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Reducing energy consumption in food drying: opportunities in desiccant adsorption and other dehumidification strategies

James C Atuonwu [a]*, Xin Jin[a], Gerrit van Straten[a], Henk C van Deventer[b], Antonius, J.B. van Boxtel[a]

[a]*Systems and Control Group, Wageningen University, P O Box 17, Wageningen 6700AA, The Netherlands*
[b]*TNO, P O Box 360 Zeist 3700AJ, The Netherlands*

Abstract

This work assesses the energy efficiency of dehumidification drying vis-à-vis conventional convective drying techniques. Mathematical models are developed by means of which the energy efficiencies of different dehumidification dryer types are expressed in terms of that of a conventional convective dryer operating at the same temperature. This permits the isolation of important design and operational parameters specific to each dryer type which when optimized, improve energy efficiency for the same product quality requirement and ensure better product quality for the same efficiency as a conventional dryer. Desiccant dehumidification systems have the advantage of providing further opportunities for beneficial heat integration.

Keywords: food drying; zeolite adsorption; dehumidification; energy efficiency; product quality

1. Introduction

Drying is arguably one of the most popular methods for preserving fruits, vegetables and other foods. Recent figures [1], suggest the market for dried foods in Japan, China, the US and Europe to be highly significant with the annual market value of products running into several millions and in some cases, billions of US dollars. A market survey covering about 53 countries of the world and conducted between the years 2001-2006 reveals an annual global dried food market growth rate of about 3.3% [2]. This trend is expected to be maintained or even accelerated in the coming years. Of paramount importance in food drying is the achievement of desired levels of quality. Quality indicators such as colour, flavour, texture, availability of nutrients amongst others determine the food value, consumer acceptance and to a large extent, the market value of dried food products. Since drying is highly energy intensive (due to the latent

* Corresponding author. Tel.: +31-317-483364; fax: +31-317-484957.
E-mail address: james.atuonwu@wur.nl

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heat of evaporation required), it is equally important that drying processes be energy efficient. It is therefore not surprising that energy efficiency and product quality have been identified as the key drivers of research and development in drying technology, as a result of which over 400 design variations are currently available [3]. Technologies currently deployed for high quality product drying include amongst others, freeze drying, microwave drying and some convective approaches like heat pump and adsorption drying. Compared to air drying, non-convective drying methods are yet to make significant inroads into industry for a variety of reasons. Freeze drying for instance is very expensive, thus, in spite of the very high quality of its products, application is limited to high-value products [4]. Microwave drying uses high grade and more expensive electrical energy. Moreover, problems like uneven heating, textural damage and limited penetration of microwave radiation within the product occur in microwave drying. In recent times therefore, microwave drying is increasingly being used in conjunction with convective dryers to form so-called combination or assisted systems, examples of which include the microwave-assisted air drying, microwave-assisted whole air drying and microwave as final stage of air drying [1]. These systems have high starting costs and are relatively complicated [4]. Till now, over 85% of all industrial dryers are of the convective type [3]. At low drying temperatures, conventional convective dryers have low thermal efficiencies. Drying at high temperatures is the standard way to improve efficiency, but at the expense of product quality. Heat pump and adsorbent-based drying have good potentials to dry efficiently at low temperatures. Both drying methods are based on dehumidification of drying air. Heat pumps however also require high grade energy, usually electrical, and in a few cases, gas power to drive the compressor. In addition, heat pump drying is inherently a heat recovery process as a result of which, in contrast to adsorption drying, no further opportunities for heat recovery can be identified from the process streams. Adsorption dryers require additional energy for adsorbent regeneration. For temperature swing adsorption processes, high temperature heat is required.

In this work, the effect of dehumidification on the efficiency of the overall drying process is studied, taking into cognizance, the associated energy consumption which may be in form of high-grade regeneration energy (for adsorption systems), or compressor power (electrical or gas-fired) for heat pump systems. Starting from first principles, the dehumidification dryers, namely the adsorption type, the condensation type and heat pump dryers are compared with the conventional convective dryers in terms of energy efficiency. To facilitate this, the efficiencies of dehumidification dryers are referred to that of the conventional dryer. Also, the heat recovery possibilities of an adsorption dryer are examined. Finally, using the drying behaviour and degradation kinetics of specific nutrients in a chosen food, quality degradation is compared for conventional and dehumidification dryers at the same energy efficiency.

