OVERVIEW OF NEW TECHNIQUES FOR DRYING BIOLOGICAL MATERIALS WITH EMPHASIS ON ENERGY ASPECTS

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ABSTRACT
With increasing concern about environmental degradation, it is desirable to decrease energy consumption in all sectors. Drying has been reported to account for anywhere from 12 to 20% of the energy consumption in the industrial sector. Drying processes are one of the most energy intensive unit operations.
There are a number of approaches to reduce energy consumption in dryers. This paper reviews some novel strategies used to decrease energy consumption in drying operations. Drying conditions can be modified or the drying equipments can be modified to increase overall efficiencies. Hybrid drying techniques can also be used, such as combining vacuum or convective drying with electro-technologies (microwave, radio frequency, infrared heating). There is much debate on how to define drying and energy efficiencies. Some techniques to determine these efficiencies can be misleading when the goal is to take a holistic approach to determining energy consumption.
Keywords: Efficiency; Novel techniques; Drying; Greenhouse gas emissions.

INTRODUCTION

To obtain proper long term storage of many biological materials, these products need to be dried to low moisture contents. Drying spans all types of agricultural products, including cereals, fruits, vegetables, and spices. It is an energy intensive operation, consuming anywhere from 0.38 to 0.63 GJ/t of grain (Raghavan, 2003). Though not all cereal grain is artificially dried, it has been estimated that about 34% of the world's cereal crop is grown in nations where artificial drying is needed for some of the crops (Raghavan, 2003).
The majority of artificial drying operations are based on hot air drying, where air is heated by the combustion of fossil fuels prior to being forced through the product. This type of drying requires high energy inputs, due to the inefficiencies of such dryers. Often, the exhaust air is simply released to the surrounding ambient air. Some systems allow for the recycling of exhaust heat, which can greatly increase the overall energy efficiency of the dryer.
With increasing pressures to reduce environmental degradation, both from the public and from governments, it is necessary to improve drying processes to reduce energy consumption and greenhouse gas (GHG) emissions, while still providing a high quality product with minimal increase in economic input. In order to achieve these goals, much work needs to come from the advances in novel technologies for drying. This paper discusses some of the novel techniques that are being studied and developed, along with a discussion of energy sources and GHG emissions.

CALCULATION OF DRYING EFFICIENCY

There is great debate about the proper method to calculate energy efficiencies for the purpose of providing an objective comparison between different dryers and drying processes. The basic approach to calculating any energy efficiency, h, is to take the ratio of energy required, E_r, to energy supplied, E_s:

$$\eta = \frac{E_r}{E_s} \quad (1)$$

However, the energy efficiency can be calculated for the drying process as a whole (total energy required and total energy supplied), instantaneous efficiency (energy required and energy supplied at given time), or it may be only for the drying chamber, not including other peripheral energy requirements.

Typical convective dryers account for about 85% of all industrial dryers (Mujumdar and Beke, 2003). The drying medium is generally hot air or direct combustion gases. The energy efficiency for convective dryers, h_{cov}, is usually calculated based on the temperature of the drying medium at the inlet, T_{in}, outlet, T_{out}, and the ambient air temperature, T_{amb}:

$$\eta_{cov} = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \quad (2)$$

The temperature of the heating medium can not drop below the wet bulb temperature, T_{wb}. This will result in a maximum efficiency of a convective dryer as:

$$\eta_{cov,\ max} = \frac{T_{in} - T_{wb}}{T_{in} - T_{amb}} \quad (3)$$

This is, however, only the efficiency of the dryer itself, not including any energy inputs or losses that are not directly associated with the drying chamber (inputs to blowers, heat loss prior to entry into the drying chamber), though these other inputs and losses are generally quite small.

