Acta Polytechnica **61**(3):448–455, 2021
https://doi.org/10.14311/AP.2021.61.0448

Published by the Czech Technical University in Prague

IMPROVING THE EFFICIENCY OF A STEAM POWER PLANT CYCLE BY INTEGRATING A ROTARY INDIRECT DRYER

Michel Sabatini*, Jan Havlík, Tomáš Dlouhý

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Energy Engineering, Technická 4, 166 07 Prague 6, Czech Republic

* corresponding author: michel.sabatini@fs.cvut.cz

Abstract. This article deals with the integration of a rotary indirect dryer, heated by low pressure extraction steam, into the Rankine cycle. The article evaluates the power generation efficiency of a steam power plant, with an integrated indirect dryer, which combusts waste biomass with a high moisture content and is further compared to the same plant without the dryer. The benefits of the dryer's integration are analysed in respect to various moisture contents of biomass before and after the drying. The evaluation of the power generation efficiency is based on parameters evaluated from experiments carried out on the steam-heated rotary indirect dryer, such as specific energy consumption and evaporation capacity. The dryer's integration improves the efficiency of the cycle in comparison to a cycle without a dryer, where moist biomass is directly combusted. This improvement increases along with the difference between the moisture content before and after the drying. For the reference state, a fuel with a moisture content of 50 % was dried to 20 % and the efficiency rised by 4.38 %. When the fuel with a moisture content of 60 % is dried to 10 %, the power generation efficiency increases by a further 10.1 %. However, the required dryer surface for drying the fuel with a moisture content of 60 % to 10 % is 1.9 times greater as compared to the reference state. The results of the work can be used both for the prediction of the power generation efficiency in a power plant with this type of dryer based on the moisture content in the fuel and the biomass indirect dryer design.

Keywords: Indirect drying, biomass drying, power generation efficiency.

1. Introduction

Climate change and environmental degradation may become a threat to Europe and the world in the future. The European Union has, therefore, created the Green Deal, which places decarbonisation demands on the energy sector. One way to achieve this is to increase the efficiency of power plants and increase the share of carbon-neutral fuels in the energy mix. Among these fuels are many kinds of biomass, which provide an excellent source of clean energy and possess a great potential for further use, yet, nevertheless, the potential of high-quality dry biomass in the Czech Republic is now almost fully exploited. Therefore, there is an effort to find ways how to efficiently use low-grade biomass with a high moisture content for electricity and heat generation. The quality of fuel for electricity and heat generation is described by its heating value, which is dependent on the amount of water and ash in the fuel. The ash content in biomass is relatively low and can range from 0.5 % to 12 % on a dry basis [1]. In general, the ash content is not significant as compared to the moisture content varying from 10 % to 70 % on a wet basis. Due to this fact, the quality of fuel can significantly be improved by reducing the moisture content.

The cheapest method appears to be solar drying, but combustion of biomass in a steam power plant requires a significant mass flow, so, accordingly, a large storage space would be needed. Moreover, the storage of wet fuel causes microbial activity and especially fungal growth, which reduces the quality of the fuel and may cause health problems [2, 3]. Therefore, the fuel is usually dried before the combustion process in a dryer, or the fuel enters the boiler wet, and the drying process is done directly there. The heat released from the combustion is partially consumed by the drying process and is not involved in the steam generation [4]. This process reduces the efficiency of the boiler, which consequently decreases the efficiency of the entire power plant [5]. Furthermore, it is difficult to combust a wood fuel with a moisture content of 60 % or more separately [1]. Additionally, the boiler designed for dry fuels could possess smaller dimensions compared to a boiler designed for wet fuel due to the reduced flue gas production at a higher temperature and, therefore, boiler ducts as well as the area of heating surfaces may be smaller [6].

The fuel in a power plant is usually dried in convective (direct) dryers heated by the flue gas taken from the boiler, or by the hot air preheated in a boiler. These two methods still use the heat released from the combusted fuel, therefore, they contribute only partially to the improvement of the power plant's efficiency. Utilisation of the flue gas leaving the boiler for drying of very moist fuel to a sufficiently low moisture content would require very high flue gas temperatures [7] and, moreover, poses a fire risk [6]. Many works are devoted to the issue of drying the fuel previous to its combustion or further use. Fuel drying for energy purposes in convective dryers using flue gas was researched in [8, 9]. Thermodynamics and economics of fuel drying for an organic Rankine cycle were analysed in [10]. An investigation into the lignite drying process in the indirect tubular dryer was conducted in [11]. The integration of a dryer or thermal mechanical dewatering unit into a power plant was investigated in [12]. However, all of these articles mainly concern the drying of lignite. Several methods regarding how to dry biomass for power generation are explained in [13]. In [14], the drying of biomass for the production of a second generation of biofuels was investigated. Integrated drying in a gasification plant is analysed in [15, 16].

