Exergy analysis of encapsulation of photochromic dye by spray drying

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Abstract. Application of exergy analysis methodology for encapsulation of photochromic dyes by spray drying was presented. Spray drying system was investigated considering two subsystems, the heater and the dryer sections. Exergy models for each subsystem were proposed and exergy destruction rate and exergy efficiency of each subsystem and the whole system were computed. Energy and exergy efficiency of the system were calculated to be 5.28\% and 3.40\%, respectively. It was found that 90\% of the total exergy inlet was destroyed during encapsulation by spray drying and the exergy destruction of the heater was found to be higher.

1. Introduction
Efficient use of natural resources such as energy and water is one of the main prerequisites of sustainable development to protect our common future. Therefore, energy consumption of industrial processes, particularly thermal systems, should be analysed and possible energy saving measures should be investigated. Exergy analysis methodology is an effective method based on the evaluation of thermodynamic losses follows from the Second Law [1]. Exergy is defined as “the work potential of a system in a specified environment” and represents the maximum amount of useful work that can be obtained as the system is brought to equilibrium with the environment [2]. It can be used as an essential tool for system design, analysis and optimisation of thermal systems [3].

Textile production processes have high rates of energy consumption, and even higher when technical and functional properties are desired. UV protection is an important class of these functional properties of late years due to global warming and ozone layer depletion. Recently the use of photochromic dyes to develop UV protective textile materials has been appeared in research phase, in which the first results were presented by the authors of present contribution [4]. Direct application of photochromic dyes onto textile materials is problematic due to insolubility in water, low heat resistance and poor wash fastness. Thus, photochromic dyes for textiles can be produced in encapsulated form to overcome these problems. Within various encapsulation methods, spray drying method is often used for industrial applications. The process of spray drying is also a thermal process since it is based on drying. Drying processes are energy-intensive with a great industrial significance. Moreover, it has been reported that spray drying is the most energy-intensive drying method subsequent to freeze drying [5]. Therefore, to reveal an optimum and sustainable photochromic textile production process, investigation of exergy efficiency of spray drying during production of phochromic microcapsules is of importance as well as product properties such as microcapsule yield, homogeneity and dimensions of microcapsules and colour build-up properties when applied onto photochromic textiles.
Although numerous studies have been performed on the exergy analysis of drying processes, studies on the exergy analysis of spray drying process are still limited. Exergy analysis of fish oil encapsulation [6-10], cheese powder production [11-14], drying of milk droplets [15] and drying of cornelian cherry puree [16] by spray drying have been appeared in the literature. Besides, application of exergy analysis methodology to the encapsulation of photochromic dyes by spray drying has been carried out for the first time in this study.

2. Method and Analysis
A spirooxazine based photochromic dye was encapsulated with ethyl cellulose using laboratory scale spray dryer (Buchi B-290). 3% w/v photochromic dye and 3% w/v ethyl cellulose were dissolved in water/ethanol mixture (80/20%). During spray drying, prepared solution was fed to the spray dryer, atomised into the drying cabinet through which a stream of hot air (150 °C) passes and microcapsules were produced. Mass flow rate of drying air and feeding rate of the solution was set to be 95% and 10%, respectively.

Exergy analysis of spray dryer system was investigated considering two main subcomponents, namely heater and drying cabinet as shown in Figure 1. The following assumptions were made during the analysis:
- All processes are steady-state with negligible kinetic and potential energy effects.
- Heat transfer to the system and work transfer from the system are positive.
- Air is considered as an ideal gas with a constant specific heat.
- Temperature and pressure of the dead state were taken as the mean ambient conditions (24 °C, 101.325 kPa)
- Electrical efficiency of heater was assumed as 99%.

Figure 1. Control volume model of the spray dryer

Considering the assumptions above, mass, energy and exergy balances for any steady-state system can be written as

\[ \sum \dot{m}_i = \sum \dot{m}_e \] \hspace{1cm} (1)
\[ \sum \dot{E}_i = \sum \dot{E}_e \] \hspace{1cm} (2)
\[ \sum \dot{E}_i - \sum \dot{E}_e = \sum \dot{E}_d \] \hspace{1cm} (3)

The specific exergy was calculated as in equation (4), where \( h \) is the specific enthalpy, \( s \) the specific entropy and the subscript zero indicates properties at the dead state.

\[ e = (h - h_0) - T_0(s - s_0) \] \hspace{1cm} (4)
The exergy rate of each stream was evaluated as

$$\dot{E} = \dot{m} \cdot e$$  \hspace{1cm} (5)

