

Article

Economic Evaluation of Drying of Soot Sludge and Sawdust Mixture at Low Temperatures Using the Characteristic Drying Curve Method[†]

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Abstract: Soot sludge is a waste stream formed in the fuel oil gasification of formic acid and hydrogen peroxide production. The soot sludge has a high moisture content (95%) and is presently combusted with heavy fuel oil in order to dispose of the sludge. Experimental tests earlier conducted by the authors have shown that the sludge can be convectively dried with sawdust in a fixed bed. By upgrading the sludge from waste to fuel, the utilization of oil can be decreased. In this study, characteristic drying curves (CDC) are determined for the sludge and sawdust mixture. The CDCs are further used to evaluate the economy of the mixture drying in a belt dryer by using the payback period method. Results show that the linear CDCs of the mixture can be used to extrapolate drying data from specific drying conditions to another when the bed height is 200 or 300 mm, and the inlet air temperature 40–100 °C. The economic analysis shows that drying is economical for all inlet air temperatures if the oil price is ≥ 350 €/t-oil. Sensitivity analyses reveal that the heat, sawdust and emission prices have no remarkable influence on the economy of drying if the oil price does not fall below c. 300 €/t-oil.

Keywords: carbon black; carbon soot; characteristic drying curve; constant drying curve; payback period

1. Introduction

The production plant of the Eastman Chemical Company [1] forms a waste stream called soot sludge. This stream is waste generated in a production process of formic acid and hydrogen peroxide. The soot sludge has an extremely high moisture content (c. 95% wb) as well as a sticky and viscous nature. The soot sludge is currently disposed of by combusting it in a combined heat and power plant (CHP) by mixing fuel oil with the soot sludge in order to combust it. In Eastman's production plant, moist soot sludge is formed approximately 20 t_{wb}/d. The moisture content of waste sludges can be reduced by removing water without vaporization (e.g., mechanical dewatering) [2,3] or using thermal drying [4–9].

A previous study by the authors [5] experimentally examined the ways soot sludge could be upgraded from waste to fuel by drying it at low temperatures (below 100 °C) before combustion. Drying tests were conducted in a fixed bed. In practice, drying pure soot sludge in a fixed bed is impossible; therefore, sawdust was mixed with it before the drying. Drying curves were determined for bed heights of 200 and 300 mm, inlet air temperatures of 40, 80, and 100 °C, and for air velocities of 0.75 and 0.9 m/s. The previous study showed that the most optimal mixture ratio of soot sludge and sawdust is 50% soot sludge and 50% sawdust (vol. %). The previous study [5] also studied

other mixture ratios for soot sludge and sawdust mixture. The goal was to find a mixture ratio that minimizes the use of sawdust but does not increase drying time too much. When the amount of soot sludge was higher (70% soot sludge and 30% sawdust) drying times became approximately three times higher than in the case of 50%:50%. When the amount of soot sludge was just 30% in a mixture drying time was shorter than in the case of 50%:50% (1.5 h vs. 2.3 h) but it was at the same magnitude and therefore the mixture ratio of 50:50 was chosen.

Usually, it is necessary to know the drying time in order to design a dryer. One option is to use drying models to define the drying time. Unfortunately, drying models may sometimes yield extremely inaccurate estimates of the real drying time. Experimental drying tests usually evaluate drying times more precisely. However, large amounts of measurements are needed to define drying curves under various drying conditions. Experimental drying tests are usually time consuming and they can even be costly. A single drying curve, called a characteristic drying curve (CDC), can be formed by normalizing measured drying curves with respect to the constant drying rate and critical moisture content. A characteristic drying curve can be used to extrapolate drying data from one set of external conditions to another. This reduces the number of measurements. Furthermore, a single curve also describes the drying rate over a wide range of different drying conditions. [10,11].

Recently, characteristic drying curves have been defined in several studies. Many of those studies focus on convective air drying of fruits, plants and vegetables in fixed beds as ginger roots [12], eucalyptus [13], banana [14], green sweet pepper [15], cactus [16], spearmint [17], prickly pear fruit [18], rosemary leaves [19], and cellulosic fibres from citrus fruits [20]. Characteristic drying curves have also been formed for wood-based materials, such as granulated cork (bark) [21], softwood timber [22], bark [11], and wood fibres (MDF) [23]. Characteristic drying curves have also been defined for sardine [24], and plaster [25]. In this study, characteristic drying curves are determined for a soot sludge and sawdust mixture which has been dried in fixed beds at different bed heights and air temperatures. To be able to define the constant drying rate in various drying conditions, a volumetric heat transfer coefficient is also defined for the mixture. In addition, characteristic drying curves are used in an economic analysis in which the profitability is evaluated of the soot sludge drying before combustion.

2. Materials and Methods

2.1. Generation of the Soot Sludge

Figure 1 shows the formation process of the soot sludge. Syngas is formed in the gasification process of heavy fuel oil with oxygen (partial oxidation) and steam at high pressure. The syngas contains carbon soot 1–2% of the amount of the used heavy fuel oil. The syngas is led for cooling in a waste heat boiler. Then, it is scrubbed with water, and the gas (CO, H₂, CO₂, H₂S) and soot water are separated. The soot water is led into a centrifugation process from which the soot sludge is obtained. After an amine-wash of the gas (recovery of sulphur and CO₂), the gas is led into a separation process in which CO and H₂ are separated for the production of formic acid and hydrogen peroxide [26].

2.2. Experimental Test Equipment

Figure 2 presents the experimental test equipment which has been used in drying tests. The dryer is a fixed-bed batch dryer where heat transfers convectively from drying air to the material. Hot pressurized air is mixed with the indoor air in an air duct. By adjusting the temperature of the pressurized air and the mass flow rate of the indoor air, a desired air temperature and velocity are achieved before the bed. The mass flow rate of the indoor air is adjusted by changing the rotation speed of the fan. The drying air moves through the bed from top to bottom. The drying time of the sample is defined using a direct method: the whole drying chamber lays on a scale which measures and saves the mass of the mixture sample on the computer at 10 s intervals. When the sample dries, its mass decreases. Drying curves can then be defined on the basis of the mass change and initial

moisture content [27]. Drying conditions and the experimental tests for the soot sludge and sawdust mixture are described in more detail in [5].