However, previous works are mostly concerned with the drying of lignite for power generation or biomass drying for synfuel generation, pyrolysis and gasification plants. None of these studies are focused on increasing the power generation efficiency in a power plant, where very moist biomass is being combusted. Our research focuses on the evaluation of the power generation efficiency of a power plant with an integrated rotary indirect dryer. Indirect drying is a specific type of drying where the drying medium is separated from the material being dried by a heat transfer surface [17]. The heat is fed to the dried material through this surface, which defines the drying space. This type of dryer, heated with an extraction steam, should be a suitable option for the case of a small steam power plant. Low-pressure steam extracted from the steam turbine can be effectively utilized for drying because this steam has already done the major part of the work in the turbine for electricity generation, but it still has enough energy in the form of condensation heat, which would otherwise be mostly lost in the condenser. This principle is similar to regenerative feed water preheating. It is generally known that this method increases the efficiency of the thermodynamic cycle in the steam power plant, the effect is explained as an example in [18]. Furthermore, the common energy consumption for evaporation of 1 kg of water for this type of dryer ranges between $2800 - 3600\,\mathrm{kJ/kg}$ in comparison with direct dryers, where their energy consumption ranges between $4000 - 6000\,\mathrm{kJ/kg}$ [19].

The indirect rotary dryer, which uses extraction steam from the turbine, is integrated into the steam power plant cycle and its contribution to the drying of wet fuel to the efficiency of power generation is evaluated. The efficiency is calculated at various moisture contents in the fuel entering the cycle and then further compared to the cycle where the fuel is not dried.

2. Methodology

2.1. Dryer integration into a steam power plant

Figure 1a illustrates a simple power plant scheme based on the steam Rankine cycle with an extraction turbine and steam extraction for deaeration. Wet fuel enters the boiler directly. The aim of this work is to integrate the rotary indirect biomass dryer into this basic scheme and evaluate its contribution to the efficiency of the plant. Figure 1b depicts the integration of the indirect dryer heated by low pressure extraction steam, which has the same parameters as the deaeration steam. The fuel is firstly dried in the dryer and is then transported directly into the boiler for combustion.

The parameters of the steam power plant cycle are based on the typical parameters of biomass power plants located in the Czech Republic.

