Energy and exergy analyses of an industrial wood chips drying process

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Abstract

In this study, a comprehensive thermodynamic investigation through energy and exergy analyses is conducted to assess the performance of an industrial chips drying process and study how its operating conditions and efficiency can be improved further. In this regard, energy and exergy efficiencies are evaluated with the actual thermodynamic data available, as obtained from the factory, in Turkey. Energy and exergy efficiencies of the drum drying system (DDS) are found as 34.07% and 4.39%, respectively. The analysis results show that exergy efficiency is less than energy efficiency. The main reason of this low exergy efficiency for this drying process is high exergy destruction, as 41.5% of input exergy value. Energy can be recovered via an economizer from hot moist air leaving from the system. If stack gas temperature decreases from 130 to 90°C, regain energy and exergy values are to be 51 976 and 8162 kW, respectively. These recovered potentials can be used for district heating system in winter season and for district cooling system in summer season by using absorption cooling system. Energy and exergy efficiency values can be increased to 93.15 and 43.08%, respectively, by incorporating a heat exchanger into the system.

Keywords: drying; energy; exergy; efficiency; wood

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1 INTRODUCTION

Drying is generally used to remove moisture or liquid from a wet solid by converting this moisture into gaseous state. In most drying operations, water is the liquid evaporated and air is normally employed as purge gas [1].

Although a large number of experimental and theoretical studies are about drying process, few papers have appeared on energy and exergy analyses of drying systems [1–10].

Syahrul *et al.* [1] studied the exergy analysis of fluidized bed drying of moist particles for optimizing the operating conditions and the quality of the products. Dincer and Sahin [2] carried out a new model for thermodynamic analysis, in terms of exergy, of a drying process. Exergy efficiencies are derived as functions of heat and mass transfer parameters. Celma and Cuadros [3] studied the energy and exergy analyses of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer. Midilli and Kucuk [4] studied the energy and exergy analyses of the drying process of shelled and unshelled pistachios using a solar drying cabinet. Ceylan *et al.* [5] investigated the energy and exergy analyses of timber dryer assisted heat pump system. Liu *et al.* [6] studied the exergy analysis for a freeze-drying process. They have used a mathematical model for exergy loss analysis of a freeze-drying process to evaluate the exergy losses in the individual operations and the distribution of exergy losses in a freeze-dryer. Zvolinschi *et al.* [7] studied about the second-law optimal operation of a paper drying machine. Colak and Hepbasli [8] investigated the performance evaluation of a single layer drying process of green olives in a tray dryer using exergy analysis method. Aghbashlo *et al.* [9] presented the energy and exergy analyses of drying process in a semi-industrial continuous band dryer. Liapis and Bruttini [10] studied the exergy analysis of freeze drying of pharmaceuticals in vials on trays.

There are a very few papers about wood chip drying in literature. Lostec *et al.* [11] presented the thermal and economic analysis of a mobile wood chip drying process with an absorption heat pump. Fyhr and Rasmuson [12] made a simulation of the drying of wood chips in superheated steam in their study.

In this study, an industrial wood chips drying process is investigated with a perspective of energy and exergy analysis.

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Energy and exergy analyses are conducted on an industrial drying process for wood chips in order to improve the operating conditions and system efficiency. For that purpose a local wood drying facility in Turkey is chosen. The energy and exergy analyses of industrial wood chips drying process are investigated by using the thermodynamic data obtained from the factory. To the best of authors' knowledge, this kind of study about the energy and exergy analyses of industrial wood chips drying process has never been done before or reported in the literature.

