Thermodynamics Analysis of The Experimental Freeze Drying System

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Abstract: The drying process is an area with high energy consumption in the sector. The freeze-drying process carried out at low vapour pressure involves a longer drying time than other drying systems; therefore, it involves significant energy consumption. Aim should be to reduce time and energy consumption while maintaining the quality of the sample. In this study, energy and exergy analysis of an experimental freeze-drying system were made. Thus, it will be possible to integrate this system with other drying systems, to reduce energy consumption and to increase energy efficiency.

Deneysel Dondurarak Kurutma Sisteminin Termodinamik Analizi

Anahtar Kelimeler
Dondurarak kurutma,
Enerji,
Ekserji

Özet: Kurutma işlemi enerji tüketimi yüksek olan bir sektördür. Düşük buhar basıncında gerçekleştirilen dondurarak kurutma işleminde, diğer kurutma sistemlerinden daha uzun bir kuruma süresi söz konusudur. Bu nedenle, enerji tüketimi fazladır. Kurutma işleminde amaç, numunenin kalitesini korurken zaman ve enerji tüketimini azaltmak olmalıdır. Bu çalışmada deneysel bir dondurarak kurutma sisteminin enerji ve ekserji analizi yapılmıştır. Böylece bu sistemi diğer kurutma sistemleriyle entegre etmek, enerji tüketimini azaltmak ve enerji verimliliğini artırmak mümkün olabilecektir.

1. Introduction

Freeze drying is a drying technology proper for heat-sensitive materials. For this reason, it operates at low pressure and temperature. The freeze-dried products have gained many benefits such as decreasing the chemical alteration during food depot and therefore longer shelf life, more accessible transportation, and packaging, besides producing an excellent quality dried product [1-5]. The main disadvantage of freeze-drying is that it involves an extended drying time compared to other drying systems; therefore, it has a significant energy consumption compared to other drying systems [6, 7]. The success of the drying process depends on many freeze-drying conditions, including vacuum pressure, material flow rate, raw material type, cycle process.

The freeze-drying process is made of three main steps: freezing, primary drying, and secondary drying. The freezing process described by proceeding the drying stage can be carried out in the freeze-drying unit or an out freezer

In this process, the shelf temperature is reduced to a temperature at which converting the water into ice, and the sample usually contains 15–20% unfrozen water. Then the shelf temperature is increased to about 2–3°C below the sample collapse temperature. This process is carried out in the primary drying (sublimation drying). In primary drying, almost 45% of the total energy required for drying is used [8]. Next, the temperature is continued to increase to remove the unfrozen water by desorption in the secondary drying process [9, 10]. The vacuum applied during the drying process is shorten the drying time, and it carried out the sublimation process. Significant energy consumed during the freeze-drying is consumed during the vacuum process [11]. Thought the dried product quality, energy consumption in the freeze-drying process could be unimportant. [12, 13].

2. Thermodynamic Analysis

Since the drying is not a fixed process, energy efficiency alters throughout the drying during. The specific moisture extraction rate (SMER) is generally used as a determiner to decide the performance of the dryer [14, 15].

$$\text{SMER} = \frac{\text{Mass of Moisture Removed from the Product}}{\text{Energy Consumed}} = \frac{(m_p)_{input} - (m_p)_{output}}{W_{input}} \quad (1)$$

SMER indicates the quantity of water removed for 1 kWh of energy. High SMER value means low operational costs and will be quickly amortizing the initial investment [15, 16].

SPC is uttered as specific power consumption.

$$\text{SPC} = \frac{\text{Energy Consumed}}{\text{Mass of Moisture Removed from the Product}} = \frac{1}{SMER} \quad (2)$$

The moisture extraction rate (MER), which utters the mass of moisture removed from the dryer per unit time, is determined as follows:

$$\text{MER} = \frac{\text{Mass of Moisture Removed from the Product}}{\text{Drying Time}} = \frac{(m_p)_{input} - (m_p)_{output}}{t_{process}} \quad (3)$$

In the thermodynamic analysis of the freeze-drying system, the system can simulate the three main interactions of the chamber with the input and output terms. (Fig.1). The moist product enters the chamber from 2 parts, and the dry product comes out from 4 parts. The humid air removed from the product leaves the chamber from 3 parts.