Exergy balance equations for heater and dryer sub-system of the spray dryer were calculated according to equations (6) and (7), respectively, considering the notations of each stream given in Figure 1.

$$\dot{W}_1 + \dot{\cal E}_x_2 = \dot{\cal E}_x_3 + \dot{\cal E}_{x,d,e}$$  \hspace{1cm} (6)

$$\dot{\cal E}_x_3 + \dot{\cal E}_{x,4} + \sum \dot{\cal E}_{x,5} + \dot{W}_c + \dot{W}_1 = \sum \dot{\cal E}_{x,7} + \sum \dot{\cal E}_{x,9} + \dot{\cal E}_{x,4} + \dot{\cal E}_{x,d,d}$$  \hspace{1cm} (7)

Mass flow rate of drying air, compresses air and solution were taken from the device catalogue depending on the machine settings. The inlet and outlet drying air temperatures were obtained directly from the screens of the device. Spray dryer surface temperature and material temperatures were measured with an IR thermometer (Proscan 520). Other data was calculated by the energy balance equations. Thermodynamic properties of air, water and ethanol were obtained from thermodynamic tables. Enthalpy and entropy values for water vapour and ethanol vapour were calculated according to equations (8) and (9), where $T_m$ is the mean material temperature, $h_{fg}$ and $s_{fg}$ are the enthalpy and entropy of vaporisation at mean material temperature, respectively.

$$g = c_p,f(T_m - T_c) + f(T_m, P) + c_p,g(T_g - T_g)$$  \hspace{1cm} (8)

$$s_g = c_p,f l_h \frac{T_m}{T_c} + s_f(T_m, P) + c_p,g l_i \frac{T_m}{T_m}$$  \hspace{1cm} (9)

Specific exergy of air was calculated as follows [1]:

$$e = c_p(T - T_0) - T_0(c_p l_h \frac{T}{T_0} - R \frac{P}{P_0})$$  \hspace{1cm} (10)

Prepared solution and resultant capsules contain ethyl cellulose and photochromic dye. It is stated in the literature that the change in the solids content in the spray drying process has no effect on the exergy parameters [9, 16]. Hence, since the specific heat of photochromic dye is unknown, the exergy change in the photochromic dye was neglected in the exergy analysis.

Exergy efficiency of dryers depends on the ratio of the exergy use in the drying of the product to the exergy supplied to the system. The product term is the exergy rate of the evaporated fluids (water and ethanol in this case). Exergy supply is the sum of the electric power and the compresses air entering the system. Therefore, the total exergy efficiency of the spray dryer system was calculated as in equation (11) [17].

$$\varepsilon_t = \frac{\sum{\dot{\cal E}_x}_f}{\sum{\dot{\cal E}_x}_t} = \frac{\sum{\dot{\cal E}_x}_f}{\dot{W}_1 + \dot{W}_c + \dot{W}_1 + \dot{\cal E}_{x,4}}$$  (11)

$$\dot{\cal E}_{x,f} = (1 - \frac{\gamma_c}{\gamma_m}) \dot{\cal Q}_f$$  \hspace{1cm} (11a)

$$\dot{\cal Q}_f = \dot{m}_w \cdot c_pW + \dot{m}_e \cdot c_pW$$  \hspace{1cm} (11b)

Exergy efficiency of each sub-system (heater and dryer) was calculated as follows:

$$\varepsilon_{he} = \frac{\dot{\cal E}_{x,f} + \dot{\cal E}_{x,3}}{\dot{W}_1}$$  \hspace{1cm} (12)

$$\varepsilon_d = \frac{\sum{\dot{\cal E}_x}_f}{\sum{\dot{\cal E}_x}_t} = \frac{\sum{\dot{\cal E}_x}_f}{\dot{\cal E}_{x,3} + \dot{\cal E}_{x,4}}$$  \hspace{1cm} (13)

Energy efficiency of the system was calculated by the ratio of the energy required to evaporate the water and ethanol to the energy inlet.

$$\eta = \frac{\dot{Q}_f}{\dot{E}_i}$$  \hspace{1cm} (14)
Sustainability index, proposed by Rosen et al. [18] was calculated according to equation (15). This relationship shows how the change in the exergy efficiency of a process or a system influences sustainability.

\[ \varepsilon = 1 - \frac{1}{S} \]  

(15)