2 SYSTEM DESCRIPTION

In the factory, drum dryer is utilized for wood chips drying. Wood chips are mainly utilized in the furniture industry and interior paneling for ceilings, walls and floors. Basically, drying process can be expressed in three main parts as heating system, drum and high efficiency cyclones. Flow diagram of the drying system is shown in Figure 1. The factory has a co-generation system and produces its electrical need. For electricity production, gas turbine is utilized in the system. Preparation and drying process of the wood chips can be explained in three parts (see Fig. 1): in the first part, exhaust gas which comes from gas turbine is reheated via waste heat boiler system. Exhaust gas enters the heating system at 260°C and heated up to 470°C. In the second part, the wood raw material cut into chips with chipping machine, and then taken into wet chip silos. Wood material and drying air enter the directly heated and automatically controlled drum dryer for drying. In the drying process all temperature, pressure and mass flow data are measured and controlled with an automatic control system. Thermodynamic data are controlled with special computer program during the process. All the data utilized in the calculations were taken from that computer program. Capacity of the drum drying system (DDS) ranges between 10 and 180 t/h (wet product). In the third part, the dried chips are discharged at dropout boxes. Large size wood chips particles can easily be collected in dropout boxes. But small wood chips particles leave from drum with moist air. These small chips should be separated from this moist air. In this regard, high-efficiency cyclones are utilized. After passing through the fan unit, the small particles move to cyclones. Dust separation occurs in the cyclones. Fan blades continually get damaged due to the exposure to small wood chips and moisture, so they are changed after every 6–7 mounts. Finally, moist air leaves from the chimney at about 120–130°C, respectively.

3 ANALYSIS

Drying system is illustrated in Figure 2 with input and output terms. There are four major interactions [2]:

(1) Input of drying air to the drying chamber to dry the products.
(2) Input of moist products to be dried into the chamber.
(3) Output of the moist air containing the evaporated moisture removed from the products.
(4) Output of the dried products, with moisture content reduced to the desired level.

Mass balance equations for the dryer are given as follows:

$$\dot{m}_a h_1 + \dot{m}_p (h_p)_2 + (\dot{m}_w)_2 (h_w)_2 + \dot{W} = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (\dot{m}_w)_4 (h_w)_4 + Q_1$$

$$(\dot{m}_p)_2 = (\dot{m}_p)_4 = \dot{m}_p \text{ (for product)} \quad (1)$$

$$(\dot{m}_a)_1 = (\dot{m}_a)_3 = \dot{m}_a \text{ (for air)} \quad (2)$$

$$\omega_1 \dot{m}_a + (\dot{m}_w)_2 = \omega_3 \dot{m}_a + (\dot{m}_w)_4 \text{ (for water)} \quad (3)$$

An energy balance can be written for the entire system, by equating input and output energy terms:

$$\dot{m}_a h_1 + \dot{m}_p (h_p)_2 + (\dot{m}_w)_2 (h_w)_2 + \dot{W} = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (\dot{m}_w)_4 (h_w)_4 + Q_1 \quad (4)$$

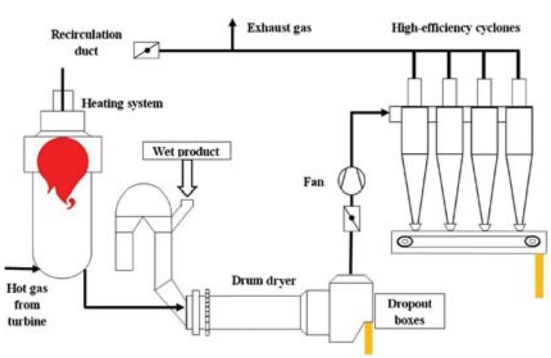

Figure 1. *Flow diagram of the drying system.*

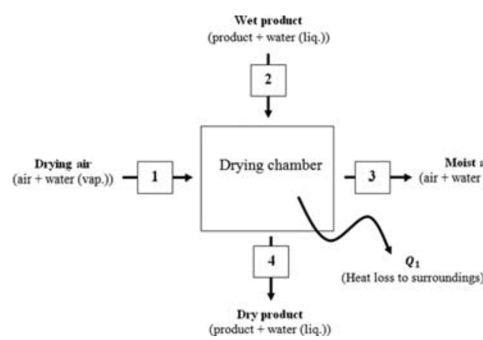

Figure 2. *Thermodynamic illustration of the drying process showing input and output terms.*

where

$$h_1 = (h_a)_1 + \omega_1 (h_v)_1 = (h_a)_1 + \omega_1 (h_g)_1 \quad (5)$$

$$h_3 = (h_a)_3 + \omega_1 (h_v)_3 \quad (6)$$

An exergy balance for the entire system can be written analogous to the energy balance and as follows:

$$\dot{m}_a \mathrm{ex}_1 + \dot{m}_p (\mathrm{ex}_p)_2 + (\dot{m}_w)_2 (\mathrm{ex}_w)_2 + \dot{E}x^w = \dot{m}_a \mathrm{ex}_3 + \dot{m}_p (\mathrm{ex}_p)_4 + (\dot{m}_w)_4 (\mathrm{ex}_w)_4 + \dot{E}x^q + \dot{E}x^d \quad (7)$$

The specific exergy for the flow at Point 1 can be expressed as

$$\mathrm{ex}_1 = [(C_p)_a + \omega_1 (C_p)_v](T_1 - T_0) - T_0 \left\{ [(C_p)_a + \omega_1 (C_p)_v] \ln\left(\frac{T_2}{T_0}\right) - (R_a + \omega_1 R_v) \ln\left(\frac{P_2}{P_0}\right) \right\} + T_0 \left\{ (R_a + \omega_1 R_v) \ln\left(\frac{1 + 1.6078\omega^0}{1 + 1.6078\omega_1}\right) + 1.6078\omega_1 R_a \ln\left(\frac{\omega_1}{\omega^0}\right) \right\} \quad (8)$$

and the specific exergy at Point 3 as

$$\mathrm{ex}_3 = [(C_p)_a + \omega_3 (C_p)_v](T_3 - T_0) - T_0 \left\{ [(C_p)_a + \omega_3 (C_p)_v] \ln\left(\frac{T_3}{T_0}\right) - (R_a + \omega_3 R_v) \ln\left(\frac{P_3}{P_0}\right) \right\} + T_0 \left\{ (R_a + \omega_3 R_v) \ln\left(\frac{1 + 1.6078\omega^0}{1 + 1.6078\omega_3}\right) + 1.6078\omega_3 R_a \ln\left(\frac{\omega_3}{\omega^0}\right) \right\} \quad (9)$$

The specific exergy for the moist products can be written as

$$\mathrm{ex}_p = [h_p(T,P) - h_p(T_0,P_0)] - T_0[s_p(T,P) - s_p(T_0,P_0)] \quad (10)$$

and the specific exergy for the water content as

$$\mathrm{ex}_w = [h_f(T) - h_g(T_0)] + v_f[P - P_g(T)] - T_0[s_f(T) - s_p(T_0)] + T_0 R_v \ln\left(\frac{P_g(T_0)}{x_v^0(P_0)}\right) \quad (11)$$

The exergy flow rate due to heat loss can be expressed as follows:

$$\dot{E}x^w = \left(1 - \frac{T_0}{T_{ave}}\right) Q_1 \quad (12)$$

where T_{ave} is the average outer surface temperature of the dryer.

The heat capacity of wood depends on the temperature and moisture content of the wood but is practically independent of density or species. Heat capacity of dry wood $(C_p)_p$ (kJ/kg K) is approximately related to temperature T (K) by [13]

$$(C_p)_p = 0.1031 + 0.003867 \cdot T \quad (13)$$

3.1 Energy efficiency

Energy efficiency of the drying process is the ratio of energy used for evaporation of moisture in the product to the total energy (including the work done on the system) of the drying air supplied to the system and can be given as

$$\eta = \frac{\text{Energy used for evaporation of moisture in product}}{\text{Energy of drying air supplied} + \text{work}} \quad (14)$$

$$\eta = \frac{(\dot{m}_w)_{ev}[h_3 - h_2]}{\dot{E}_{da} + \dot{W}} \quad (15)$$

3.2 Exergy efficiency

Exergy efficiency of the drying process is the ratio of exergy used in the drying of the product to the total exergy (including the work done on the system) of the drying air supplied to the system. That is,

$$\varepsilon = \frac{\text{Exergy used for evaporation of moisture in product}}{\text{Exergy of drying air supplied} + \text{work}} \quad (16)$$