2. Materials and Methods

The energy efficiency of each dryer is evaluated based on the mathematical models derived as follows:

2.1. Conventional convective dryer

For an adiabatic dryer, the sensible heat lost by the drying air equals latent heat gained by moisture accumulation. So, for a conventional dryer (Fig. 1) with air mass flowrate F_a, inlet moisture content Y_{ain}, inlet temperature T_{ain}, outlet moisture content Y_{aout} and outlet temperature T_{aout}, the energy balance is

$$F_a\left[\left(C_{pa}+Y_{ain}C_{pv}\right)T_{ain}-\left(C_{pa}+Y_{aout}C_{pv}\right)T_{aout}\right]=F_a\left(Y_{aout}-Y_{ain}\right)\Delta H_v=Q_{out} \quad (1)$$

where, C_{pa} and C_{pv} are specific heat capacities of dry air and water vapour respectively while ΔH_v is the specific latent heat of vaporization of water at the evaporating temperature. F_p is the product flowrate (dry basis) X_{pin}, the inlet product moisture content while X_{pout} is the outlet product moisture content. The thermal efficiency of the drying process is defined as the ratio of the latent heat gained by the drying air to the amount of heat supplied. For air, heated from the ambient T_{amb} to T_{ain}, the input energy supplied and the approximate thermal efficiency thus respectively become

$$Q_{in} = F_a\left(C_{pa} + Y_{ain}C_{pv}\right)\left(T_{ain} - T_{amb}\right) \tag{2}$$

$$\eta = Q_{out}/Q_{in} \approx \left(T_{ain} - T_{aout}\right)/\left(T_{ain} - T_{amb}\right) \tag{3}$$

Thus, for a given ambient temperature, the thermal efficiency control variables with respect to the drying air are T_{ain} and T_{aout}. Energy efficiency can be improved essentially by either raising the inlet temperature or decreasing the outlet temperature. Raising the inlet temperature which can be achieved explicitly by supplying more heat through an external heater (Fig. 1) is however not a good option for heat sensitive food products. For these products, the better approach to energy efficiency improvement is to reduce T_{aout}. This can be achieved implicitly by reducing the inlet moisture content Y_{ain} of the air so the air is able to absorb more moisture. Hence, within limits determined by dryer size, product drying kinetics and equilibria, temperature T_{aout} can be further reduced. The effect of each of the stated control variables on thermal efficiency can be seen from the sensitivity equations below (derived from (3)):

$$\partial\eta/\partial T_{ain} = \left(T_{aout} - T_{amb}\right)/\left(T_{ain} - T_{amb}\right)^2 \tag{4}$$

$$\partial\eta/\partial T_{aout} = -1/\left(T_{ain} - T_{amb}\right) \tag{5}$$

The sensitivity of T_{aout} to Y_{ain} shows that a slight reduction Y_{ain} leads to a considerable reduction in T_{aout}

$$\partial T_{aout}/\partial Y_{ain} = \left(C_{pv}T_{ain} + \Delta H_v\right)/\left(C_{pa} + Y_{aout}C_{pv}\right) \tag{6}$$

2.2. Adsorption dryer

In the adsorption dryer (Fig. 2), ambient air is dehumidified in the adsorber while the spent adsorbent is regenerated in the regenerator by high temperature heat. The efficiency of the adsorption dryer follows directly from that of the conventional dryer (3) but with the following fundamental differences:

- The ambient air temperature T_{amb} is modified to the adsorber outlet temperature $T_{aA}>T_{amb}$ due to the released adsorption heat so, $T_{aA}=T_{amb}+\Delta T_{ads}$. The air can be heated further to drying temperature T_{ain} via Heater2. Regeneration heat is supplied via Heater1 and can be recovered via heat exchanger HX1.
- For the dryer, the air inlet and outlet moisture contents are modified due to dehumidification
- The outlet temperature of the air from the dryer is reduced based on sensitivity equation (6)
- Energy $F_{aR}(C_{pa}+Y_{amb}C_{pv})(T_{aRin}-T_{amb})$ is spent on regeneration where F_{aR} and T_{aRin} are the regeneration air flowrate and inlet temperature
- For this dryer, high temperature heat is available in the regenerator exhaust since the regeneration air inlet temperature (e.g. for a zeolite system) is usually as high as 300°C. The regenerator exhaust air and zeolite are therefore available to preheat the regenerator inlet air [5]. If the regenerator exhaust air at temperature T_{aR} is used in pre-heating the inlet air, for a heat exchanger temperature difference δ, the net energy spent reduces to $F_{aR}(C_{pa}+Y_{amb}C_{pv})(T_{aRin}-T_{aR}-\delta)$. Modifying (3) based on the above, the thermal efficiency (after heat recovery) is determined as

$$\eta_{AD} \approx \left(T_{ain} - T_{aD}\right)/\left(\left(F_{aR}/F_a\right)\left(T_{aRin} - T_{aR} - \delta\right) + \left(T_{ain} - T_{aA}\right)\right) \tag{7}$$

where,

$$T_{aD} = T_{aout} - \left(\partial T_{aout}/\partial Y_{ain}\right)dY_{ain} = T_{aout} - \left(\left(C_{pv}T_{ain} + \Delta H_v\right)/\left(C_{pa} + Y_{aA}C_{pv}\right)\right)\left(Y_{amb} - Y_{aA}\right) \tag{8}$$

