# A Comparative Study on Exergetic Efficiencies of Two Different Drying Processes

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**Abstract:** Food drying is an energy-intensive process. Its energy consumption accounts for 7-15% of the total energy consumption in all industries in developed countries and its thermal efficiency generally varies from 25 to 50%. In this context, studies conducted have focused on improving the efficiencies of processes and drying equipment. Exergy analyses can reveal whether or not and by how much it is possible to design more efficient thermal systems by reducing the sources of existing inefficiencies. In this study, two different food drying systems, tray dryer and fluid-bed dryer systems, were analyzed and compared using energy and exergy analysis methods for performance evaluation purposes. Since the drying of medical and aromatic plants has gained a big importance in the recent years, parsley was selected as the drying material. Drying temperature was in the range of 40-60°C, while drying air velocity varied from 0.5 to 1.5 m/s in the tray drier, and 1.7 to 3.7 m/s in the fluid bed drier. Although fluid bed drying was faster than tray drying for parsley, the exergy efficiency of tray drying was higher than that of fluid bed drying for each temperature and air velocity values studied. Higher temperature and lower velocity led to higher exergy and energy efficiencies in both drying methods. It may be concluded that exergy analysis method may be applied as the effective tool in assessing the performance of various drying processes similar to energy analysis.

**Key words:** Drying, Exergy analysis, Parsley, Tray Dryer, Fluid-bed dryer.

## INTRODUCTION and LITERATURE REVIEW

Drying is an energy-intensive operation that easily accounts for up to 15% of all industrial energy utilization, often with relatively low thermal efficiency in the range of 25–50%. Thus, to reduce energy consumption per unit of product moisture, it is necessary to examine different methodologies to improve the energy efficiency of the drying equipment (Chua et al., 2001).

Exergy analysis is a very useful tool, which can be successfully used in the design of an energy system and provides the useful information to choose the appropriate component design and operation procedure. This information is much more effective in determining the plant and operation cost, energy conservation, fuel versatility and pollution. In the recent years, exergy analysis has been widely used for the performance evaluation of thermal systems. By using exergy analysis method, magnitudes and locations of exergy destructions (irreversibilities) in the whole system are identified, while potential for energy efficiency improvements is introduced.

Exergy analysis method may be used to identify magnitudes and locations of exergy destructions (irreversibilities) in the whole system considered. In evaluating the performance of food systems, energy analysis method has been widely used, while studies on exergy analysis, especially on exergetic assessment of drying process, are relatively few in numbers (Midilli and Kucuk, 2003; Dincer and Sahin, 2004; Akpinar, 2004; Akpinar et al., 2005a,2006). In these previous studies conducted, the drying process was thermodynamically modeled by Dincer and Sahin

(2004), while drying of different products, such as wheat kernel (Syahrul et al., 2003), pistachio (Midilli and Kucuk, 2003), red pepper slices (Akpinar, 2004), potato (Akpinar et al., 2005a), apple slices (Akpinar et al., 2005b) and pumpkin (Akpinar et al., 2006) was evaluated in terms of energetic and exergetic aspects using various drying devices, such as a fluidized bed dryer, a solar drying cabinet, and cyclone type dryers.

The main objective of this paper is to perform an energy and exergy analysis to study energy and exergy efficiencies during fluidized bed drying and tray drying of parsley under different operating conditions.

## MATERIAL and METHOD
### Material

Fresh parsley (Petroselinum crispum) was purchased from a local market in Izmir. The purchased parsley washed with water and then excess water on the surface of parsley was removed with a filter paper. The purchased parsley was processed within 24 hours.

### Methods
### Experimental set-up

Parsley was dried in a laboratory type tray drier (Armfield UOP8, Hampshire, UK), shown schematically in Figure 1. and in a laboratory type fluid bed drier (Sherwood Scientific, Cambridge, UK), shown schematically in Figure 2.

In the tray drier, the drying air velocity was adjusted by an axial flow fan and fan speed control unit. The air was heated with an electric 3 kW heater placed inside the duck and air temperature was controlled by a heater power control unit. Drying compartment dimensions were 0.3 m x 0.3 m x 0.4 m. The drier included 4 sample trays.