$$\varepsilon = \frac{(\dot{m}_w)_{ev}[(\mathrm{ex}_w)_3 - (\mathrm{ex}_w)_2]}{\dot{m}_a \mathrm{ex}_1} \quad (17)$$

where

$$(\dot{m}_w)_{ev} = (\dot{m}_w)_2 - (\dot{m}_w)_4 \quad (18)$$

$$(\mathrm{ex}_w)_3 = [h(T_3, P_{v3}) - h_g(T_0)] - T_0[s(T_3, P_{v3}) - s_g(T_0)] + T_0 R_v \ln\left(\frac{P_g(T_0)}{x_v^0 P_0}\right) \quad (19)$$

and

$$P_{v3} = (x_v)_3 P_3 \quad (20)$$

3.3 Specific moisture extraction ratio

The specific moisture extraction ratio (SMER) can be defined as the ratio of mass flow rate of the moist air to the total energy input to the dryer or in other words, the reciprocal of the total energy required to remove 1 kg of water (moisture) from the wet (moist) product. Total energy input to the dryer also includes the fan-motor power [14,15].

$$\mathrm{SMER}_{ds} = \frac{(\dot{m}_w)_{ev}}{\dot{E}_{da} + \dot{W}} \quad (21)$$

3.3 Effect of heat recovery option on system performance

Here we also consider heat recovery option to investigate how adding a heat recovery unit to the facility will change the system performance. In this regard, both energy and exergy efficiency are rewritten as follows:

$$\eta_{\text{improved}} = \frac{\begin{array}{c}\text{Energy used for evaporation of moisture in product}\\ +\text{ energy recovery}\end{array}}{\text{Energy of drying air supplied+work}} \tag{22}$$

$$\varepsilon_{\text{improved}} = \frac{\begin{array}{c}\text{Exergy used for evaporation of moisture in product}\\ +\text{ exergyrecovery}\end{array}}{\text{Exergy of drying air supplied+work}} \tag{23}$$

Table 1. *Data used for the drying process calculations.*

T_0	288 K
P_0	101.3 kPa
x_v^0	0.0113
$(x_v)_3$	0.1691
ω^0	0.007
ω_1	0.009
ω_3	0.1122
R_a	0.287 kJ/kg K
R_v	0.4615 kJ/kg K
$(C_p)_v$	2.12 kJ/kg K (748 K)
	2.01 kJ/kg K (403 K)
$(C_p)_a$	1.004 kJ/kg K (288 K)
	1.014 kJ/kg K (403 K)
	1.087 kJ/kg K (740 K)
$(C_p)_p$	1.217 kJ/kg K (288 K)
	1.507 kJ/kg K (363 K)

4 RESULTS AND DISCUSSION

In this paper, we have presented the energetic and exergetic analyses of the industrial wood chips drying process for the drum dryer, shown in Figure 2. This is the first study about the energy and exergy analyses of industrial wood chips drying process in the literature. Some typical data used in calculation of energy and exergy efficiency are given in Table 1.

The exhaust gas (hot gas) is utilized as energy input for drying process. So, thermodynamic properties of exhaust gas are taken same as that of ideal gas. The Sankey diagram, showing energy input and output terms and energy efficiency values, is drawn for the drying system and given in Figure 3. Also, Grasman diagram, showing input and output exergy values and exergy efficiency, is drawn for the system and given in Figure 4. Energy and exergy values of the inlet drying air are obtained as 90 385 and 20 256 kW, respectively.

The analysis results show that exergy efficiency is less than energy efficiency. Energy and exergy efficiency values of the DDS are found as 34.07 and 4.39%, respectively. The main reason of low exergy efficiency is the high exergy destruction,