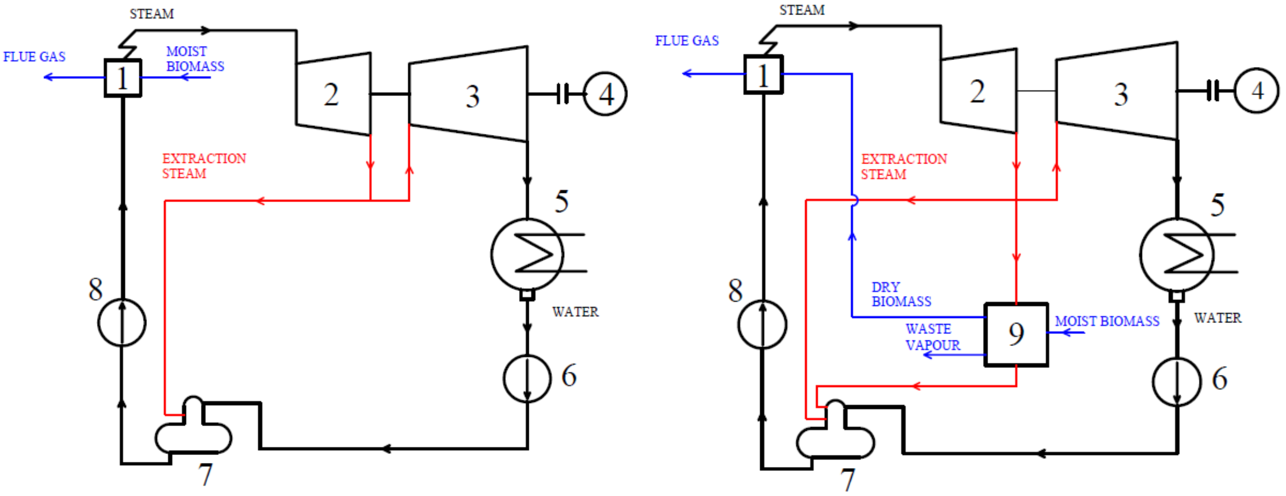
Parameters

Power plant output	$P = 10\,\mathrm{MW_e}$
Admission steam temperature	$t_1 = 490\,\mathrm{°C}$
Admission steam pressure	$p_1 = 6.7\,\mathrm{MPa}$
Extraction steam pressure	$p_2 = 2.32\,\mathrm{bar}$
Emission steam temperature	$t_3 = 45\,\mathrm{°C}$
Turbine thermodynamic efficiency	$\eta_t = 84\,\%$
Mechanical efficiency	$\eta_m = 99\,\%$
Electric motor efficiency	$\eta_{mot} = 95\,\%$
Generator efficiency	$\eta_g = 98\,\%$

2.2. Boiler efficiency

Moisture content affects the efficiency of the boiler. The boiler efficiency (Fig. 2) is calculated via the indirect method described in [20] and is related to the lower heating value of the fuel. The method is based on the estimation of the heat losses in the boiler. The effect of the variable moisture content in the fuel was reflected only in the change of the chimney loss, which expresses the relative heat loss in the flue gas leaving the boiler; in this case, at the temperature of 150 °C and with the excess of air of 1.5. When burning drier fuel, the volume of flue gases is lower, the chimney loss decreases, and the efficiency of the boiler increases. The values of other losses, i.e., losses due to incomplete combustion, by heat in the bottom ash and by radiation and convection to the surroundings, were considered constant and amounted to a total of 3.5 %. A fuel with a moisture content higher than 60 % on the wet basis is difficult to burn separately. Drying is essential for the utilisation of waste biomass with a very high moisture content.

As well as the efficiency of the boiler increasing with a decreasing moisture content in the fuel, the efficiency of the entire power plant also increases. For a comparison of the cycles with and without a dryer, it is necessary to know the energy balance for the chosen type of the integrated dryer and to verify its suitability for use with the considered material. These data are specified for each dryer type and the material used.



(A) . Power plant cycle without the dryer.

(B) . Power plant cycle with the dryer.

FIGURE 1. Power plant cycle without and with the dryer (1 - boiler; 2 - HP steam turbine; 3 - LP steam turbine; 4 - electric generator; 5 - condenser; 6 - condensate pump; 7 - deaerator; 8 - feedwater pump; 9 - indirect dryer).

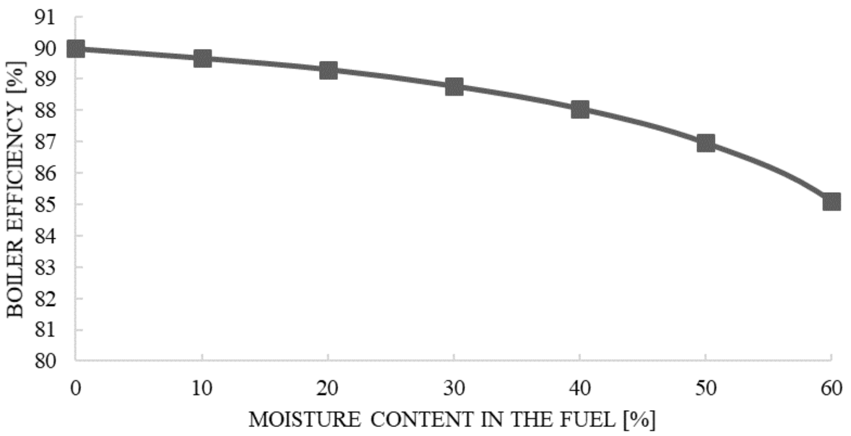


FIGURE 2. Boiler efficiency in dependence to the moisture content in the fuel.

Therefore, a set of experiments had to be prepared to provide data for evaluation (energy consumption, surface evaporation capacity and the energy loss of the dryer) for the steam rotary indirect dryer and the fuel used in the power plant.