In the fluid bed drier, air was drawn through a mesh filter in the base of the cabinet and blown by a centrifugal fan over a 2 kW finned electrical heater and through a stainless steel filter gauze before being delivered to the distributor gauze at the base of the drier body. This distributed the air uniformly to the bed and also supported it. The air blower was controlled by a thyristor circuit to give a smooth vibration over a wide range of motor speeds, and

giving fine control of the drying temperature. The tub unit locked into position on the cabinet top by a simple bayonet fitting. A filter bag was employed to retain any stray particles of the sample being fluidized while allowing the passage of exit gases.

### Drying Procedure and measurements

Parsley was spread onto the trays as a thin layer and drying experiments were carried out at the drying air velocities of 0.5, 1.0 or 1.5 m/s in the tray drier. In fluid bed drier, the drying air velocities were chosen as 1.7, 2.7 or 3.7 m/s. Drying temperatures were 40, 50 or 60 °C for both equipment.

Humidities, temperatures and velocities were measured with robust humidity probes (Testo, 0636.2140, Freiburg, Germany), vane/temperature probes (Testo, 0635.9540, Freiburg, Germany), professional telescopic handle for plug-in vane probes (Testo, 0430.0941, Freiburg, Germany), respectively. Measurements of drying air temperature, velocity and relative humidity were recorded at inlet and outlet holes at every 10 minutes for tray drier and 5 minutes for fluid bed drier. The surface temperature of equipments was measured with a digital multimeter (Metex ME-32, Seoul, Korea) and the surface temperature of parsley during drying was measured with an infrared thermometer with laser sighting (Testo 525-T2, Freiburg, Germany). A digital balance (Scaltec SBA 61, Goettingen, Germany) was used to measure the weight loss of sample during drying experiments. The ambient temperature and the relative humidity were observed and recorded with a multi-function instrument (Testo 350-XL/454, Control unit, Freiburg, Germany).

The sample moisture content is determined with vacuum-oven method (Anonymous,1990). The protein, fat, carbohydrate, ash, fibre contents of parsley were determined $C_p$ is calculated from Eq. (1) (Rahman, 1995);

$$C_p = C_{prot}X_{prot} + C_{fat}X_{fat} + C_{carb}X_{carb} + C_{ash}X_{ash} + C_{fibre}X_{fibre} + C_wX_w$$
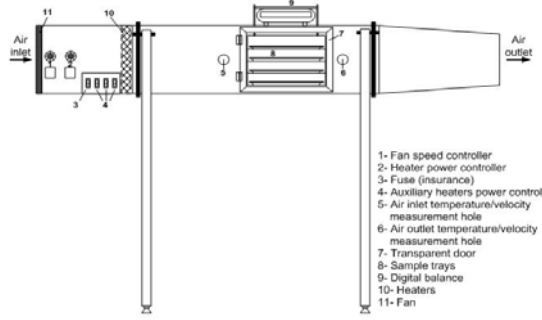
$$(1)$$

**Figure 1. Schematic illustration of the tray drier.**



1 - Control Panel
2 - On/Off Button
3 - Manual Timer Button
4 - Timer Set
5 - Air Velocity Controller
6 - Heater Power Controller
7 - Drying Chamber
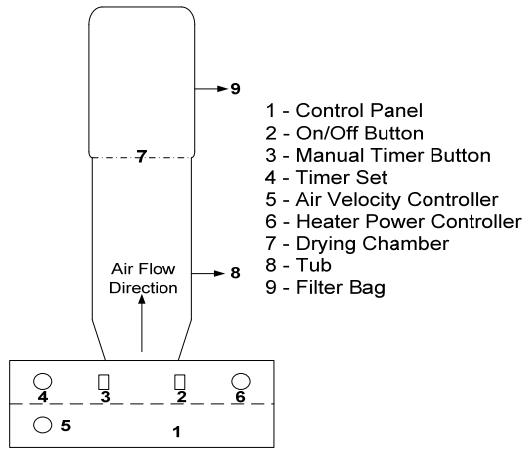8 - Tub
9 - Filter Bag

**Figure 2. Schematic illustration of the fluid bed drier.**

## MODELING and ANALYSIS

Mass, energy and exergy balances were employed to find heat inputs, rates of exergy destructions, and energy and energy efficiencies. Steady-state, steady-flow processes were assumed. A general mass balance can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

where $\dot{m}$ was the mass flow rate, and the subscript in stands for inlet and out for outlet.