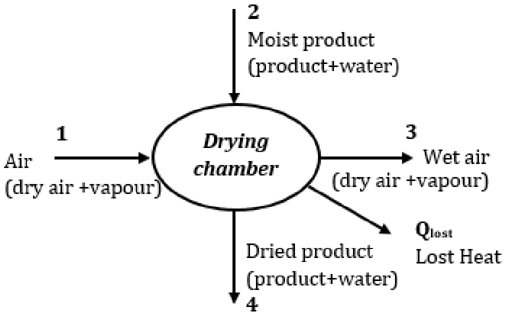

Fig.1. The drying process [17]

The energy analysis is carried out according to the general mass and energy equations. Data of the freezing temperature, the drying temperature and pressure, the energy inflows and outflows, the mass of the removed moisture are required for energy analysis. Energy balance of the complete system can be written as [17-20]:

$$(m.h)_{air,1} + (m.h)_{product,2} + (m.h)_{water,2} = (m.h)_{air,3} + (m.h)_{product,4} + (m.h)_{water,4} + \dot{Q}_{lost} \quad (4)$$

The input energies of the drying chamber are the fan, cooling machine, electric water heating and circulation pumps.

$$W_{input} = W_{vacuum} + W_{heat} + W_{fan} + W_{cool} \quad (5)$$

Heat energy output from the system:

$$Q_{output} = Q_{heater} + Q_{product} + Q_{condensation} \quad (6)$$

If the heat losses caused by the insulation of the drying chamber are neglected; at the first start of the heating process, the required heat energy for heating the air inside is specified as follow [19]:

$$Q_{heater} = V\rho C_p(T_{surface} - T_o) \quad (7)$$

The index "0" in equation represents its value in the outdoor environment reference point (dead state). Heating the water to be removed from the product:

$$Q_{product} = m_{product}C_p(T_{product} - T_o) \quad (8)$$

The input and output air the drying cabinet is humid air. Therefore, the enthalpy of air is determined as kJ / kg dry air as [19]:

$$h = h_{air} + \omega h_{vapor} \quad (9)$$

$$h_{air} = C_p T_{air} \quad (10)$$

We can find the efficiency of the drying system by proportioning the energy output to the energy input. According to this;

$$\eta_{all} = \frac{Q_{output}}{W_{input}} \quad (11)$$

Exergy analysis is calculated from the first law energy balance using data of during drying operation [20]. The exergy analysis of the freeze-drying is based on the general exergy equation. In calculating exergy losses, exergy losses in the drying air and exergy losses in the products are separately calculated. Total exergy expression;

$$\dot{Ex} = \dot{m}_{product}[(h - h_o) - T_o(s - s_o)] \quad (12)$$

The exergy balance of the system in the drying process can be written as follows [17];

$$(m.ex)_{air,1} + (m.ex)_{product,2} + (m.ex)_{water,2} = (m.ex)_{air,3} + (m.ex)_{product,4} + (m.ex)_{water,4} \quad (13)$$

The exergy efficiency can be inscribed as the ratio between the loss exergy and the input exergy. It could be written as follows [22].

$$\eta_{Ex} = \frac{Input\ exergy - Exergy\ loss}{Input\ exergy} = 1 - \frac{\dot{E}x_{loss}}{\dot{E}x_{Input}} \qquad (14)$$

3. Analysis Results

The quality of the product during drying is maintained, while it is very important to reduce time and energy consumption. The freeze-drying process need a longer drying time because it carried out at low vapour pressure [23]. The compressor and vacuum units of the freeze-dryer are the parts where the system consumes the most energy [24]. In freeze-dryer, the value of energy consumption at different pressures and temperatures for mint leaves is given in Fig 2. While the drying temperature and chamber pressure are increased, the energy consumption of the vacuum pump is decreased. Total energy consumption in freeze dryer is decreased due to decreasing pressure and increasing temperature. In the process of high drying temperatures, drying times are reduced, but damage to the physical and chemical structure of the product increases. The optimum drying temperatures for products should be specified experimentally [25]. Improving exergy efficiency reduces the energy needed by systems in many areas.