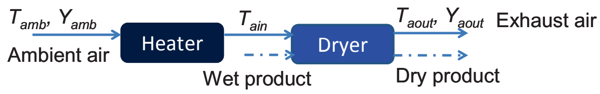

Fig.1. Conventional dryer

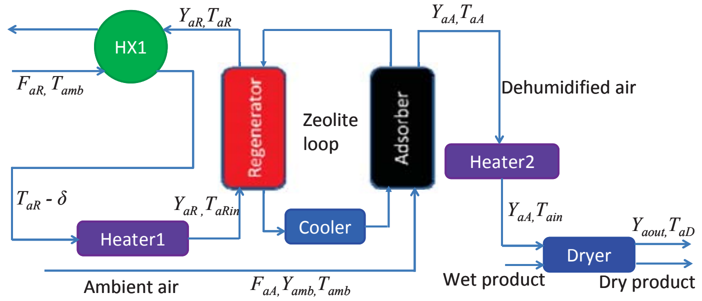

Fig. 2. Adsorption Drying Process

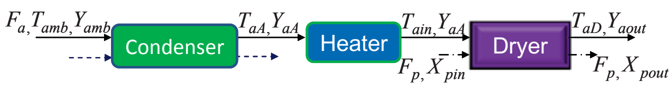

Fig. 3. Condensation dryer

2.3. Condensation dryer

Here (Fig. 3), the ambient air is dehumidified by cooling through a temperature drop ΔT_{dpt} to dew point T_{dpt}, and then, through another temperature drop ΔT_{cool} for moisture condensation. A major demerit is that sensible and latent heat gained by the refrigerant in the condenser is not recovered by the drying air which loses sensible heat so, energy efficiency improvement is little. Assuming the ambient air is dehumidified to the same moisture content as that of the adsorber outlet air Y_{aA}, and then, raised to the same dryer inlet temperature T_{ain}, the fundamental difference from the adsorption dryer is:

- Instead of adsorption heat release, there exists two-stage cooling, one to the dewpoint and then below dew point (during which time, latent heat is recovered). Also, no regeneration energy is spent.

By the same approach used in deriving equation (3), the energy efficiency simplifies to

$$\eta_{CD} = (T_{ain} - T_{aD})/(T_{ain} - T_{aA}) \quad (9)$$

2.4. Heat pump dryer

The main differences between the condensation dryer (Fig. 3) and the heat pump dryer (Fig. 4) are:

- Here, the dryer exhaust air is dehumidified instead of the inlet air so that the dew point is higher. As a result, the degree of cooling ΔT_{dptHP} and ΔT_{coolHP} needed for the same dehumidification is less
- Sensible heat loss in the air at the evaporator is recovered in the refrigerant together with latent heat and sent to condenser by the compressor, driven by energy q_w.

The drying energy efficiency of heat pump dryers is usually expressed in terms of the specific moisture extraction rate (SMER) defined as the ratio of the mass of moisture evaporated to the energy input (usually electrical in kWh). To ensure realistic comparison, we convert the electrical energy to the equivalent thermal primary energy since. Hence, two efficiencies are included in the expression, namely: η_{comp}, the efficiency of the compressor in converting electrical energy to thermal energy in the refrigerant and η_{elect} accounting for the overall efficiency of electrical energy generation, assuming an electrically driven compressor. The product $\eta_{comp}\eta_{elect}$ is chosen as 0.5 for the calculations presented in this work. Also here, $T_{aA}=T_{amb}-\Delta T_{dptHP}-\Delta T_{coolHP}$ and T_{aD} is given by (8). The energy efficiency simplifies to (10). Also, heat pump drying is inherently a heat recovery process, so no further heat is recoverable from its streams.

$$\eta_{HPD} = (T_{ain} - T_{aD})/((T_{ain} - T_{aout}) + \Delta T_{dptHP} + \Delta T_{coolHP} + (q_w / \eta_{comp}\eta_{elect}(F_a(C_{pa} + Y_{aA}C_{pv})))) \quad (10)$$