Another drawback of Equations (2) and (3) is that the cumulative energy efficiency only holds true if all the temperatures remain constant, and if the outlet temperature is representative of the during process (Grabowski et al., 2002). Kudra (1998) defined the instantaneous energy efficiency, h_{ins}, as:

$$\eta_{ins} = \frac{\text{energy used for evaporation at time t}}{\text{input energy at time t}} \quad (4)$$

The cumulative energy efficiency, h_c, can be calculated by integrating Equation (4) with respect to time:

$$\eta_c = \frac{1}{t}\int_0^t \eta_{ins}(t)dt \quad (5)$$

The cumulative energy efficiency is the same as Equation (2) if the outlet temperature in Equation (2) is calculated as an integral average over the same drying time (Grabowski et al., 2002). Equations (4) and (5) are affected by all aspects of the drying process, including material properties, dryer type and configuration, operating parameters, and initial-final moisture contents (Kudra, 1998). This also takes into account the heat required to heat the material to the drying temperature along with any changes in product temperature during drying and the heat supplied and required to remove capillary-bound water. It is an overall efficiency, but does not describe the ability of the heat to remove moisture from the product. To describe this aspect, Kudra (1998) defined the instantaneous drying efficiency, e_{ins}, as:

$$\varepsilon_{ins} = \frac{\text{energy used for evaporation at time t}}{\text{(input energy - output energy with outlet gas) at time t}} \quad (6)$$

This equation can also be integrated to give the cumulative drying efficiency, e_c:

$$\varepsilon_c = \frac{1}{t}\int_0^t \varepsilon_{ins}(t)dt \quad (7)$$

Further equations for drying efficiencies have been developed for more specific applications. Yongsawatdigul and Gunasekaran (1996) developed a drying efficiency, DE (MJ/kgH_2O), for continuous microwave-vacuum drying:

$$DE = \frac{t_{on}P(1 - m_f)10^{-6}}{M_i(m_i - m_f)} \quad (8)$$

where t_{on} is the total time of applied microwave power (s), P is the power input of the microwave (W), m_i and m_f are the initial and final moisture contents (fraction), and M_i is the initial sample mass (kg). However, this is an energy consumption rate, rather than a drying efficiency (Beaudry et al., 2003).

An alternative indicator of the energy efficiency, often used for heat pump dryers, is the specific moisture extraction ratio, SMER (kg/kW·h):

$$\text{SMER} = \frac{\text{amount of water evaporated}}{\text{energy used}} \qquad (9)$$

The SMER can be calculated either as an instantaneous value or as an average value during drying. During the drying process, the SMER value invariably decreases as the removal of moisture becomes more difficult due to smaller water vapor deficits at the surface of the product. In theory, the maximum value for SMER in a conventional dryer is 1.55 kg/kW·h, which is based on the latent heat of water evaporation at 100ºC (Strumillo et al., 1995). For dryers with heat recovery systems, such as heat pump dryers, the SMER value can be above the theoretical maximum value.

ENERGY SOURCES

Increasing concern of global warming and related environmental problems are causing changes in all sectors of industry. Increasing legislation and tighter environmental policies are requiring that companies and corporations evaluate their energy use and GHG emissions. GHG emissions are generally calculated based on their CO_2equivalent emissions. Using equivalent emissions, natural gas, light fuel oil (No. 2), heavy fuel oil (No. 6), and liquid propane produce 0.18 t, 0.26 t, 0.27 t, and 0.23 t of equivalent CO_2 emissions per mega-Watt hour (MWh), respectively. Thus a change in the fuel source can increase or decrease the GHG emissions. Calculations for dryers that use electrical energy input (microwave dryers, heat pump dryers) can be a little more difficult, as the CO_2 emissions produced in the production of electricity vary to a large degree, due to the method of production and the different fuels used in the production. In Canada, the CO_2 equivalent emission factors range from 0.009 t/MWh in the province of Quebec (mostly hydroelectricity) to 1.984 t/MWh in Nova Scotia (coal burning), based on data from 1998 (Aubé, 2001). An attractive alternative energy source is biomass, which is considered to be CO_2-neutral when grown in sustainable conditions (Woods and Hall, 1994).

COMBINED TECHNOLOGIES

Hybrid or combined drying technologies include implementation of different modes of heat transfer, two or more stages of the same or different type of dryer (Kudra and Mujumdar, 2002). The efficiency of drying concerning both energy and time of process dictates intensive research in this area, and some of the most promising drying methods include the electromagnetic waves and sonic-assisted drying.

Electro Technologies

Electromagnetic waves can penetrate deep into material causing volumetric heating "targeting" mostly water, offering higher energy conversion rates and therefore shorter process time. Unfortunately, this technology is still only being accepted in industry, mainly because of high capital costs and a lack of documented energy savings (Sanga et al., 2000). Nevertheless, the implementation of electromagnetic waves could be one of the most promising drying techniques in the future, especially because of its potential for savings in energy and time, and providing high quality products.