2.3. EVALUATION OF THE POWER GENERATION EFFICIENCY

Evaluation of the power generation efficiency in dependence to the moisture content in the fuel (Fig. 5) is based on the following equations:

Power generation efficiency:

$$\eta = \frac{P_g - P_{pump}}{\dot{m}_f \cdot LHV} \cdot 100, \tag{1}$$

where $\dot{m}_f$ [kg/s] is the fuel mass flow rate, LHV [kJ/kg] is the lower heating value of the fuel.

Feedwater pump power consumption:

$$P_{pump} = \frac{\Delta h_{7-8} \cdot \dot{m}_L}{\eta_{mot} \cdot \eta_m}, \tag{2}$$

where $\dot{m}_L$ [kg/s] is the water mass flow rate, Δh_{7-8} [kJ/kg] is the enthalpy change of water in the feedwater pump.

Steam generation:

$$\dot{m}_G = \frac{\dot{m}_f \cdot LHV \cdot \eta_B}{(i_1 - i_8)}, \tag{3}$$

where $\dot{m}_G$ [kg/s] is the steam mass flow rate, η_B [-] is the boiler efficiency.

The differences between cycles with and without the drying are in the boiler efficiency (Fig. 2) and heating value of the fuel.

Power plant output:

$$P_g = (P_{HPT} + P_{LPT}) \cdot \eta_t \cdot \eta_m \cdot \eta_g. \tag{4}$$

High pressure turbine power output:

$$P_{HPT} = \dot{m}_G \cdot (h_1 - h_2). \tag{5}$$

Figure 3. Steam rotary indirect dryer.

Low pressure turbine power output:

$$P_{LPT} = (\dot{m}_G - \dot{m}_o \cdot (h_2 - h_3), \tag{6}$$

where $\dot{m}_o$ [kg/s] is the mass flow rate of the extracted steam.

The steam mass flow through the LPT is reduced due to the extraction of the steam:

- for deaeration in the cycle without the drying,
- for deaeration and drying in the cycle with the drying.

Mass flow rate of the extracted steam:

- the cycle without drying

$$\begin{aligned} \dot{m}_{o1} &= \dot{m}_G \cdot \frac{h_7 - h_6}{h_2 - h_6}, \\ \dot{m}_{o2} &= 0 \end{aligned} \tag{7}$$

- the cycle with drying

$$\begin{aligned} \dot{m}_{o1} = \frac{\dot{m}_{pv1}}{(h_2 - h_9)} \cdot \Bigg(\left(1 - \frac{w^r_{in} - w^r_{out}}{1 - w^r_{out}}\right) \cdot h_{f,out} - \\ - h_{f,in} + \left(\frac{w^r_{in} - w^r_{out}}{1 - w^r_{out}}\right) \cdot h_{WV} \Bigg), \end{aligned} \tag{8}$$

h_{WV} [kJ/kg] waste vapour enthalpy, h_f [kJ/kg] enthalpy of fuel, W^r [-] moisture content in fuel.

$$\dot{m}_{02} = \frac{\dot{m}_{01} \cdot (h_6 - h_9) + \dot{m}_G \cdot (h_7 - h_6)}{h_2 - h_6}, \tag{9}$$

$$\dot{m}_o = \dot{m}_{01} + \dot{m}_{02}. \tag{10}$$

Dryer dimensions:

Based on the moisture content in the fuel used in the cycle and the moisture content required after drying, the amount of evaporated water $\dot{m}_w$ can be calculated.

Dryer volume needed for the evaporation of water:

$$V = \frac{\dot{m}_w \cdot 3600}{o_V} \tag{11}$$

Parameter	Unit	Value
Dryer dimensions		
Inner surface	m^2	6.42
Inner volume	m^3	0.579
Diameter of the shell	m	0.6
Length of the shell	m	2
Steam extracted from the turbine		
Steam temperature	°C	135
Steam pressure	bar	3.2

Table 1. Dimensions of the dryer and steam parameters.

Dryer surface needed for the evaporation of water:

$$S = \frac{\dot{m}_w \cdot 3600}{o_S} \tag{12}$$

The required surface and volume of the dryer can be reached by changing the length or diameter of the shell in the process of the dryer design. Additional surface area can be added through heated flights.

2.4. Experimental dryer

For many kinds of inhomogeneous biomass materials used for power generation, it would be a suitable option to use the rotary indirect dryer. The indirect dryer is more energy efficient than conventional direct dryers [19]. For the design of such an industrial dryer, it is necessary to know its operating characteristics, which are not usually available. For this purpose, experiments were carried out on a laboratory rotary steam indirect dryer (Fig. 3).

