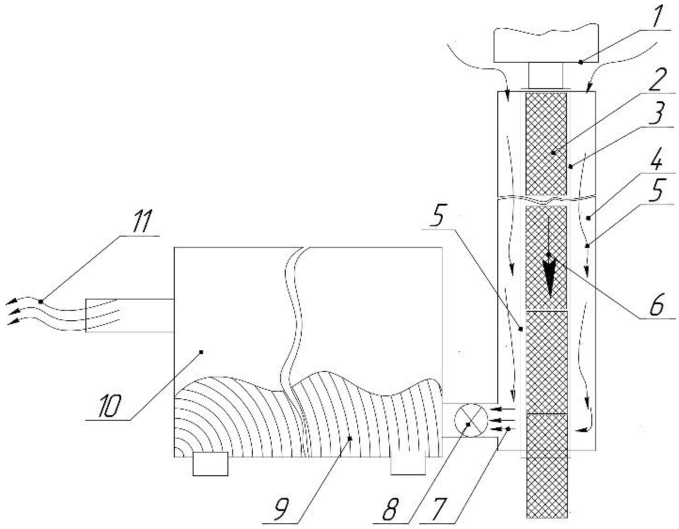

Fig. 1. **Schematic diagram of a recuperator for drying chopped straw**

The technological process of drying chopped straw is carried out as follows, Fig. 1. From the briquetting press 1, Pini Kay 2 briquettes with a temperature of 170 °C enter the heat recuperator, which contains an air channel 4 and a briquette channel 3, separated by a heat-conducting metal wall. Hot briquettes 2, which come out of the press at a temperature of 170 °C, enter the briquette channel 3 and move in the direction 6, forming a cooling line. Air 5 moves in a direct flow with the briquettes through the air duct 4. The air enters the recuperator through the inlet on the press side, moves in the air duct 4 in direction 5 due to the vacuum created by the fan 8, is heated by heat transfer through the wall from hot briquettes and is directed 7 to the drum dryer 10, where hot air comes into contact with crushed straw 9, removes moisture from the straw and through the outlet pipe 11 moist air leaves the dryer. The cooled briquettes from the heat recuperator are sent for packaging. This design ensures heat transfer only through the walls, without mixing the flows, which allows the heat of the briquettes to be used without burning them.

Thanks to the design of the recuperator with separate channels for briquettes and air, separated by a heat-conducting wall, the heat of the hot briquettes is used efficiently, which reduces the energy consumption for drying straw and increases the overall efficiency of the process.

The study is based on the application of analytical mathematical methods, including mass and energy balance equations, as well as thermophysical modelling of heat and mass transfer processes during drying. Equations (1)-(7), describing the mass and energy balance of the process, were used to determine the relationships between process parameters and to quantify the heat demand and heat recovery potential. The calculations were performed under steady-state conditions, assuming constant thermophysical properties of the materials. The obtained results were analysed using deterministic modelling, which allowed assessing the degree of coverage of the thermal demand of the drying process by the recovered sensible heat.

The mass flow rate of dry matter in straw was determined by the expression:

$$G_{dry} = G_s \left(1 - W_1\right), \tag{1}$$

where G_{dry} – mass flow rate of dry matter in straw, kg·h^{-1};
G_s – mass flow rate of straw, kg·h^{-1};
W_1 – initial moisture content of straw, %.

Mass of straw after drying:

$$G_{s2} = \frac{G_{dry}}{1 - W_2}, \tag{2}$$

where G_{s2} – mass of straw after drying, kg·h^{-1};
W_2 – final moisture content of straw, %.

The amount of moisture removed from the straw was calculated based on the mass balance of dry matter at given values of initial and final moisture content:

$$G_w = G_s - G_{s2}, \tag{3}$$

where G_w – mass of moisture removed, kg·h^{-1}.

Heat of moisture evaporation:

$$Q_{ev} = G_w \cdot r, \tag{4}$$

where Q_{ev} – heat of moisture evaporation, J·h^{-1};
r – specific heat of vaporisation, J·kg^{-1}.

The heat consumption for heating straw was determined by the expression:

$$Q_{heat} = G_s \cdot c_s \cdot \Delta T, \tag{5}$$

where c_s – specific heat capacity of straw, J·(kg·°C)$^{-1}$;
ΔT – heating temperature difference, °C.

The heat demand of the drying process was determined as the sum of the heat of evaporation of moisture and the heat of heating the material to the working drying temperature:

$$Q_{need} = Q_{ev} + Q_{heat}, \tag{6}$$

where Q_{need} – total heat consumption, J·h^{-1}.

The heat recovery potential was estimated based on the sensible heat of Pini Kay briquettes released during their cooling from the press outlet temperature to the temperature acceptable for further transportation and packaging:

$$Q_b = G_b \cdot c_b \cdot \left(T_{b.in} - T_{b.out}\right), \tag{7}$$

where Q_b – amount of sensible heat released during cooling of briquettes, MJ·h^{-1};
G_b – mass flow rate of Pini Kay briquettes, kg·h^{-1};
c_b – specific heat capacity of briquettes, J·(kg·°C)$^{-1}$;
$T_{b.in}$ – temperature of briquettes at the press outlet, °C;
$T_{b.out}$ – temperature of briquettes after cooling (acceptable for transportation and packaging), °C.