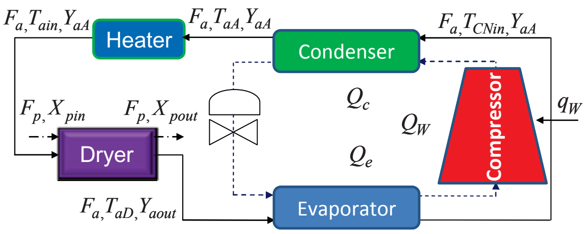

Fig. 4. Heat pump dryer

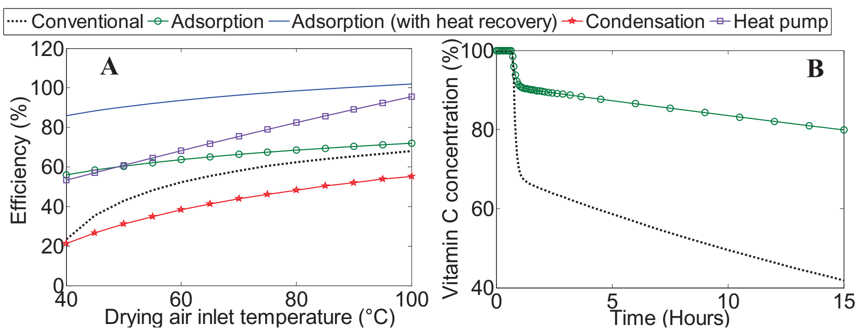

Fig. 5 A). Energy efficiency for different dryer types (see top of figure), B). Vitamin C degradation for drying with and without air dehumidification both with energy efficiency at 60%

3. Quality degradation

Dehumidification dryers make it possible to dry more efficiently at low temperatures, good for nutrient retention. In particular, vitamin C, found in many fruits and vegetables decays with temperature. It is generally observed that if vitamin C is well retained, other nutrients are also well retained so that vitamin C is taken as an index of nutrient quality of foods [6]. The degradation rate of vitamin C is given [7] as

$$dC/dt = -C\exp\left(a_1 X_p + a_2 T^{-3} + a_3 X_p{}^3 + a_4 X_p{}^2 T^{-1} + a_5 X_p T^{-2} + a_6 X_p{}^3 T^{-3} + a_7\right) \qquad (11)$$

a1, …a7 are constants [7], k is the degradation rate constant (per min) and C is the vitamin C concentration. The model is used in simulating degradation for different dryers at same efficiency levels.

4. Results and Discussion

Comparing the efficiencies of the conventional dryer (3), the adsorption dryer (7), condensation dryer (9) and heat pump dryer (10), the efficiency of each dehumidification dryer is seen to be expressible in terms of that of the conventional dryer, with extra terms introduced. The extra terms include the dehumidification induced dryer exhaust air temperature drop, the extra energy term (regeneration energy for the adsorption dryer and compression energy for the heat pump dryer), and the drying air cooling terms (for the heat pump and condensation dryers). Also included are heating terms (adsorption heat for the adsorption dryer and exhaust air sensible heat recovery as shown in the presence of T_{aout} in the denominator of the heat pump dryer efficiency as against T_{amb} for the conventional dryer). In each case, the efficiency rise corresponding to the dehumidification induced exhaust air temperature drop is incurred at the expense of extra energy (e.g. due to the cooling and hence extra heat requirement, regeneration and compression). Optimization of the variables contained in these extra terms within constraints thus holds the key to fully utilizing the benefits of dehumidification. In the case of the adsorption dryer, the variables (F_a, F_{aR} and T_{aRin}) affect the regeneration energy term, the extent of dehumidification and the released adsorption heat. These variables thus have to be optimized in addition to the adsorbent flow rate F_z, which affects the relationship among them. This is consistent with previous results [5] where by degree of freedom analysis, the same conclusion was arrived at. Fig. 5(A) shows the energy efficiency of the different dehumidification dryers at a dryer inlet air of 5g/kg compared to a conventional dryer at 10g/kg. The heat pump and adsorption dryers perform better than conventional dryers. To achieve the same efficiency, conventional dryers must be operated at higher temperatures. For instance, a-60% efficiency is achieved by the adsorption and conventional dryers at 50 and 75°C respectively. At these temperatures, vitamin C degradation is simulated for the drying curve of pumpkin [8]. The result in Fig. 5(B) shows that for the same energy consumed, vitamin C degradation is reduced using dehumidification dryers.

5. Conclusion

From this work it is concluded that dehumidifying the drying air introduces energy advantages the magnitude of which depends on specific dehumidification-induced operating conditions. For the same energy consumption, quality degradation is reduced using dehumidification dryers. Adsorption dryers and heat pumps are at the top of the ladder but efficiencies attained depend on extent of dehumidification.

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