A determination of the surface and volumetric evaporation capacities are required for designing the dryer and determining its optimal size. The dimensions of the dryer and heating steam parameters are summarized in Table 1.

2.5. Material

The tested type of biomass was predominantly spruce wood chips, which were bought from an external supplier and stored in an outdoor open area, so the inlet moisture content ranged between 55 % and 66 %. This material is very inhomogeneous, which may cause small deviations in experimental results. In Fig. 4, the comparison of the material before and after the drying to approximately 10 % is shown.

3. Results and discussion

A series of drying experiments were performed. Their goal was to verify the functionality of the dryer and determine the energy consumption of drying under different conditions. The input parameters were chosen to represent common conditions in a biomass power plant - the steam pressure was 3.2 bar and its saturation temperature was 135 °C. Table 3 shows the results

Parameter	Unit	Value
Moisture content	%	65
Low heating value ($W = 65\,\%$)	MJ/kg	4.4
Bulk density	kg/m^3	420
Average thickness of the woodchip	mm	10

TABLE 2. Material parameters.

FIGURE 4. Material before drying (left side) and after drying (right side).

of selected experiments, which differed in the initial and final moisture of the biomass, and mainly the volumetric filling ratio of the dryer. The determined values of the energy consumption ranged between 3 and 3.52 MJ/kg$_\mathrm{w}$, the surface and volumetric evaporation capacity varied between $o_S = 1.59 - 2.03\,\mathrm{kg_w/(m^2 \cdot h)}$ and $o_V = 17.1 - 21.8\,\mathrm{kg_w/(m^4 \cdot h)}$. The results of experiments showed that these parameters are most affected by the volumetric filling ratio of the dryer. By [21], there is no recommended filling ratio for indirect dryers, so there is a lot of room for finding the optimum in sizing and operating a real dryer. Optimizing other parameters, such as heating medium temperature and pressure, should be a result of a technical-economical assessment for each specific case.

The energy consumption of 3 MJ/kg$_\mathrm{w}$ for an evaporation of 1 kg of water from biomass was used for the following calculations of the contribution of biomass drying for improving the power generation efficiency in Fig. 5.

3.1. THE IMPACT OF THE DRYER'S INTEGRATION ON THE POWER GENERATION EFFICIENCY

Based on the experimentally determined drying characteristics, the efficiency of the power plant with an integrated dryer (Fig. 1b) was evaluated. Figure 5 shows the power generation efficiency calculated for various moisture contents in the fuel after the drying process. The figure indicates that the highest efficiency gain is achieved when very wet fuel enters the cycle and is dried to the values of about 10 % to 20 %. Fuel with a moisture content of 60 % or more is difficult to burn directly and co combustion with a quality fuel is usually necessary. In practice, the moisture content of very moist biomass such as bark stored outdoors during winter can be up to 65 %. A fuel with such a high moisture content can be used without drying for co-combustion with a high-quality fuel. Therefore, the moisture content of the fuel was considered to be up to 70 % for the purpose of evaluating the efficiency benefits of the dryer's integration. The fuel drying has a significant impact on the boiler efficiency, which affects the efficiency of the entire power plant. Moreover, the effect of drying has a positive effect on increasing the heating value of the fuel. In this way, the heat from the extraction steam is partially reverted back into the steam cycle by means of fuel. It is apparent that the curves begin to flatten in the range of 10 % – 20 %, and thus drying fuel to a very low moisture level will not significantly increase the efficiency compared to the costs incurred.

3.2. INCREASE IN THE POWER PLANT'S EFFICIENCY

Figure 6 describes the power generation efficiency increase in dependence on the change of the moisture content after drying for two different moisture contents of 50 % and 60 % in the fuel, which enters the power plant. The comparison is based on the assumption that the fuel enters those power plant cycles with the same moisture content and is either directly burned or dried to various moisture contents and then burned. The greatest benefit is achieved when the moisture content of the fuel, which enters the power plant, is the highest and the moisture content of the fuel after drying is the lowest. Commonly used biomass, e.g. generally wood chips, has the moisture content of about 50 % and it can be dried to 20 %, which results in an increase in efficiency of 4.4 %. If the moisture content of the fuel, which enters the cycle, was 60 % and the moisture content after drying of the fuel was 10 %, the efficiency could increase by 10.1 %. Using a fuel with a lower moisture content reduces the contribution of the dryer to the efficiency. The contribution of the dryer also changes in dependence on the moisture content in the fuel after drying. In the cycle where the fuel with a 60 % moisture content is used, the contribution decreases from 10.1 % to 4.7 % whereas the moisture content after drying rises from 10 % to 40 %.