3. Results and Discussion

Exergy performance parameters of total system and comparison of the sub-systems were given in Table 1. Grassmann (exergy loss and flow) diagram of the system was illustrated in Figure 2. As can be seen from the Grassmann diagram, the exergy destruction in the system was quite excessive. 90% of the total inlet exergy flow was destroyed. In the heater, drying air is heated by an electric heater and this stage 84% of the inlet exergy flow was destroyed. Heated drying air flows through the drying chamber where it is in contact with the process solution sprayed by compressed air. In the drying chamber, the water and ethanol in the process solution was evaporated to obtain capsules, in which 73% of the inlet exergy flow (exergy of hot air, compressed air and electric energy) was destroyed. Finally, the exhaust air (together with the water vapour and ethanol vapour) was discharged as an exergy loss stream. Total exergy losses of the system including heat losses from the surfaces were found to be approximately 7% of the inlet exergy flow.

Table 1. Exergy performance parameters of spray drying system

|        | \( \dot{E}_{x_i} \) | \( \delta \) | \( RI \) | \( \eta \) | \( \varepsilon \) | \( SI \) | \( \dot{E}_{x_{I,a}} \) | \( \dot{E}_{x_q} \) | \( \dot{E}_{x_i} \) |
|--------|-------------------|------|-------|--------|-----------|-------|-----------------|----------------|--------|
| Heater | 1.30              | 0.84 | 0.71  | 16.47  | 1.20      | 1.56  | 1.20            | 0.71           | 2.01   |
| Dryer  | 0.52              | 0.73 | 0.29  | 9.63   | 1.11      | 0.71  |
| Total system | 1.82          | 0.90 | 1.00  | 5.28   | 3.40      | 0.126 | 0.065 | 2.01 |

Figure 2. Grassmann diagram of spray dryer system for photochromic dye encapsulation

It was found that most of the exergy destruction (71%) occurred in the heater. Electric energy is a form of high-quality energy. As a result of the heating process, the electric energy was transformed into thermal energy and its quality was greatly reduced. For this reason, the destruction in the heater part was large. Although the exergy destruction in heater was high, exergy efficiency was found to be higher compared to dryer. In the heating section, the resultant product is a high temperature air stream. On the other hand, in the dryer, the exergy of hot air stream was used for evaporation and the exergy is destroyed due to the irreversible heat transfer. The resulting product is also low in exergy content.

Although the rate of exergy loss and exergy efficiency of the heater and dryer sections vary greatly, the sustainability indices are very close. The sustainability index of a system can be at least 1. As shown in Table 1, the sustainability index of both the individual system parts and the total system is very close to 1. This demonstrates the importance of efforts to increase the efficiency of spray dryers.
4. Conclusion

Exergetic modelling of photochromic dye encapsulation by spray drying was investigated and exergy analysis methodology was presented. Exergy parameters of sub-systems and whole drying system were revealed. Exergy destruction of the heater section was found to be higher. Total system energy and exergy efficiency was found to be 5.28% and 3.40%, respectively. When the thermal inefficiency of drying processes is considered, low exergy efficiency values are expected. At this point, it is important for the machine manufacturers to introduce machine designs to reduce exergy destruction and improve exergy efficiency. On the other hand, for machine users, it is necessary to determine the optimum process conditions at which the highest exergy efficiency can be achieved. Preliminary results showed that the decrease in drying air temperature and mass flow rate decreased the exergy destruction rate and increased exergy efficiency of the system. Thus, further research on the effects of the process parameters on the exergy performance parameters of photochromic dye encapsulation process by spray drying was planned to be investigated as a continuation of this study.

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Nomenclature

- \(c_p\): specific heat (kJ/kgK)
- \(ex\): specific exergy (kJ/kg)
- \(\dot{E}x\): exergy rate (kJ/s)
- \(h\): enthalpy (kJ/kg)
- \(\dot{m}\): mass flow rate (kg/s)
- \(P\): pressure (kPa)
- \(\dot{Q}\): heat flow rate (kJ/s)
- \(R\): gas constant (kJ/kgK)
- \(RI\): relative irreversibility
- \(s\): entropy (kJ/kgK)
- \(SI\): sustainability index
- \(T\): temperature (K)
- \(\dot{W}\): power (kW)

Greek symbols

- \(\delta\): exergy destruction ratio
- \(\varepsilon\): exergy efficiency
- \(\eta\): energy efficiency

Subscripts

- \(0\): dead state
- \(a\): air
- \(d\): destruction
- \(e\): exit, ethanol
- \(f\): fluid, fuel
- \(fg\): evaporation
- \(g\): gas
- \(i\): inlet
- \(L\): loss
- \(m\): material
- \(q\): heat transfer related
- \(t\): total
- \(w\): water
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