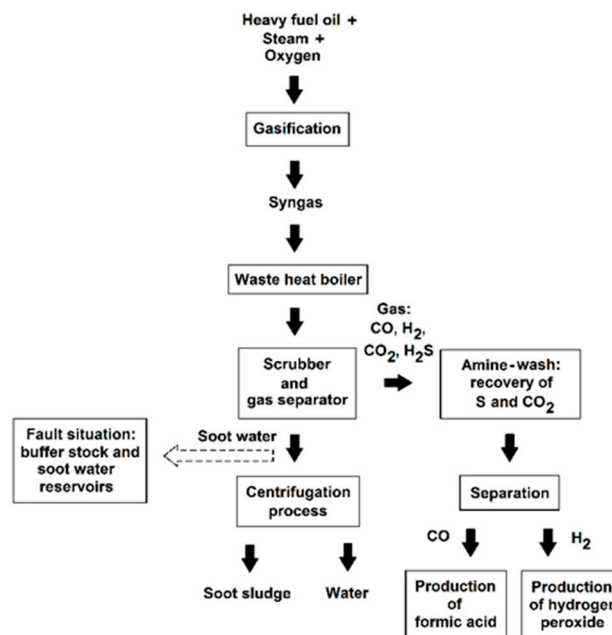


Figure 1. Formation process of the soot sludge (Reproduced from [5]. Illustration is based on the text in [26]).

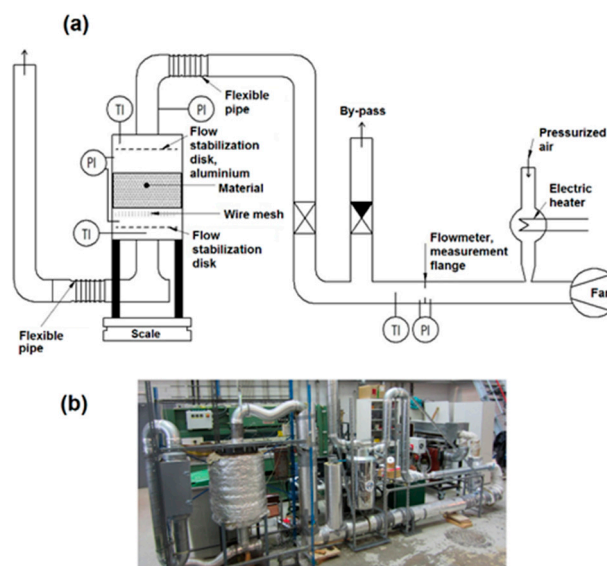


Figure 2. Test rig used in the tests: (a) Flow diagram of the equipment, and (b) The test rig in the laboratory at Aalto University. The most important technical data of the test rig: maximum drying air temperature ~ 200 °C, maximum air velocity per free cross-sectional area of the drying chamber ~ 1 – 1.2 m/s, height of the drying chamber 800 mm and diameter 400 mm. (Reproduced from [5]).

2.3. Soot Sludge and Sawdust Mixture

Figure 3a,b display examples of the moist soot sludge and the moist sawdust from which the mixture was created for the drying tests. Figure 3c shows an example of the moist soot sludge and sawdust mixture when the mixture ratio is 50%_{soot sludge} and 50%_{sawdust} (vol. %). Ultimate analysis of both sawdust and soot sludge are shown in Table 1. As Figure 3a indicates, the soot sludge is an extremely moist, viscous, sticky and homogenous material. It is impossible to dry the soot sludge alone

in a fixed bed, because the drying air cannot evenly move through the material bed. When sawdust was mixed with the soot sludge (Figure 3c), the air could flow evenly through the bed enabling drying [5]. The total moisture content and the bulk density of the mixture of 50%_{soot sludge} and 50%_{sawdust} are 84% (wet basis) and 116 kg_{db}/bulk-m³, respectively.

In general, the sawdust should be as dry as possible to reduce the water content of the mixture. Unfortunately, it is not always possible to get dry sawdust. The moisture content depends on where the sawdust comes from. For example, the sawdust used in these tests came directly from the sawmill, and therefore it's moisture content was at the same magnitude as the moisture content of fresh wood.



Figure 3. (a) Moist soot sludge (95% wb), (b) moist sawdust (56% wb), (c) moist soot sludge and sawdust mixture (mixture ratio in vol. %: 50% soot sludge and 50% sawdust). (Reproduced from [5]).

Table 1. Ultimate analysis of soot sludge and sawdust [5].

Material	Moisture Content (% w.b.)	C (% in d.b.)	H	N	S	O	Cl	Ash
Soot Sludge	95	65.9	0.66	0.35	1.34	4.50	-	27.2
Sawdust	56	48–50	6–6.5	0.5–2.3	0.05	38–42	<0.01	0.4–0.6

2.4. Characteristic Drying Curve

The characteristic drying curve corresponds to the relative drying rate as a function of the relative moisture content. The relative drying rate (m_R) is defined using the following equation:

$$m_R = \frac{m}{m_0}, \quad (1)$$

where m is the drying rate at the time t and m_0 is the drying rate during the constant drying rate period. The relative moisture content (X_R) is defined as follows:

$$X_R = \frac{X - X_{eq}}{X_{cr} - X_{eq}}, \quad (2)$$

where X is the moisture content at the time t , X_{eq} denotes the equilibrium moisture content, and X_{cr} is the critical moisture content. Critical moisture content is a moisture content at which the constant drying rate period ends and the falling drying rate period begins. In many cases, approaches 0 and Equation (2) results in:

$$X_R = \frac{X}{X_{cr}}. \quad (3)$$

When the characteristic drying curve is used the drying rate is expressed as follows [10]:

$$m = m_0 f(X_R), \quad (4)$$

where m_0 is the drying rate in period of constant drying rate and $f(X_R)$ is the characteristic drying curve. The change of the moisture content of the bed over a small time interval becomes:

$$m = -\frac{dX}{d\tau}. \quad (5)$$

Substituting Equation (4) into (5) and integrating the equation, the drying time can be calculated as follows:

$$\tau = -\frac{X_{cr}}{m_0} \int_{X_{R1}}^{X_{R2}} \frac{dx_R}{f(x_R)}, \quad (6)$$

where X_{cr} is the critical moisture content. In this paper, the constant drying rate m_0 is always given per dry mass of the bed [$\text{kg}_{\text{H}_2\text{O}}/(\text{kg}_{\text{db}} \text{ s})$].