To obtain dried fuel, more water, in dependence on the moisture content before and after drying, has to be evaporated. This will result in considerably higher

Experiment number	1	2	3	4	5	6
Filling ratio [%]	9	10	15	17	27	27
Moisture content in the fuel before drying [%]	69.2	62.2	64.5	64.5	65.5	60.6
Moisture content in the fuel after drying [%]	16.6	21.1	4.1	3.7	14.8	17.0
Surface evaporation capacity [kg/(m^2·h)]	1.85	1.89	1.59	1.68	2.03	1.94
Volumetric evaporation capacity [kg/(m^3·h)]	19.9	20.3	17.1	18.0	21.8	20.9
Energy consumption [MJ/kg$_w$]	3.43	3.46	3.52	–	3.24	3

Table 3. Experiment conditions and results.

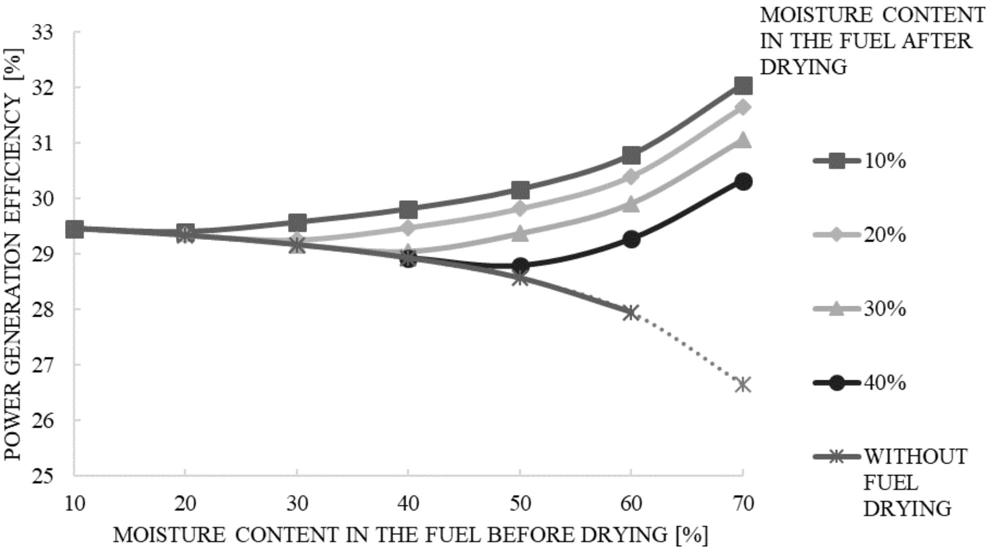


Figure 5. Power generation efficiency in dependence to the moisture content in the fuel after drying.

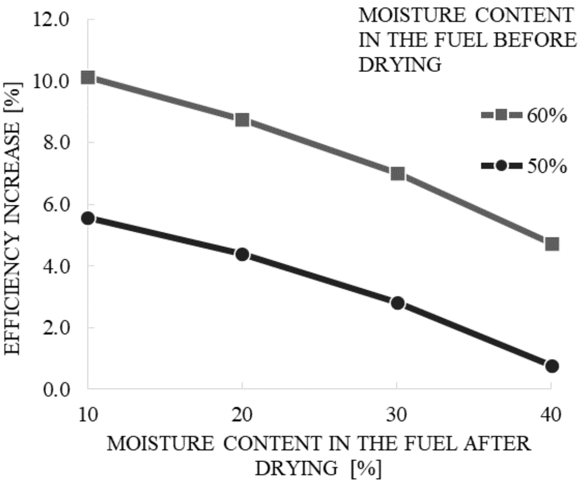


Figure 6. Efficiency increase in the cycle with an integrated dryer compared to the cycle without a dryer.