Dielectric heating is based on volumetric heat generation throughout the material being dried. Radio frequencies cover the electromagnetic spectra with frequencies of 1 to 300 MHz, but special care should be taken here: only specific frequencies have been designated within both radio frequency (RF) and microwave (MW) spectra for industrial applications 13.56, 27.12, and 40 MHz for RF, and 915 (896 MHz in Europe) and 2450 MHz in the MW region (Kudra and Mujumdar, 2002). RF drying can be appropriate for large loads such as paper and timber drying, where high power and short duration are required. This is well documented by many published papers on RF as an energy source related to timber and wood products, with a few exceptions in food applications such as biscuit post-baking drying (Clark, 1997) and meat/fish tempering (Bernard, 1997).

Microwaves cover electromagnetic wave spectrum with wavelengths from 1 mm to 1 m. They are the most extensive researched electromagnetic waves in drying so far, but as with all other methods, there is a lack of documented energy analysis in most publications published to date, and the majority of papers dealing with MW are related to the influence of MW-assisted drying on the quality of specific product. Biological materials are very attractive for MW drying, because they are heat sensitive and can benefit from the "targeted" heating obtained with MW.

Tulasidas et al. (1995) used MW to dry grapes, and calculated specific energy consumption (defined as the total energy in MJ used to evaporate a unit mass of water) for convective drying, and for MW-convective drying. For convective drying, specific energy consumption ranged between 81.2 and 90.4 MJ/kg, whereas under similar convective conditions and with implementation of MW, this consumption decreased radically: 7.1 to 24.3 MJ/kg (depending on process conditions).

Enhancement of MW-assisted drying can be achieved by introducing intermittent MW power exposure, as opposed to continuous exposure. In the work of Shivhare et al. (1992), it has been proven that discontinuous MW power can substantially reduce the energy loss. The total drying time was increased, but the total MW exposure was shorter, giving the product of higher quality. Beaudry et al. (2003) demonstrated that energy consumption (defined as MJ per kg of evaporated water) was influenced by both MW cycling period and MW power density in intermittent MW drying.

Further improvement of MW drying can be achieved in drying under vacuum. Yongsawatdigul and Gunasekaran (1996) calculated drying efficiency using Equation (8) for MW-vacuum dried cranberries, and showed that pulsed MW power mode is more energy efficient than the continuous mode. Sunjka et al. (2004) compared the drying performance (defined as kg of evaporated water per MJ of supplied MW power) and cumulative energy efficiency for MW-convective and MW-vacuum drying, and found out that drying performance ranged between 0.1 to 0.12 kg/MJ for MW-convective, and between 0.13 to 0.35 kg/MJ for MW-vacuum drying. Cumulative energy efficiency ranged between 0.23 and 0.26 for MW-convective, and 0.31 to 0.83 for MW-vacuum drying, showing an obvious energy saving benefit of implementing vacuum when drying with MW.

Far infrared (FIR) waves are those with wavelengths between MW and visible light. Afzal et al. (1999) dried barley using FIR-convective drying unit, and compared drying time and energy consumption results for this method with convection alone. Specific energy consumption (in MJ/kg of water) more than halved when FIR was introduced in convective drying process, and drying time was significantly shorter.

Sonic Drying

Sonic drying is usually used for viscous products difficult to dry with other methods, and is especially suitable for temperature-sensitive products because it is a non-thermal drying (separation or dewatering) process. Sound used in industrial applications has low frequencies (20 to 40 kHz) (Kudra and Mujumdar, 2002). Unfortunately, there is only a few papers which consider the energy requirements for sonic drying, stating that consumption of sonic energy per kg of evaporated water is approximately the same or even higher as in convective drying (Borisov and Gynkina, 1973). However, when sound effect is used in pulse-combustion drying, which combines heat and sound, this vibrating air stream removes water much faster than conventional air drying, and uses 3.53 MJ/kg, when conventional air drying uses between 5.8 and 7.0 MJ for one kilogram of evaporated water (Anon, 1986).