If Equation (6) can be integrated, the drying time can be analytically calculated. If Equation (6) cannot be integrated, the drying time must be numerically solved. When Equation (6) is used for the fixed bed, the constant drying rate can be calculated as follows:

$$m_0 = \frac{\alpha a}{\rho_{bulk} \cdot l_v} \cdot \frac{t_{air, in} - t_{air, out}}{\ln \frac{t_{air, in} - t_{wb}}{t_{air, out} - t_{wb}}}, \quad (7)$$

where t_{wb} is the surface temperature of the material during the constant drying rate period, which is the same as the wet bulb temperature [$^{\circ}\text{C}$], $t_{air, in}$ is the temperature of air before the bed, $t_{air, out}$ represents the temperature of air after the bed, ρ_{bulk} is the bulk density of dry material [$\text{kg}_{\text{db}}/\text{m}^3$], and l_v is the vaporization heat of water at t_{wb} [J/kg]. In Equation (7), the product αa represents the volumetric heat transfer coefficient. A rough approximation for the volumetric heat transfer coefficient of the soot sludge and sawdust mixture is defined in Section 3.2.

2.5. Economic Analysis

The economic analysis assesses whether it is economical to dry the soot sludge in a fixed bed belt dryer before the combustion. Drying of the soot sludge is an energy efficiency investment. The

economy of the energy efficiency investment is typically evaluated using the payback period without interest (Equation (8)). The characteristic drying curve is used for calculation of the drying time of the specific drying process in an economic analysis. The payback period for the dryer is

$$PBP = \frac{I_{tot,dryer}}{S_{net}}, \quad (8)$$

in which $I_{tot,dryer}$ is the total investment costs [€], and S_{net} is the annual net savings when the soot sludge and sawdust mixture is dried, instead of the direct combustion of moist soot sludge [€/years]. Savings result from reduced heavy fuel consumption and lower CO₂ emissions. Operational costs of the dryer and purchased cost of sawdust result in some additional expenses. When savings and additional expenses are taken into account, net savings become

$$S_{net} = P_{savings,fuel} + P_{savings,CO_2} - P_{oper} - P_{sawdust}. \quad (9)$$

The total investment costs of the dryer ($I_{tot,dryer}$) are calculated using the following equation [28]:

$$I_{tot,dryer} = A_{dryer} \cdot \left[-3095 \ln \left(\frac{A_{dryer}}{480} \right) + 5838 \right], \quad (10)$$

where A_{dryer} is the cross-sectional area of a continuous-working belt dryer [m²]. When the residence time of the material inside the dryer (τ , [s]) is known, the cross-sectional area of the dryer (A_{dryer}) can be approximately defined as follows:

$$A_{dryer} = \frac{\dot{m}_{db} \cdot \tau}{\rho_{bulk} Z}, \quad (11)$$

where \dot{m}_{db} is the mass flow rate of dry material [kg_{db}/s], ρ_{bulk} denotes the bulk density of dry material [kg_{db}/m³] and Z is the bed height [m]. The savings, in Equation (9), are calculated as follows:

$$P_{savings,fuel} + P_{savings,CO_2} = \Delta \dot{m}_{fuel} \cdot \gamma \cdot C_{fuel} + \Delta \dot{m}_{fuel} \cdot \gamma \cdot q_{oil} \cdot S_{CO_2} \cdot C_{CO_2}, \quad (12)$$

where $\Delta \dot{m}_{fuel}$ is the reduced heavy fuel oil consumption [kg/h], γ is the annual operating time of the dryer [h/a], C_{fuel} represents the price of the heavy fuel oil [€/t-oil], q_{oil} denotes the heating value of heavy fuel oil [MJ/kg-oil], S_{CO_2} is CO₂ emission factor of heavy fuel oil [kg-CO₂/MWh] and C_{CO_2} is the price of the CO₂ emissions [€/t-CO₂]. The reduced heavy fuel oil consumption is calculated as follows [5]:

$$\Delta \dot{m}_{fuel} = \frac{(u_1 - u_2) \cdot 2.443 + r \cdot q_{sawdust} - 2.443 \cdot r \cdot u_2}{q_{oil}} \cdot \dot{m}_{soot} \quad (13)$$

where \dot{m}_{soot} is the mass flow rate of the soot sludge [kg_{db}/s], u_1 is the moisture content of the moist soot sludge [kg_{H₂O}/kg_{db}], u_2 is the moisture content of the soot sludge and sawdust mixture after drying, r denotes the mass ratio (dry basis) of sawdust to soot sludge in the mixture [-] (This value is known from the drying data) and $q_{sawdust}$ is the lower heating value of the sawdust [MJ/kg_{db}]. The term 2.443 represents the vaporization heat of water at 25 °C.

The annual operational costs of the dryer (P_{oper} , Equation (9)) include both the electricity and the heat costs.

$$P_{oper} = P_{elec} \cdot C_{elec} \cdot \gamma + \emptyset \cdot C_{heat} \cdot \gamma, \quad (14)$$

where P_{elec} is the electricity consumption of the dryer's fans [MW], \emptyset represents the heat consumption of the dryer (heating of the drying air) [MW], C_{elec} is the price of the electricity, C_{heat} is price of the heat [€/MWh] and γ is the annual operational time of the dryer. The electricity consumption is calculated as follows:

$$P_{elec} = \frac{v \cdot A_{dryer} \cdot \Delta P_{pres}}{\eta_{fan}}, \quad (15)$$

where v is the velocity of air before the fan(s) [m/s], ΔP_{pres} is the total pressure drop over the dryer configuration [Pa] and η_{fan} denotes the efficiency of the fan(s). It is assumed that the fan(s) are situated before the heat exchanger(s) in the dryer configuration. The total pressure drop ΔP_{pres} is the sum of the pressure drops over the material bed, the plate heat exchanger(s), and the air duct system (i.e., $\Delta P_{pres} = \Delta P_{material} + \Delta P_{he+ad}$). The heat consumption is calculated as

$$\dot{Q} = \dot{m}_{da} \cdot (h_{out} - h_{in}) = v \cdot A_{dryer} \cdot \delta_{da} \cdot (h_{out} - h_{in}), \quad (16)$$