The following initial parameters were used for the research (Table 1).

Table 1

Main process parameters

Parameter	Designation	Value
Mass flow rate of straw, kg·h^{-1}	G_s	1000
Initial moisture content of straw, %	W_1	16
Final moisture content of straw, %	W_2	12
Heat capacity of straw, kJ·(kg·°C)$^{-1}$	c_s	1.3
Briquette mass (hourly productivity), kg·h^{-1}	G_b	960
Briquette inlet temperature, °C	$T_{b.in}$	170
Briquette outlet temperature, °C	$T_{b.out}$	70
Specific heat capacity of briquettes, kJ·(kg·°C)$^{-1}$	c_b	1.6
Specific heat of vaporisation of water, kJ·kg^{-1}	r	2257

The calculations used the specific heat capacities of straw and briquettes, as well as the tabulated value of the specific heat of water vaporisation. At this stage of research, the efficiency coefficient (EC) of the recuperator is assumed to be equal to one, which allows the maximum theoretical potential of the system to be estimated.

A comparative analysis of energy costs was carried out by comparing the obtained heat demand for drying with the amount of heat that can be extracted from briquettes in the recuperator. The results of the calculations are systematised in the form of tables and graphical dependencies, which allows for a visual assessment of the degree to which the heat demand of the drying process is covered by the recovered energy.

Results and discussion

Among the alternative methods of drying straw, the most promising is the recovery of sensible heat from hot briquettes after pressing. The Pini Kay briquetting process generates a significant amount of post-press heat: the temperature of the briquettes at the press outlet reaches 150-220 °C, but in most production schemes this heat is not utilised and is dissipated into the environment [6; 10]. Existing briquette cooling systems are primarily focused on reducing product temperature for safety and packaging reasons, without providing controlled heat transfer for drying raw materials [4].

Table 2 presents approximate energy consumption values for the considered drying technologies.

Table 2

Approximate drying costs

Technology	Energy consumption, MJ·h^{-1}	Fuel consumption
Gas dryer	110-150	12-17 m^3·h^{-1}
Solid fuel	120-180	15-25 kg·h^{-1}
Electric heat generator	150-210	40-60 kW·h^{-1}
Pini Kay recovery	0	0

As can be seen from Table 2, the highest energy consumption during the drying of chopped straw is associated with the electric drying technology. At the same time, the use of this technology ensures high stability of the drying process and accuracy in maintaining the specified temperature regime. Sufficient temperature stability is also achieved when using gas dryers. On the other hand, the use of drying units operating on solid fuel does not ensure adequate stability of the temperature regime of the process.

To solve the problem of reducing the energy intensity of the straw drying process by using sensible heat, the use of a heat recuperator is proposed (Fig. 1). To confirm the proposed hypothesis, theoretical calculations were performed according to expressions (1)-(7) without taking into account the efficiency of the recuperator. The calculations were based on the mass balance of the drying process and the change in enthalpy of the wet material. The main objective of the study was to determine the potential for heat recovery from Pini Kay briquettes leaving the press to the cooling line for use in the drying process of crushed straw.

The results of the calculations are presented in Table 3.

Table 3

Results of heat recovery potential calculations

Parameter	Designation	Value
Mass flow rate of dry matter in straw, kg·h^{-1}	G_{dry}	840
Mass of straw after drying, kg·h^{-1}	G_{s2}	954.5
Mass of evaporated moisture, kg·h^{-1}	G_w	45.5
Heat of moisture evaporation, MJ·h^{-1}	Q_{ev}	102.7
Heat of straw heating (20 → 60°C), MJ·h^{-1}	Q_{heat}	52.0
Total heat demand, MJ·h^{-1}	Q_{need}	154.7
Sensible heat of briquettes, MJ·h^{-1}	Q_b	153.6

Calculation of the thermal potential of Pini Kay post-press briquettes showed (Table 3) that when briquettes are cooled from 170 °C to 70 °C, the sensible heat is 153.6 MJ·h^{-1}, which almost completely covers the heat demand of the drying process (99.3%). Thus, within the limits of the accepted assumptions, it can be stated that it is fundamentally possible to implement an energy-closed drying process without the use of external heat sources.

The sensible heat of Pini Kay post-pressed briquettes almost completely covers the heat demand of the drying process required to reduce the moisture content of chopped straw from 16% to 12%. The heat energy deficit is only about 0.7%. Under these conditions, the calculated moisture content of the straw at the outlet will be approximately 12.03%.