Energy and exergy balances, equating total energy (energy) inputs to total energy (energy) outputs were written as

$$\dot{E}_{in} = \dot{E}_{out} \tag{3}$$

The specific flow exergy of refrigerant, air or water was evaluated as

$$\psi_{r,w} = (h - h_0) - T_0(s - s_0) \tag{4}$$

The enthalpy and entropy of air were calculated from the following equations, respectively (Schmidt et al., 1998).

$$h = C_p T + \omega h_{fg} \tag{5}$$

$$s = C_{p,air} \ln \frac{T}{T_0} - R_{air} \ln \frac{P_0 - RH.P''}{P_0} + \omega \left( s'' - R_w \ln RH \right) \tag{6}$$

The exergy rate was determined as

$$\dot{Ex} = \dot{m}\psi \tag{7}$$

where h was enthalpy, s was entropy, and the subscript zero indicated properties at the dead (reference) state (i.e., at $P_0$ and $T_0$).

Energy efficiency of the dryer column was derived by using the energy balance equation. The thermal efficiency of the drying process was defined as (Syahrul, et. al., 2002):

$$\eta_E = \frac{\text{Energy transmitted to the solid}}{\text{Energy incorporated in the drying air}} \tag{8}$$

$$\eta_E = \frac{W_d \left[ h_{fg}(M_{p1} - M_{p2}) + cm(T_{m2} - T_{m1}) \right]}{mda(h_1 - h_0)\Delta t} \tag{9}$$

The rate of exergy transfer due to evaporation in the dryer was:

$$E_{evap} = \left(1 - \frac{T_0}{T_m}\right) m_w h_{fg} \tag{10}$$

where $\dot{m}_w$ was the moisture in kg water per hour.

The exergy efficiency was expressed as the ratio of total exergy output to total exergy input:

$$\varepsilon = \frac{\dot{Ex}_{output}}{\dot{Ex}_{input}} \tag{11}$$

where "output" referred to "net output" or "product" or "benefit" or "desired value", and "input" referred to "driving input" or "fuel".

The exergy efficiency of the dryer can be defined as the ratio of exergy output to exergy input. The product was only the rate of exergy evaporation process and the fuel was exergy rate of drying air entered the dryer column, the exergy efficiency on the basis of the exergy rate balance was given as:

$$\eta_{Ex} = \frac{E_{evap}}{E_{da1}} \tag{12}$$

where $E_{evap}$ was the rate of exergy evaporation (kJ·s$^{-1}$) and $E_{da1}$ was the rate of exergy drying air entering the drying column (kJ·s$^{-1}$).

To evaluate the effects of temperature and velocity on drying time statistically, SPSS 11.0.1 statistical

package was used (SPSS, 2001). The confidence level was 95%.

Since the initial moisture content of parsley used in the experiment under various inlet air conditions was different, comparison of drying time and efficiency in terms of absolute moisture content might be misleading. Since the normalized moisture content provided a more meaningful way of interpreting the data, it was used to analyze data (Figures 3 and 4). Normalized moisture was calculated by dividing the moisture of the parsley to moisture of the raw parsley (Eq.13);

$$\text{Normalized moisture} = \frac{Mp}{Mp_i} \qquad (13)$$

## RESULTS and DISCUSSION

### Effect of temperature on energy and exergy efficiencies

The inlet temperature of drying air significantly influenced the drying time of parsley ($p < 0.05$) (Figures. 3 and 4).  Increasing the temperature effectively reduces the moisture content of particles for the same period of drying time.

On the other hand, drying processes in the fluid bed dryer were faster than those of the tray drier, due to either higher velocities reached at the same temperature and the efficient contact of drying air with the material surface at fluid bed drier.

To compare the performance of drying methods, energy and exergy efficiencies were analyzed. The energy efficiencies were found to be higher than exergy efficiencies for both drying method (Figures 5 and 6). As the temperature increased the enthalpy of the drying air for the same period of time increased. These differences at the initial stage of drying were higher than that of the final stage. Similarly, the entropy of drying air was also increased with temperature, thus led to higher energy and exergy efficiencies (Figures 5 and 6). The final temperature of the material after long time became almost equal to the temperature of inlet drying air.