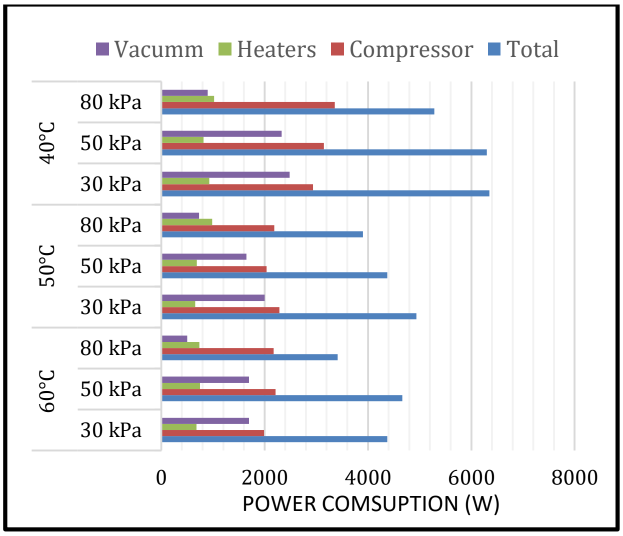

Fig.2. The energy consumption at different temperatures and pressures in the freeze dryer for mint leaves [25].

Exergy analysis increases exergy efficiency by decreases the irreversibility in the freeze-dryer [17, 26, 27]. Generally, exergy losses of the freeze-dryer minimize at high temperature and low chamber pressure.

The exergy efficiency during drying time for mint leaves is given in Fig.3. Exergy efficiency has decreased due to exergy losses at the beginning of drying. As the drying process continued, the exergy efficiency is continued to increase. While the moisture content of mint leaves is reduced, the amount of energy needed for freeze-dryer is reduced; consequently exergy efficiency increases.

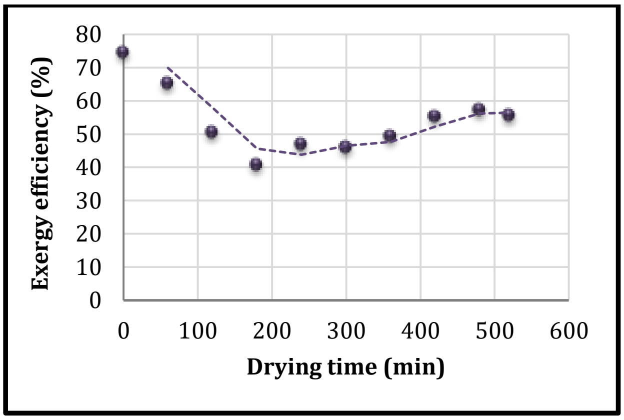

Fig.3. The exergy efficiency during drying time in the freeze-drying for mint leaves [25].

4. Conclusion

The drying process is an area with high-energy depletion in the sector. In the drying systems, our aim should be not only to obtain quality products but also energy efficiency. Therefore, given the amount of energy needed by the freeze-drying system, integrating this system with other drying systems may be the appropriate method for reducing energy consumption and increasing energy efficiency. One way to reduce exergy losses during freezing is to adjust the cooling source to optimal temperature. At the same time, operating at the minimum chamber pressure suitable for the system is reduced energy consumption. Consequently, the studies of energy and exergy analysis of drying methods should be developed.

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Nomenclature

C_p : Specific heat, kJ/kg
h : Enthalpy, kJ/kg
m : Mass, kg
T : Temperature, °C
Q : Heat transfer, kJ
V : Volume of the chamber, m^3
W : Power, kW
Ex : Exergy, kJ
ρ : Density, kg/m^3
ω : Specific humidity, kg_{air}/kg_{water}
η : Efficiency

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