where \dot{m}_{da} is the mass flow of dry air [kg_{da}/s], δ_{da} is the density of dry air [kg_{da}/m³] and h denotes the enthalpy of humid air before and after the heat exchanger [kJ/kg_{da}]. The enthalpy of humid air is calculated as follows:

$$h = c_{p,da} \cdot t + x(c_{p,w} \cdot t + 2501) \quad (17)$$

in which $c_{p,da}$ is the specific heat capacity of dry air [kJ/kg°C], t is temperature of drying air [°C], x is moisture content of air [kg/kg_{da}] and $c_{p,w}$ represents specific heat capacity of water vapour [kJ/kg°C]. The annual cost of the sawdust is determined as follows:

$$P_{sawdust} = \dot{m}_{sawdust} \cdot \gamma \cdot C_{sawdust} \cdot q_{sawdust}, \quad (18)$$

where $\dot{m}_{sawdust}$ is the mass flow rate of the sawdust into the dryer [kg_{db}/s] and $C_{sawdust}$ is the price of the sawdust [€/MWh].

3. Results and Discussion

3.1. Determination of Characteristic Drying Curves

Figure 4 shows the characteristic drying curves for soot sludge and sawdust mixture for the bed heights of 200 and 300 mm, and air temperatures of 40, 80 and 100 °C. Figure 4 reveals that the shape of the characteristic drying curve is almost linear for both bed heights, regardless of the temperature level. This indicates that the relative drying rate is independent of the level of the inlet air temperature over the temperature range of 40–100 °C. Furthermore, results indicate that characteristic drying curves for the bed heights of 200 mm and 300 mm could also be used to define the drying time when the air temperature is to some extent over 100 °C. Figure 5 presents an almost linear characteristic drying curve for the air velocities of 0.75 and 0.9 m/s. It is reasonable to conclude that the relative drying rates are quite independent of the air velocity over the velocity range used in this study for the bed height of 200 mm.

The accuracy of the characteristic drying curves (Equations (19)–(21)) was evaluated by comparing the drying times calculated using the characteristic drying curves (Equation (22)), and experimentally measured drying times from earlier studies of the authors [5]. In the drying time calculations, the constant drying period was taken into account as Equation (22) shows. The critical moisture contents (X_{cr}) and the constant drying rates (m_0) were defined for every bed height and air temperature combination from the original drying curves [5].

$$f(x_R) = 0.9559x_R + 0.0495 \quad (19)$$

$$f(x_R) = 0.9958x_R - 0.0064 \quad (20)$$

$$f(x_R) = 0.9804x_R + 0.0248 \quad (21)$$

$$\tau = -\frac{X_{cr}}{m_0} \int_{X_{R1}}^{X_{R2}} \frac{dx_R}{f(x_R)} = -\frac{X_{cr}}{m_0} \left[\int_{X_{R1}}^1 dx_R + \int_1^{X_{R2}} \frac{dx_R}{f(x_R)} \right] \quad (22)$$

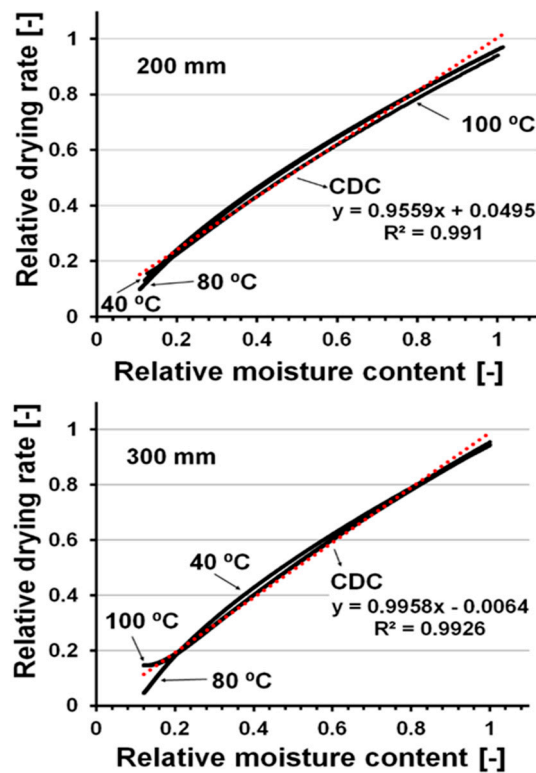


Figure 4. Characteristic drying curves for the bed heights of 200 mm and 300 mm. Air velocity 0.75 m/s in all cases. Mixture ratio 50%_{soot}:50%_{sawdust}.

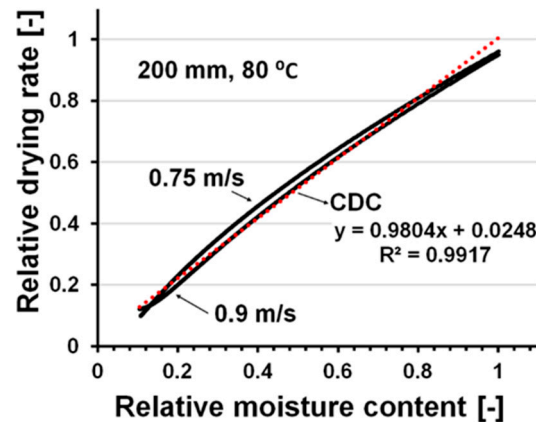


Figure 5. Characteristic drying curve for the air velocities of 0.75 and 0.9 m/s. Bed height 200 mm and air temperature 80 °C in both cases. Mixture ratio 50%_{soot}:50%_{sawdust}.

Table 2 shows the results of the comparison. The relative errors between the drying times vary from 0.5 and 2.7% when the characteristic drying curves have been used for the bed heights of 200 mm and 300 mm. For air velocities of 0.75 and 0.9 m/s, the relative errors between the drying times range from 2.6 to 3.8%. In general, these results signify that the characteristic drying curves (Equations (19)–(21)) estimate drying times with a good accuracy. Table 2 also shows the critical moisture contents of the specific drying processes used in CDC calculations. The values for the term m_0 can be seen in Tables 3 and 4.

Table 2. The comparison of the experimentally measured drying times (DC), and the calculated drying times using the characteristic drying curves (CDC). Initial and final moisture contents have been 5.3 (84% wb) and 0.7 kg_{H2O}/kg_{db} (41% wb) in all cases.