As a result of analytical calculations, it was established that in order to reduce the moisture content of crushed straw from 16% to 12% at a mass flow rate of 1000 kg·h^{-1}, the total heat capacity required is 154.7 MJ·h^{-1}, of which 102.7 MJ·h^{-1} is accounted for by the heat of evaporation of moisture, and 52 MJ·h^{-1} is accounted for by heating the material to the working drying temperature. The results obtained are consistent with the data of fundamental research on the theory of industrial drying, presented in [9; 15], which shows that the main part of the heat consumption during biomass drying is the latent heat of phase transition.

Similar heat recovery concepts were previously considered in [10], which investigated self-heat recuperation technology for biomass drying, but the main focus was on the recirculation of heat from air flows. In contrast, in the proposed system, the heat source is directly the material flow – hot briquettes, which eliminates the need for additional heat generators and minimises heat transfer losses.

The results of the work are consistent with studies [12; 13], which experimentally confirmed the presence of significant post-press thermal potential of briquettes and the possibility of its use for technological needs. In particular, [14] proposes a technological scheme for combined cooling and drying of briquettes, but without a quantitative assessment of the degree of coverage of the thermal requirements for drying. This study is the first to confirm that the sensible heat of briquettes can almost completely meet the energy requirements for drying straw.

It is also important to compare the results obtained with classical industrial drying technologies. According to review works [4; 11], the energy consumption of gas and electric dryers for biomass is in the range of 110-210 MJ·h^{-1} for similar productivity, which is fully consistent with the data in Table 1. This means that the proposed system has the potential to reduce primary energy consumption by 90-100%, which is fundamentally important from the point of view of production economics.

In addition to the energy effect, the proposed solution has important technological advantages. According to [4; 6], the stability of the moisture content of raw materials is a key factor in ensuring the strength and durability of briquettes. The use of an internal heat source with controlled heat transfer allows for a more stable drying temperature regime compared to solid fuel dryers, where the temperature fluctuates significantly depending on the quality of the fuel and the combustion mode.

From the perspective of the modern concept of resource efficiency and circular economy, the proposed system complies with the principles of energy reuse within a single technological cycle. Similar approaches are considered in [1], where it is emphasised that the integration of thermal processes is one of the most effective ways to improve the energy efficiency of solid biofuel production.

At the same time, it should be noted that the results obtained are based on an idealised thermal model without taking into account the actual efficiency of the recuperator, heat losses to the environment and temperature field irregularities. This means that in real conditions, the degree of coverage of thermal needs may be slightly less than 100%, but even with a recovery efficiency of 70–80%, the expected energy effect remains significantly higher compared to traditional drying installations.

Thus, the results of the study confirm the feasibility of using the sensible heat of Pini Kay post-press briquettes as the main energy source for drying straw and form the scientific basis for further experimental research and industrial implementation of the proposed technology. At the same time, it should be noted that the obtained results are based on theoretical calculations and have not yet been experimentally validated. Therefore, the presented findings should be considered as a theoretical justification of the proposed approach, while experimental verification under real operating conditions is planned as a direction for further research.

Conclusions

1. An analysis of modern technologies for drying chopped straw has shown that this stage is one of the most energy-intensive in the technological process of solid biofuel production and can account for up to 30-40% of total energy costs. The use of traditional drying installations based on gas, solid fuel or electric heat generators leads to an increase in the cost of production and is accompanied by additional environmental burdens.
2. The feasibility of using secondary heat resources in production, in particular the sensible heat of Pini Kay post-press briquettes, the temperature of which at the press outlet is 150–220 °C, has been substantiated. A schematic diagram of a recovery system for drying crushed straw based on a heat exchange recuperator with separate channels for briquettes and air heat transfer medium is proposed, which ensures heat transfer without mixing the flows.
3. Based on mass and heat balances, analytical calculations of the straw drying process were performed with a decrease in moisture content from 16% to 12% at a mass flow rate of 1000 $kg\cdot h^{-1}$. It was established that the total heat demand of the process is 154.7 $MJ\cdot h^{-1}$, of which 102.7 $MJ\cdot h^{-1}$ is accounted for by the heat of evaporation of moisture and 52.0 $MJ\cdot h^{-1}$ by the heating of the material. It has been shown that when cooling briquettes from 170 °C to 70 °C, the sensible heat is 153.6 $MJ\cdot h^{-1}$, which covers 99.3% of the heat demand of the drying process and confirms the possibility of implementing an energy-closed system without the use of external heat sources. In real operating conditions, taking into account the efficiency of the heat recuperator and heat losses, the expected degree of heat recovery may decrease to approximately 70-80%, which still ensures a significant reduction in external energy consumption compared to conventional drying technologies.

Author contributions:

Conceptualization, Yu.S.; Methodology, Yu.S. and S.S.; Validation, O.Sav., O.Sar. and S.S.; Formal analysis, Yu.S. and O.Sav.; Investigation, Yu.S.; Data curation, Yu.S.; Writing – original draft preparation, Yu.S. and S.L.; Writing – review and editing, O.Sav., S.L. and Yu.S.; Visualization, Yu.S. and O.Sav.; Project administration, O.Sav.; Funding acquisition, O.Sav. All authors have read and agreed to the published version of the manuscript.

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