Although fluid bed drying was faster than tray drying for parsley, the energy and exergy efficiency in the tray drier was found to be higher than those of in the fluid bed drier, for drying temperature range studied. It could be due to differences in mechanical configuration of both driers, heat losses occurred during drying in two different drying systems, etc. It

was recommended that energy and exergy efficiencies of these systems could be useful to compare the performance of different drying systems rather than comparing drying times lonely.
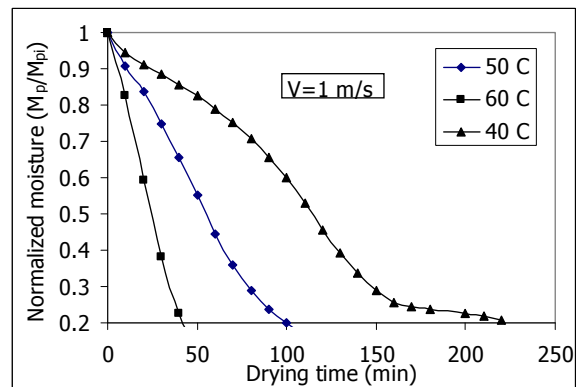


**Figure 3. Effect of inlet air temperature normalized moisture content vs drying time in the tray drier.**
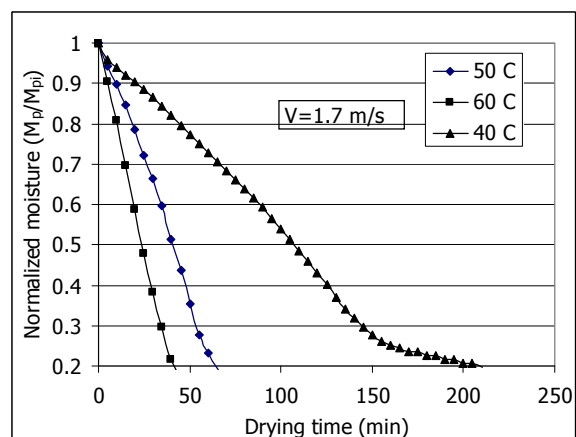


**Figure 4. Effect of inlet air temperature on normalized moisture content vs drying time in the fluid bed drier.**

### Effect of air velocity on energy and exergy efficiencies

Figures 7 and 8 illustrate the effect of air velocity on drying time and efficiency of the dryers, respectively. For the same temperatures, energy and exergy efficiencies were highest for lowest air velocities in both drying methods. On the other hand, exergy efficiencies at other velocities for each drying method were close to each other. It was concluded that it would be advantageous to use an air velocity higher than the minimum fluidization velocity at the first drying stage, and to reduce it later to the lowest value to increase the system performance.
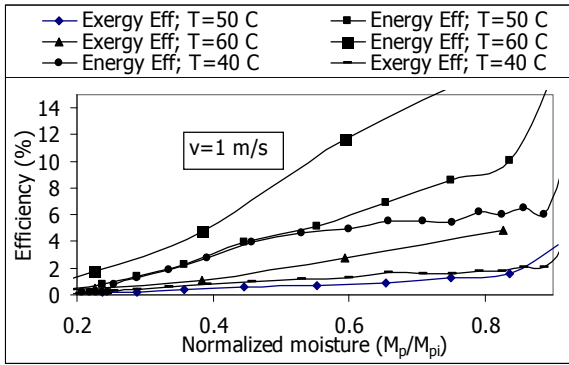
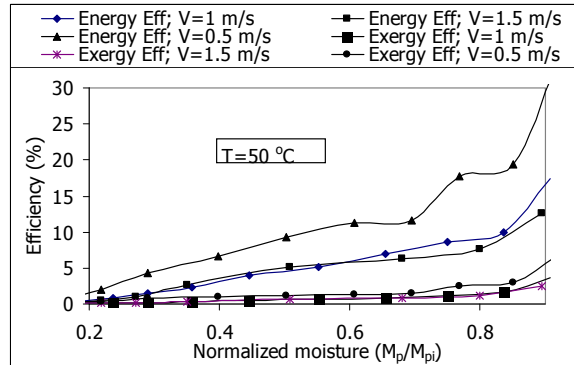**Figure 5.** Effect of inlet air temperature on efficiency vs. normalized moisture in the tray drier.



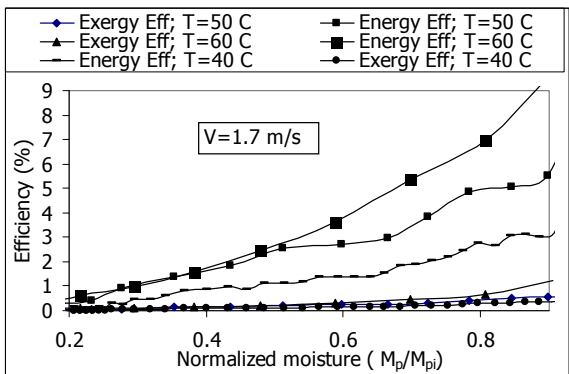**Figure 7.** Effect of gas velocity on efficiency vs. normalized moisture in the tray drier.