The Comparison of the Drying Times						
	200 mm			300 mm		
	Drying Time, DC [s]	Drying Time, CDC [s]	* Relative Error	Drying Time, DC [s]	Drying Time, CDC [s]	* Relative Error
40 °C	17,870	18,347	2.7	27,930	28,308	1.4
80 °C	7840	7790	0.6	13,010	13,219	1.6
100 °C	6650	6526	1.9	10,360	10,408	0.5
0.75 m/s; 80 °C	7840	8137	3.8			
0.9 m/s; 80 °C	7650	7453	2.6			
The Critical Moisture Contents X_{cr} [kg _{H2O} /kg _{db}]						
	200 mm; 0.75 m/s			300 mm; 0.75 m/s		
40 °C		4.50			4.16	
80 °C		5.04			4.34	
100 °C		4.30			4.46	
	200 mm; 0.9 m/s					
80 °C		4.51				

* Relative error = $|1 - \text{Time}_{\text{CDC}}/\text{Time}_{\text{DC}}| \times 100$.

Table 3. The calculated values for the term αa for the bed height of 200 mm. Bulk density of mixture 116 kg_{db}/m³ in all cases.

Air Velocity: v [m/s]	$t_{\text{air,in}}$ [°C]	$t_{\text{air,out}}$ [°C]	x_{in} [kg _{H2O} /kg _{da}]	t_{wb} [°C]	m_0 [kg _{H2O} /(kg _{db} s)]	αa [W/(m ³ K)]
0.75 m/s	40.9	21.3	0.0057	19.4	0.000461	16,160
0.75 m/s	81.4	31.1	0.0026	27.6	0.001190	18,274
0.75 m/s	101.7	37.4	0.0055	32.9	0.001249	14,895
					Average:	16,443
0.9 m/s	81.5	34.5	0.0041	28.4	0.001177	15,309

Table 4. The calculated values for the term αa for the bed height of 300 mm. Bulk density of mixture 116 kg_{db}/m³ and air velocity 0.75 m/s in all cases.

$t_{\text{air,in}}$ [°C]	$t_{\text{air,out}}$ [°C]	x_{in} [kg _{H2O} /kg _{da}]	t_{wb} [°C]	m_0 [kg _{H2O} /(kg _{db} s)]	αa [W/(m ³ K)]
40.7	20.0	0.0046	18.5	0.000308	11,435
80.0	31.3	0.0031	27.6	0.000685	10,534
103.4	35.1	0.0055	33.2	0.000893	13,266
				Average:	11,745

3.2. Determination of the Volumetric Heat Transfer Coefficient

A value for the term αa can be calculated from the experimental data. Measuring the outlet air temperature during the constant drying rate period, and assuming that the surface temperature of the particles in the bed is the wet bulb temperature, the term αa can be solved from the Equation (7). Tables 3 and 4 show the volumetric heat transfer coefficients for the bed heights of 200 and 300 mm, respectively, when the inlet air temperatures have been 40, 80, and 100 °C. The air temperatures before the bed ($t_{\text{air,in}}$) and after the mixture bed ($t_{\text{air,out}}$) have been experimentally measured, and the values have been taken as average values when the drying has been in the period of the constant drying rate.

The average values of the term αa can be used to calculate the constant drying rate (m_0 , Equation (7)) for the soot sludge and sawdust mixture in a fixed bed when the inlet air temperature is ≤ 100 °C. The average αa value can also be used to estimate the constant drying rate although the inlet temperature is slightly higher than 100 °C if more accurate data is not available.

The results show that the volumetric heat transfer coefficient becomes lower when the bed height increases. The obvious reason for this is that vapor from the drying air condenses in the bottom part of the bed (air moves from top to down). Therefore, the drying rate (m_0) remains lower for higher bed heights. In fact, there is no constant drying rate period over the whole bed when the bed height is 300 mm. In general, this is a quite normal behaviour in the fixed beds when the bed heights are sufficiently high and mass transfer resistances from the material to air are low.

3.3. Economic Analysis

3.3.1. Base Case

The economic analysis was only conducted for the bed height of 200 mm. All drying times were defined using the characteristic drying curve shown in Figure 4 or the actual drying curves if they were available. The bed height of 200 mm has been found to be the most optimal one in a previous study [5] of the authors. Inlet air temperatures in the economic analysis were 40, 60, 80, 100 and 120 °C. It is assumed in the economic analysis that the moist soot sludge is dried with sawdust in a continuous belt dryer, and the dried mixture is combusted in a boiler. As a result of drying, heavy fuel consumption in the boiler is reduced. The initial moisture content of the soot sludge and sawdust mixture was 84% (wb) in all calculations. The final moisture content of the mix was selected to be 41% because with this final moisture content, the mixture could be properly combusted in a boiler without any remarkable dusting problem. Payback periods were first calculated for the base case study. The payback periods were calculated for the air temperatures of 40, 80, and 100 °C using the drying times from the experimental data obtained earlier [5]. For air temperatures of 60 and 120 °C, the characteristic drying curve was used to define the drying time (Equations (19) and (22)). When the characteristic drying curve was used, the critical moisture content was $4.6162 \text{ kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$, and the outlet air temperature (Equation (7), $t_{\text{air,out}}$) was calculated as follows: $t_{\text{air,out}} = t_{\text{wb}} + 3.3$ °C. Both values have been extracted from the experimental data [5]. Table 5 summarizes all the initial values for the economic analysis.

Table 5. The initial values for the economic analysis.

Parameters	Initial Value
Volume ratio of the sludge and sawdust mixture	50% _{soot sludge} :50% _{sawdust}
Bed height of the mixture inside the dryer	200 mm
Inlet air velocity before the bed	0.75 m/s
Mass flow rate of moist soot sludge	20 t/d
Moisture content of pure soot sludge	95% wb
Mass flow rate of moist sawdust	7.8 t/d
Moisture content of pure sawdust	56% wb
Initial moisture content of the mixture	5.3 $\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$ (84% wb)
Final moisture content of the mixture after drying	0.7 $\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$ (41% wb)
Bulk density of the mixture	116 $\text{kg}_{\text{db}}/\text{m}^3$
Total pressure drop of the dryer for the bed height of 200 mm	318 Pa (from the drying data, average value between the pressure drops in the beginning and at the end of the tests [5])
Total pressure drop over the heat exchanger and air duct	400 Pa

Table 5. Cont.