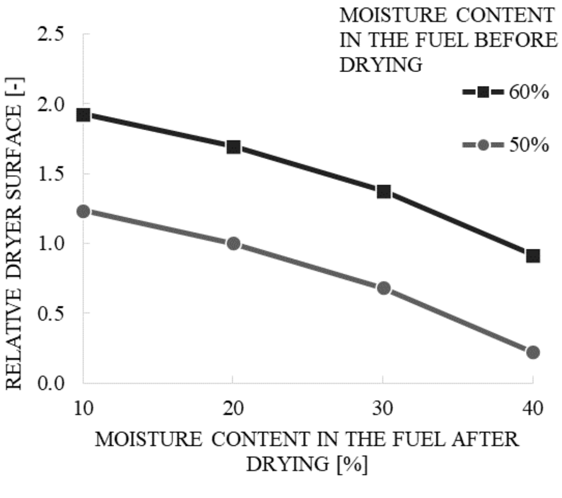


Figure 7. Relative increase in the dryer's surface.

demands on the dryer size quantified by the surface area. Figure 7 shows an increase in the required surface area against the reference case, which is the surface required for drying biomass from 50 % to 20 % moisture content. The dryer's surface area for these conditions and the fuel flow required for the power plant with parameters mentioned in chapter 2 has to be 238 m^2. If the moisture content of the fuel is 60 % and it is dried to a moisture content of 20 %, the required surface will increase 1.7 times and, for drying to a 10 % moisture content, the surface must be 1.9 times larger than the reference case. For the drying of 50 % to 30 % moisture content, the required surface would only be 70 % of the reference case. The optimal size of the dryer has to be determined on the basis of a technical-economical assessment for each specific case.

4. Conclusion

Integration of an indirect biomass dryer heated by extracted steam into the cycle of a steam power plant improves its efficiency and combustion conditions. The benefits of the dryer integration are most noticeable when the fuel is dried to a lower moisture content. Should the biomass, which enters the dryer, have a moisture content of 50 % and is then dried to 20 %, the efficiency of the entire power plant rises by 4.4 % and the dryer surface area has to be 238 m^2. If the fuel with a moisture content of 60 % is used and dried to 10 %, the power generation efficiency will rise by 10.1 % but the dryer surface area has to be 1.9 times larger.

It has been experimentally verified that a rotary steam indirect dryer is suitable for the drying of waste biomass, such as wood chips or bark. The experiments showed the influence of drying conditions on the energy consumption, therefore, a further investigation for the dryer optimization is needed.

To increase the intensity of the drying process, it would be suitable to use heated steam at a higher temperature, thereby reducing the dryer's surface area and reducing investment costs, however, subsequently reducing the electricity generation due to a lower steam flow through the low-pressure part of the steam turbine. The optimum dryer size would be determined by the results of a technical-economical assessment. The ability to dry fuel will increase the range of combustible biomass types – it will allow the burning of less valuable moist fuel, and thus decreasing the fuel costs further.

In addition, a boiler designed for a dry fuel can be smaller and thus less expensive to invest in.

Acknowledgements

This work was supported by the project from Research Centre for Low Carbon Energy Technologies, CZ.02.1.01/0.0/0.0/16_019/0000753. We gratefully acknowledge support from this grant.

List of symbols

h	specific enthalpy [kJ/kg]
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
o	evaporation capacity $[\mathrm{kg/(m^2\,h)}; \mathrm{kg/(m^3\,h)}]$
p	pressure [bar; MPa]
P	power input/output [kW; MW]
S	surface $[\mathrm{m}^2]$
t	temperature [°C]
V	volume $[\mathrm{m}^3]$
W	moisture content [–; %]

Greek symbols

η	efficiency [–; %]

Subscripts

01	steam extracted for deaerator
02	steam extracted for the dryer
1	boiler outlet
2	high pressure turbine outlet
3	low pressure turbine outlet
5	condenser outlet
6	condensate pump outlet
7	deaerator outlet
8	feed water pump outlet
9	dryer outlet
B	boiler
f	fuel
G	gas
HPT	high pressure turbine
in	in
L	liquid
LPT	low pressure turbine
m	mechanical
mot	electric motor
out	out
$pump$	pump
s	surface
t	turbine
g	generator
v	volume
w	water
WV	waste vapour

References

[1] S. van Loo, J. Koppejan (eds.). *The Handbook of Biomass Combustion and Co-firing*. Earthscan, London, 2008.

[2] R. Jirjis. Storage and drying of wood fuel. *Biomass and Bioenergy* **9**(1 - 5):181 – 190, 1995. https://doi.org/10.1016/0961-9534(95)00090-9.