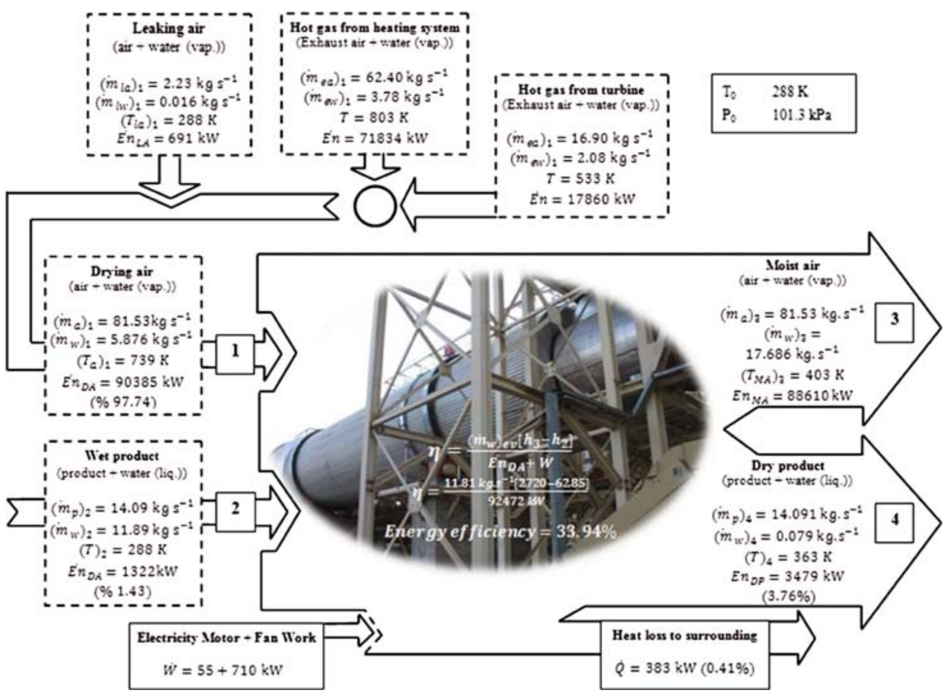

Figure 3. *Input and output energy values and efficiencies for the DDS.*

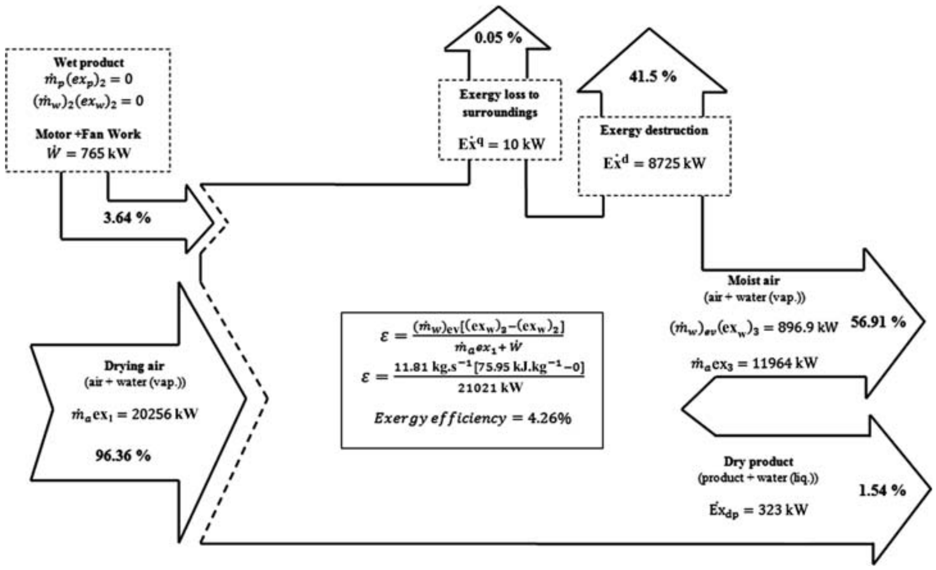

Figure 4. *Exergy flow diagram of the DDS.*

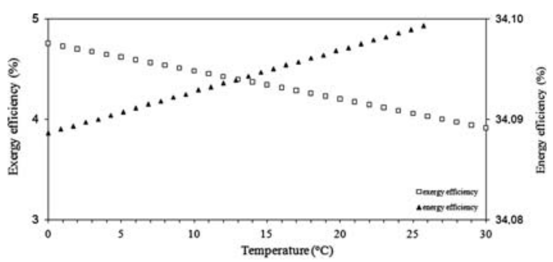

Figure 5. *Variation of exergy and energy efficiencies with reference temperature.*