Parameters	Initial Value
Drying air temperature before the fans and before heating it to the desired drying air temperature	15 °C
Moisture content of air	0.004 kg _{H2O} /kg _{da} (average value from the drying tests [5])
Efficiency of the fan (η)	0.8
Heating value of heavy fuel oil	41 MJ/kg
Emission factor of heavy fuel oil	284 kg _{CO2} /MWh
Price of the CO ₂ ton	13 €/t _{CO2} (current price [29], base case)
Lower heating value of dry sawdust	19 MJ/kg _{db}
Lower heating value of dry soot sludge	22.65 MJ/kg _{db}
Mass ratio of sawdust to soot sludge in the mixture (r)	3.4 kg _{db, sawdust} /kg _{db, soot sludge}
Price of electricity	40 €/MWh
Price of heat	5 €/MWh (base case)
Price of sawdust	19 €/MWh (current price in Finland [30], base case)
Operating time of the chemical plant and the dryer	8000 h/year

Figure 6 shows the base case results. Table 6 shows the payback period calculations for the base case when the current import price of the heavy fuel oil (410 €/t-oil, [31]) has been used. Usually, energy efficiency investments are seen as cost-effective if the payback period is 2–3 years or less. Figure 6 shows that the drying of the soot sludge and sawdust mixture is profitable (payback period is 3 years or less) when the inlet air temperature is 80 °C or more, and the heavy fuel oil price is at least 250 €/t-oil. However, drying with air temperatures of 40 and 60 °C is also profitable when the heavy fuel oil price is at least 350 €/t-oil. At the current import price of heavy fuel oil (410 €/t-oil), the drying of the soot sludge and sawdust mixture is economical for all inlet air temperatures. Table 6 shows that the payback period ranges from 1.0 to 2.4 years, when the current price of the heavy fuel oil is used in the calculations. Figure 6 also confirms that there is no reason to use a higher drying air temperature than 80 °C, because the payback periods of the air temperatures from 80 to 120 °C are at the same magnitude.

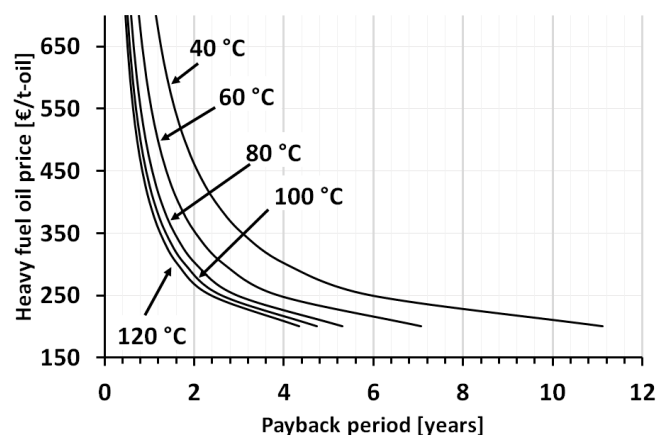


Figure 6. The payback periods for the soot sludge and sawdust mixture dryers when the inlet air temperatures are 40, 60, 80, 100 and 120 °C. All initial values are shown in Table 5.

Table 6. The payback period calculations for the base case when the current import price of the heavy fuel oil (410 €/t-oil, [31]) has been used (The term €/a represents the term €/years).

	40 °C	60 °C	80 °C	100 °C	120 °C
Cross-sectional area of the dryer	39 m ²	24 m ²	17 m ²	15 m ²	13 m ²
Investment cost	535,131 €	359,705 €	278,879 €	244,024 €	219,992 €
Savings in heavy fuel oil costs	346,256 €/a	346,256 €/a	346,256 €/a	346,256 €/a	346,256 €/a
Savings in CO ₂ emissions	35,510 €/a	35,510 €/a	35,510 €/a	35,510 €/a	35,510 €/a
Cost of sawdust	114,391 €/a	114,391 €/a	114,391 €/a	114,391 €/a	114,391 €/a
Cost of electricity	8492 €/a	5117 €/a	3726 €/a	3160 €/a	2783 €/a
Cost of heat	33,355 €/a	34,007 €/a	33,738 €/a	35,417 €/a	36,571 €/a
Payback period	2.4 years	1.6 years	1.2 years	1.1 years	1.0 years

3.3.2. Sensitivity Analysis: Influence of the Heat Price

Heat sources for drying process can be divided into primary and secondary heat sources. The temperature of primary heat (e.g., process steam) is usually high. Secondary heat sources, which are also called excess heat, are heat flows recovered from different processes. The price of heat depends on several factors, such as the production method of heat, temperature level of the heat, and fuel prices. When the heat is fairly priced, the price should always depend on the temperature level of the heat source: a higher heat price for a higher temperature. Nevertheless, this is not always the case: the price does not always depend on the temperature level. For this reason, the price was kept at a constant in the base case (Section 3.3.1), despite the variation in air temperatures. However, in this section, the influence of the heat price on the payback period is evaluated using the heat prices of 1, 5, 10 and 15 €/MWh. Figures 7 and 8 show the results of the sensitivity analysis of the heat price for the drying process with inlet air temperatures of 80 °C and 60 °C, respectively. In both figures, the curve with the heat price of 15 €/MWh ends at the heavy fuel oil price of 250 €/t-oil, because the operational costs exceed the savings with the lower prices of the heavy fuel oil.

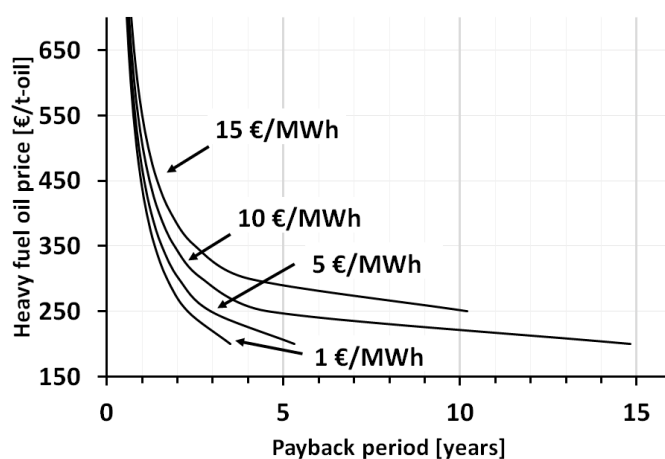


Figure 7. The payback periods when the heat prices of 1, 5, 10, and 15 €/MWh are used. The inlet air temperature of the drying air is 80 °C. All other initial values are shown in Table 5.