[3] O. Gislerud. Drying and storing of comminuted wood fuels. *Biomass* **22**(1 - 4):229 – 244, 1990. https://doi.org/10.1016/0144-4565(90)90019-G.

[4] B. G. Miller, D. A. Tillman (eds.). *Combustion Engineering Issues for Solid Fuel Systems*. Academic Press, 2008.

[5] L. Dzurenda, A. Banski. The effect of firewood moisture content on the atmospheric thermal load by flue gases emitted by a boiler. *Sustainability* **11**(1):284, 2019. https://doi.org/10.3390/su11010284.

[6] W. A. Amos. Report on biomass drying technology. Tech. rep., National Renewable Energy Laboratory, Colorado, USA, 1998. https://doi.org/10.2172/9548.

[7] T. Dlouhý, F. Hrdlička. Regenerace tepla ze sušení biomasy. In *Kotle a energetická zařízení*, pp. 16 – 22. VUT, Brno, 2003.

[8] K. Atsonios, I. Violidakis, M. Agraniotis, et al. Thermodynamic analysis and comparison of retrofitting pre-drying concepts at existing lignite power plants. *Applied Thermal Engineering* **74**:165 – 173, 2015. https://doi.org/10.1016/j.applthermaleng.2013.11.007.

[9] X. Han, M. Liu, K. Wu, et al. Exergy analysis of the flue gas pre-dried lignite-fired power system based on the boiler with open pulverizing system. *Energy* **106**:285 – 300, 2016. https://doi.org/10.1016/j.energy.2016.03.047.

[10] X. Han, S. Karellas, M. Liu, et al. Integration of organic rankine cycle with lignite flue gas pre-drying for waste heat and water recovery from dryer exhaust gas: thermodynamic and economic analysis. *Energy Procedia* **105**:1614 – 1621, 2017. https://doi.org/10.1016/j.egypro.2017.03.518.

[11] K. Hatzilyberis, G. P. Androutsopoulos, C. E. Salmas. Indirect thermal drying of lignite: Design aspects of a rotary dryer. *Drying Technology* **18**(9):2009 – 2049, 2000. https://doi.org/10.1080/07373930008917824.

[12] E. Kakaras, P. Ahladas, S. Syrmopoulos. Computer simulation studies for the integration of an external dryer into a Greek lignite-fired power plant. *Fuel* **81**(5):583 – 593, 2002. https://doi.org/10.1016/S0016-2361(01)00146-6.

[13] R. Wimmerstedt. Recent advances in biofuel drying. *Chemical Engineering and Processing: Process Intensification* **38**(4 - 6):441 – 447, 1999. https://doi.org/10.1016/S0255-2701(99)00041-0.

[14] L. Fagernäs, J. Brammer, C. Wilén, et al. Drying of biomass for second generation synfuel production. *Biomass and Bioenergy* **34**(9):1267 – 1277, 2010. https://doi.org/10.1016/j.biombioe.2010.04.005.

[15] S. Tuomi, E. Kurkela, I. Hannula, C.-G. Berg. The impact of biomass drying on the efficiency of a gasification plant co-producing Fischer-Tropsch fuels and heat - A conceptual investigation. *Biomass and Bioenergy* **127**:105272, 2019. https://doi.org/10.1016/j.biombioe.2019.105272.

[16] M. A. Adnan, M. M. Hossain. Integrated drying and gasification of wet microalgae biomass to produce H2 rich syngas - A thermodynamic approach by considering in-situ energy supply. *International Journal of Hydrogen Energy* **44**(21):10361 – 10373, 2019. https://doi.org/10.1016/j.ijhydene.2019.02.165.

[17] C. W. Hall. *Dictionary of drying*. M. Dekker, 1979.

[18] S. Basu, A. K. Debnath. *Power Plant Instrumentation and Control Handbook*. Academic Press, 2015. https://doi.org/10.1016/C2018-0-01231-1.

[19] A. S. Mujumdar (ed.). *Handbook of industrial drying*. CRC Press, 4th edn., 2014.

[20] T. Dlouhý. *Výpočty kotlů a spalinových výměníků*. ČVUT, 2nd edn., 2002.

[21] J. Havlík, T. Douhý, M. Sabatini. The effect of the filling ratio on the operating characteristics of an indirect drum dryer. *Acta Polytechnica* **60**(1):49 – 55, 2020. https://doi.org/10.14311/AP.2020.60.0049.