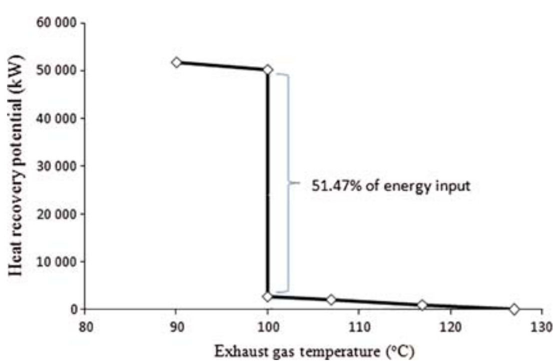

Figure 6. *Variation of heat recovery potential with exhaust gas temperature.*

accounting for 41.5% of the total exergy input in the drying process. The effect of temperature on the energy and exergy efficiencies is shown in Figure 5. It is clear from this figure that exergy efficiency decreases with outdoor temperatures while energy efficiency increases. Also, SMER value for wood chips drying is found as 0.458 kg/kWh.

Furthermore, the heat recovery potential is studied, and its change with exhaust gas temperature is given in Figure 6. From this figure, it is seen that there is a potential to recovery a 51 675 kW of energy when the moist air temperature is reduced from 130 to 90°C. During the phase chance of water in exhaust gas, a huge amount of heat occurs. This is the reason that latent heat of water vapor has a greater effect on increasing energy and exergy efficiency with some small temperature differences.

5 CONCLUSIONS

We can extract some concluding remarks from this study as:

- Energy and exergy efficiency values of the drying system are 34.07 and 4.39%, respectively. System has low exergy efficiency when compared with the energy efficiency. Main reason of low exergy efficiency is exergy destruction. Exergy destruction is 41.5% of input exergy of the drying process.
- Exergy recovery can be achieved in two ways: (i) from the lost exergy to the surrounding and (ii) exergy of the hot moist air. The summation of these two becomes about 56.95% of the total exergy input.
- Energy from moist air can be realized via heat recovery systems. By using heat recovery option there is a potential to save 51 675 kW of energy and to increase energy efficiency to 56.12%. Thus, the overall energy efficiency reaches to 93.16% (out of 37.04 + 56.12%).
- In terms of exergy recovery, it reaches to 8162 kW which brings the overall system exergy efficiency to 43.08%.
- Recovered energy can be used for space heating in the factory office building in winter season and for summer season it can assist for other heating requirements of the

firm. It can also be utilized efficiently for both cooling and heating applications.
- The literature SMER values for wood drying range between 0.382 and 0.543 kg/kWh. The present SMER for this process is found as 0.458 kg/kWh which is consistent with these literature values for wood chips drying.

NOMENCLATURE

C_p specific heat (kJ/kg K)
DDS drum drying system
$\dot{E}$ energy flow rate (kJ/s)
$\dot{E}x$ exergy flow rate (kJ/s)
ex specific exergy (kJ/kg)
h enthalpy, (kJ/kg)
$\dot{m}$ mass flow rate (kg/s)
P pressure (kPa)
P_g saturation pressure of water (kPa)
P_v vapor pressure (kPa)
Q heat transfer rate (kJ/s)
R gas constant (kJ/kg K)
s specific entropy (kJ/kg K)
SMER specific moisture extraction ratio (kg/kWh)
T temperature (°C or K)
v specific volume (m^3/kg)
$\dot{W}$ work rate (kW)
x_v mole fraction of vapor in air
ω humidity ratio of air
η energy efficiency (%)
ε exergy efficiency (%)

Superscripts

0 dead state
q heat
w work

Subscripts

a Air
av Average
d Destruction
da drying air
dp dry product
ds drying system
ea exhaust air
en Energy
ev Evaporation
ew exhaust water
ex Exergy
f saturated liquid state
g saturated vapor state
la leaking air
ma moist air
o reference state
p Product
q heat transfer related
v Vapor
w Water
wp wet product

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