Figure 7 shows that the soot sludge and sawdust mixture drying is profitable (maximum payback period 3 years) with all heat prices when the heavy fuel oil price is at least 330 €/t-oil. Furthermore, Figure 8 shows that the drying is profitable (payback period max 3 years) with all heat prices when the heavy fuel oil price is at least 360 €/t-oil. These results indicate that it is economical to dry the soot sludge with the current oil price (410 €/t-oil) despite the relatively high heat price. The heat price of 15 €/MWh is a rather typical price level for process steam in the industry. Waste heat is usually much cheaper. Results with varying heat prices also show that there is no reason to use higher drying air

temperatures than 60–80 °C because drying is always economic with current oil price even if the heat price was 15 €/MWh. If there are several heat sources with varying heat prices available, cases should be analysed in more detailed to find the optimal drying temperature. Low drying temperatures with low heat prices result in high investment costs (dryer size + heat exchanger areas) but low operational costs and vice versa when drying temperatures are high. This is a classic optimization problem that has been studied for example by Holmberg et al. [32].

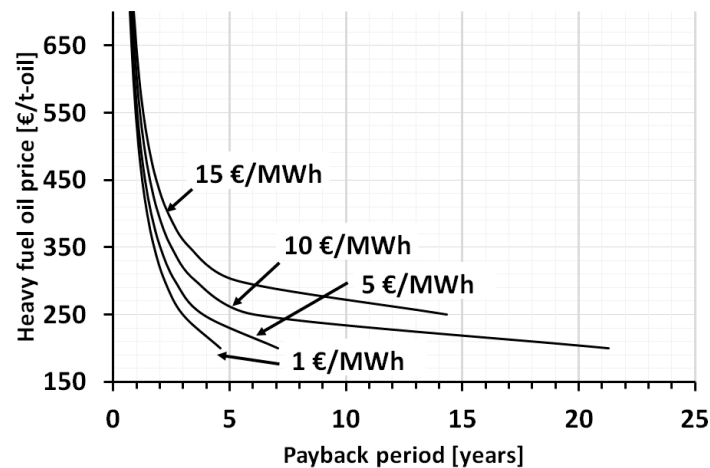


Figure 8. The payback periods when the heat prices of 1, 5, 10, and 15 €/MWh are used. The inlet air temperature of the drying air is 60 °C. All other initial values are shown in Table 5.

3.3.3. Sensitivity Analysis: Influence of the CO₂ Emission Price

This section evaluates the influence of the CO₂ emission price on the payback period when emission prices are 3, 7, 11, and 15 €/t-CO₂. Between the years of 2013 and 2018, the price of the CO₂ emission has varied from 3 to 14 €/t-CO₂ within the European Union [29]. Figure 9 shows the results of the sensitivity analysis of emission price for the drying process with an inlet air temperature of 80 °C. Figure 9 reveals that the price of the CO₂ emission does not have any remarkable influence on the profitability. The drying is economical (payback period is less than 3 years) with all emission prices when the heavy fuel oil price is at least 300 €/t-oil.

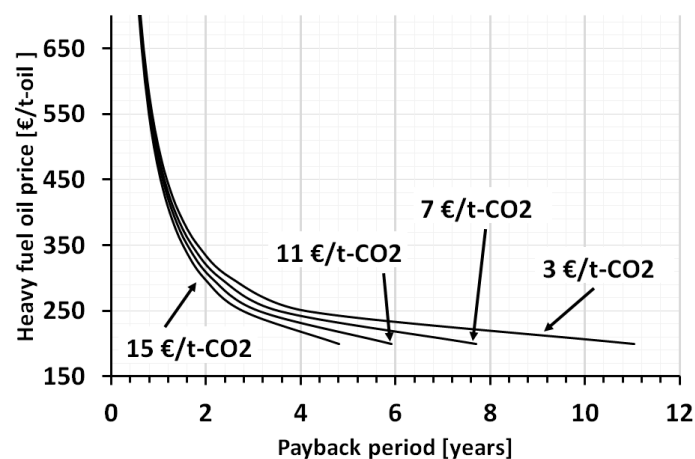


Figure 9. The payback periods when the CO₂ emission prices of 3, 7, 11 and 15 €/t-CO₂ are used. The inlet air temperature of the drying air is 80 °C. All other initial values are shown in Table 5.

3.3.4. Sensitivity Analysis: Influence of the Sawdust Price

This section studies the influence of the sawdust price on the payback period when sawdust prices of 11, 15, 19, and 23 €/MWh are used. For example, in Finland, the price of the sawdust has varied from 17 to 20 €/MWh between the years 2015 to 2018 [30]. Figure 10 displays the results of the sensitivity analysis when the inlet air temperature is 80 °C. Figure 10 shows that the sawdust price does not have any remarkable influence on the profitability: the drying is profitable (payback period is maximum of 3 years) with all sawdust prices when the heavy fuel oil price is at least 275 €/t-oil.

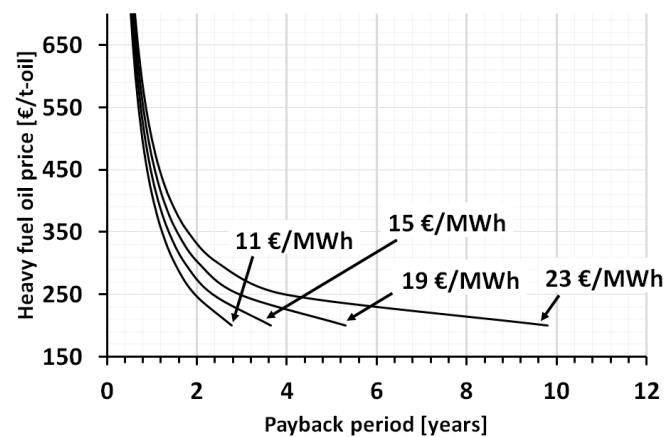


Figure 10. The payback periods when the sawdust prices of 11, 15, 19 and 23 €/MWh are used. The inlet air temperature of the drying air is 80 °C. All other initial values are shown in Table 5.