**Figure 6.** Effect of inlet air temperature on drying time versus normalized in the fluid bed drier.
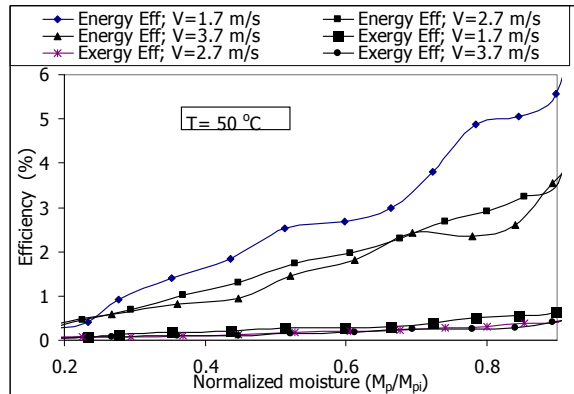


**Figure 8.** Effect of gas velocity on efficiency vs. normalized moisture in the fluid bed drier.

## CONCLUSIONS

Main conclusions drawn from the results of the present study may be listed as follows:

a) Energy efficiencies were higher than exergy efficiencies for both drying methods.

b) Although fluid bed drying was faster than tray drying for parsley, exergy efficiency of the tray drying was higher than that of the fluid bed drying for each temperature and air velocity studied.

c) Higher temperature and lower velocity led to higher exergy and energy efficiencies in both drying methods.

## REFERENCES

Anonymous (1990). *Dry matter content*. In K. Helrich (Ed.) Official Methods of Analysis of the Association of Official Analytical Chemists, Method No. 920.151, A.O.A.C, Inc., U.S.A.

Akpinar EK, 2004. Energy and exergy analyses of drying of red pepper slices in a convective type dryer. Int. Comm. Heat and Mass Transfer, 31(8): 1165-1176.

Akpinar, E. K., Midilli, A. and Bicer, Y., 2005a. Energy and exergy of potato drying process via cyclone type dryer. Energy Conversion and Management. 46(15-16): 2530-2552.

Akpinar, E. K., Midilli, A. and Bicer, Y., 2005b. Thermodynamic analysis of the apple drying process. Proc. IMechE Part E: J. Process Mechanical Engineering. 219:1-14.

Akpinar, E. K., Midilli, A. and Bicer, Y., 2006. The first and second law analyses of thermodynamic of pumpkin drying process. Journal of Food Engineering. 72(4): 320-331.

Chua, K.J, Mujumdar, A.S, Hawlader, M.N.A, Chou, S.K and Ho, J.C., 2001. Batch Drying of Banana Pieces-effect of Stepwise Change in Drying Air Temperature on Drying Kinetics and Product Colour. Food Research International. Sayı: 34, 721-731.

Dincer, I. and Sahin, A. Z., 2004. A new model for thermodynamic analysis of a drying process. International Journal of Heat and Mass Transfer. 47: 645-652.

Hawlader MNA, Jahangeer KA. 2006. Solar heat pump drying and water heating in the tropics. Solar Energy. 80:492–499.

Midilli, A. and Kucuk, H., 2003. Energy and exergy analysis of solar drying process of pistachio. Energy. 28: 539-556.

Rahman, S. (1995). Food properties handbook. US: CRC Press, 225–271.

Syahrul S, Dincer I, Hamdullahpur F., 2003. Thermodynamic modeling of fluidized bed drying of moist particles. International Journal of Thermal Sciences. 42: 691–701.

Syahrul, S., Hamdullahpur, F. and Diner, I., 2002. Exergy analysis of fluidized bed drying of moist particles. Exergy. an International Journal. 2 87–98.

Schmidt, E.L., Klöcker, K., Flacke, N. and Steimle, F., 1998. Applying the transcritical CO2 process to a drying heat pump. Int. J. Refrig. Vol. 21(3): 202-211.

Kang, Y., S. Nishiyama, 1996. Analysis of Microirrigation Systems Using a Lateral Discharge Equation. Transactions of the ASAE 39 (3): 921-929.