NEW METHODS

Superheated Steam

Superheated steam (SHS) serves here as a drying medium, supplying heat to a drying product and carrying off evaporated moisture. This method has been industrially implemented, but so far on a very small scale. The advantages are that no oxidative or combustion reactions take place in or near the dryer, higher drying rates (in some cases), and it can permit pasteurization of food products (Kudra and Mujumdar, 2002). The disadvantages are a more complex system, heat sensitive materials are prone to damage, and there is limited documented experience about this method (Kudra and Mujumdar, 2002).

Fitzpatrick and Lynch (1995) showed that substantial energy savings (more than 80% in some instances) could be made by substituting air with SHS. These savings were made by heat recovery from exhausting SHS and eliminating the need to heat from ambient temperature. Similar results were obtained by Fitzpatrick and Palmer (1995), during drying of dairy sludge.

Heat Pump Assisted Drying

A heat pump works on the principle of refrigeration to cool an air stream and condense the water contained in it. This renders the air dry and also recovers the latent heat of evaporation through water vapour removal which permits air recirculation. Prasertsan and Saen-saby (1998) showed that heat pump drying (HPD) had the lowest operating cost when compared to electrically heated convective dryers and direct-fired dryers. They pointed out that one important disadvantage of this method is that it uses an expensive energy source: electricity needed to run the compressor, but it could be economically feasible during the first stages of drying for high moisture products.

In their review on HPD, Perera and Rahman (1997) state that HPD has higher drying efficiency, offers better product quality, and it is environmentally friendly. SMER values ranged from 1.0-4.0, 0.7-1.2 and 0.1-1.3

kg/kW·h for HPD, vacuum drying, and hot air drying, respectively. Drying efficiencies were 95% for HPD, less then 70% for vacuum drying, and between 35-40% for hot-air drying.

The economical role of HPD was investigated by Sosle et al. (2001) for agri-food materials. They confirmed that HPD is useful for materials with high initial moisture content and in regions with high humidity of ambient air. The MER (moisture extraction rate in g of moisture removed per hour) values ranged from 80 g/kW for apple slices and 95 g/kW for tomato.

HPD can be combined with MW, as shown by Jia et al. (1993). They compared HPD with convective drying and pointed out that overall comparison should incorporate four aspects: capital investment, energy efficiency, product throughput, and quality. In their work, MW assisted HPD drying competed well with conventional hot-air drying, having lower SMER, and higher product throughput.

Further advancements have been made in heat pump drying which employ loop thermosyphons, which are a type of heat pipe (Phaphuangwittayakul et al., 2000). A loop thermosyphon consists of evaporator and condenser sections, with tubes connecting the two sections. When the working fluid is condensed, it is returned to the evaporator due to gravity (Phaphuangwittayakul et al., 2002). Phaphuangwittayakul et al. (2000) placed the loop thermosyphon around the evaporator of the heat pump dryer, to first pre-cool the air before entering the heat pump evaporator and then reheat the air after the evaporator. Phaphuangwittayakul et al. (2002) numerically studied the effects of by-pass air ratios and the fraction of recirculation air on the heat transfer characteristics of a heat pump dryer, with and without a loop thermosyphon. Phaphuangwittayakul et al. (2003) furthered their research by building a heat pump dryer with a loop thermosyphon to dry longan fruit.

CONCLUSIONS

The need for drying biological materials is very important in the agri-food industry, producing high quality and shelf-stable products. However, there is a downside to the process, as it is a high energy consuming process. This has two drawbacks, the first is the cost of energy, and the second is the environmental degradation that is associated with some types of energy production. In response to these concerns, there has been much work on novel drying techniques to improve energy and drying efficiencies. This article has covered some of these novel drying techniques, with hope that these techniques, along with future research, will produce dryers and drying process that are more economical and less harmful to the environment.

NOMECLATURE

DE	drying efficiency, MJ/kg H_2O
E	energy, J
m	moisture content, kg/kg
M	mass, kg
P	power, W
SMER	specific moisture extraction ratio, kg/kWh
t	time, s

Greek Symbols

η	energy efficiency, J/J
ε	drying efficiency, J/J

Subscripts

amb	ambient
c	cumulative
con	convective
f	final
i	initial
ins	instantaneous
max	maximum
on	on
r	required
s	supplied
wb	wet bulb

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