4. Conclusions

Soot sludge is a waste stream formed in the production process of formic acid and hydrogen peroxide. At present, the moist soot sludge is directly combusted in a boiler with heavy fuel oil in order to enable its combustion. Drying the mixture consisting of the soot sludge and sawdust before burning it in a boiler can result in a decrease of heavy fuel oil consumption. In this study, the characteristic drying curves for the soot sludge and sawdust mixture have been produced in order to evaluate the economy of the soot sludge and sawdust mixture drying in a continuous belt dryer. This economy has been evaluated by calculating the payback period for the dryer investment.

The results obtained show that the shape of the characteristic drying curves is almost linear for both bed heights (200 and 300 mm) regardless of the temperature level (40–100 °C). This indicates that the relative drying rate is independent of the inlet air temperature over the temperature range of 40–100 °C. Furthermore, the results indicate that the characteristic drying curves for both bed heights may also be used to calculate drying times when the inlet air temperature is a little higher than 100 °C. When real drying times are compared with those calculated by the characteristic drying curves, the relative error varies from 0.5% to 3.8%. This denotes that the characteristic drying curves approximate the real drying times with good accuracy.

The results of the economic analysis (base case) show that the drying of the soot sludge and sawdust mixture is economical (payback period is 3 years or less) when the inlet air temperature is 80 °C or more, and the heavy fuel oil price is at least 250 €/t-oil. However, it can be concluded that there is no reason to use a higher drying air temperature than 80 °C, due to the payback periods of the air temperatures from 80 to 120 °C being at the same magnitude. Drying is also economical for inlet air temperatures of 40 °C and 60 °C if the price of the heavy fuel oil is at least 350 €/t-oil. The current price of heavy fuel oil is c. 410 €/t-oil resulting in the drying of the soot sludge and sawdust mixture being cost-effective for all inlet air temperatures (40–120 °C). It is also improbable that the price of the heavy fuel oil would be as low as ~200–300 €/t-oil.

The sensitivity analyses show that the heat, sawdust and emission prices do not have any remarkable influence on the economy of drying if the heavy fuel oil price does not fall below c. 300 €/t-oil. The payback period is less than three years for most cases in the sensitivity analyses.

In conclusion, the results indicate that the drying of the soot sludge and sawdust mixture in a belt dryer is a cost-effective method to upgrade the soot sludge stream to fuel. However, the sticky property of the moist soot sludge and the dustiness of the dry soot may cause some additional challenges.

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Nomenclature

A_{dryer}	cross-sectional area of a continuous-working belt dryer [m ²]
a	specific volumetric heat transfer area/evaporation surface [m ² /m ³]
C_{CO_2}	price of the CO ₂ emissions [€/t-CO ₂]
C_{elec}	price of the electricity [€/MWh]
C_{fuel}	price of the heavy fuel oil [€/t-oil]
C_{heat}	price of the heat [€/MWh]
$C_{sawdust}$	price of the sawdust [€/MWh]
$c_{p,da}$	specific heat capacity of dry air [kJ/kg°C]
$c_{p,w}$	specific heat capacity of water vapor [kJ/kg°C]
h	enthalpy of humid air [kJ/kg _{da}]
$I_{tot,dryer}$	total investment costs of the dryer [€]
l_v	vaporization heat [J/kg]
m_0	drying rate during the constant drying period [kg _{H2O} /(kg _{db} s)]
\dot{m}_{da}	mass flow rate of dry air [kg _{da} /s]
\dot{m}_{db}	mass flow rate of material [kg _{db} /s]
$\dot{m}_{sawdust}$	mass flow rate of sawdust [kg _{db} /s]
\dot{m}_{soot}	mass flow rate of the soot sludge [kg _{db} /s]
$\Delta\dot{m}_{fuel}$	reduced heavy fuel oil consumption [kg/h]
P_{elec}	electricity consumption of the dryer's fans [MW]
P_{oper}	annual operational costs [€/years]
$P_{savings,CO_2}$	annual savings from reduced CO ₂ -emissions [€/years]
$P_{savings,fuel}$	annual savings in fuel consumption [€/years]
$P_{sawdust}$	annual costs of sawdust [€/years]
ΔP_{he+ad}	pressure drop over the plate heat exchanger(s) and the air duct system [Pa]
$\Delta P_{material}$	pressure drop over the material bed [Pa]
ΔP_{pres}	total pressure drop over the dryer configuration/pressure difference [Pa]
q_{oil}	heating value of heavy fuel oil [MJ/kg-oil]
$q_{sawdust}$	lower heating value of sawdust [MJ/kg _{db}]
r	mass ratio (dry basis) of sawdust to soot sludge in the mixture [-]
S_{CO_2}	CO ₂ emission factor of heavy fuel oil [kg-CO ₂ /MWh]
S_{net}	annual net savings [€/years]
T	air temperature [K]
t	air temperature [°C]
t_{wb}	wet bulb temperature [°C]
u	moisture content of material [kg _{H2O} /kg _{db}]

u_1	moisture content of the moist soot sludge [$\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$]
u_2	moisture content of the soot sludge and sawdust mixture after drying [$\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$]
v	velocity of air before the fan(s) [m/s]
x	moisture content of air [$\text{kg}/\text{kg}_{\text{da}}$]
X_{cr}	critical moisture content [$\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{db}}$]
Z	bed height of material inside the dryer [m]
α	heat transfer coefficient for the heat transfer between the bed and drying air in the boundary layer (convective) [$\text{W}/\text{m}^2\text{K}$]
δ_{da}	density of dry air [$\text{kg}_{\text{da}}/\text{m}^3$]
ρ_{bulk}	bulk density of dry material [$\text{kg}_{\text{db}}/\text{m}^3$]
τ	residence time of material inside the dryer/drying time [s]
γ	annual operating time of the dryer [h/years]
\emptyset	heat consumption of the dryer [MW]
η_{fan}	efficiency of the fan(s) [-]
CDC	Characteristic Drying Curve
CHP	Combined Heat and Power plant
da	dry air
db	dry basis
DC	drying curve
PBP	payback period without interest [years]
wb	wet basis
vol-%	volume-%

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