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Energy-efficient thermal drying using impinging-jets with time-varying heat input – A computational study

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ABSTRACT

This study investigates the performance of impinging-jet drying at various configurations. The computational fluid dynamic (CFD) approach was used for solving the conjugated heat/mass transfer problem during drying with impinging-jets. In short, the model considers slab material with drying chamber, and solve for conservation equations of mass, momentum, species and energy with associated turbulence model. To ensure the validity of the mathematical model, validation with the experimental data is carried out. The effect of jet velocity, pulsation and intermittency on the jet inlet, slab geometry and slab thickness are then investigated. The results are then examined to obtain optimum conditions for impinging-jet drying of model materials in the form of a thin slab. Finally, it is noted that lower energy consumption of impinging-jet with pulsating and/or intermittent flow offers comparable drying kinetics as compared to that with that of a steady jet, which shows potential for energy saving.

1. Introduction

Drying is the most common but energy-intensive process for preserving food. It is considered as an essential operation in major industries; for example, chemical, agricultural, pulp and paper, biotechnology, food, polymer, ceramic, pharmaceutical, mineral processing, and wood processing industries. Therefore, drying has attracted much attention from both industry and academia. According to the literatures, over 400 types of dryers have been reported and 100 distinct types are commercially available (Mujumdar, 2007). Various drying methods are available for different materials.

During drying, two transfer processes – heat and mass – occur simultaneously in both inside material and outside in the surrounding. The energy transfer occurs as heat is transferred from the surrounding environment (drying air in convective drying) into the drying substrate while mass transfer occurs as the moisture moves from the drying substrate to the surrounding environment. As such, the rate at which the drying process accomplished is determined by the rate of heat and mass transfer. In order to improve drying rate, either mass transfer rate or heat transfer rate or both transfer rates have to be improved. One promising method is by implementing impinging-jet which offers higher heat and mass transfer rates (Xu et al., 2010a,b; Poh et al., 2005; Zhao et al., 2004; Bórquez et al., 1999; Bond et al., 1994).

However, impinging-jet drying has certain drawbacks: high energy consumption compare to traditional parallel flow drying and not suitable for highly sensitive materials due to over-heating. Therefore, to obtain an optimum design – high transfer rate, minimum energy consumption and high quality dried product –, it is necessary to match the energy demand for drying, as governed by drying kinetics, with the external supply of heat. It can be achieved by supplying heat to the drying process concurrently or sequentially according to the needs of the drying application; for example, pulsating and intermittent flow. Numerous experimental and computational studies have demonstrated the advantages of pulsating and intermittent flow in heat transfer applications, including drying (Xu et al., 2010a,b; Poh et al., 2005; Hewakandamby, 2009; Islam et al., 2003; Tesar, 2009). It is therefore of interest to apply this concept for impinging-jet drying.

In this paper, numerical investigation of the performance of impinging-jet drying using pulsating and intermittent flow rather than the conventional steady jets will be presented. The effects of frequency and amplitude of the pulsation of the jet are investigated. Effect of slab geometries will also be studied. The results are then examined to obtain optimum conditions.

2. Model development

A mathematical model for drying air and substrate is developed, taking into account the following mechanisms: moisture diffusion

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from the inner drying substrate towards its surface, conductive heat transfer within the drying substrate, evaporation and convection of the vapor from the surface of the drying substrate into the drying air, convection heat transfer from drying air to the surface of the drying substrate. These transport phenomena are coupled and occur simultaneously. Moreover, the thermoproperties of the drying substrate is temperature and moisture content-dependent. Therefore the governing equations become fully coupled and highly non linear. In this study, the model drying substrate considered is sliced potato. This drying substrate is placed inside a drying chamber under impinging-jet, as illustrated in Fig. 1.

2.1. Assumptions

In developing the mathematical model, several assumptions are taken:

- The drying substrate is compact and homogeneous with uniform initial temperature and moisture content.
- Within the drying substrate, the diffusivity of water vapor is equal to the diffusivity of liquid water.
- The thermophysical properties of the drying substrate are temperature and moisture content-dependent and isotropic. These properties are summarized in Table 1.
- Variations in dependent variables in span wise direction are negligible, since width of the drying substrate is much larger than its height. This assumption allows for a reduction in dimensionality from three to two dimensions.
- The shape of the drying substrate remains constant during the drying period considered. Neither shrinkage nor deformation of the drying substrate is accounted for.

2.2. Governing equations

With reference to the previous assumptions, the conservation of mass and energy for the vapor and liquid water inside the drying substrate are given as (De Bonis and Ruocco, 2008)

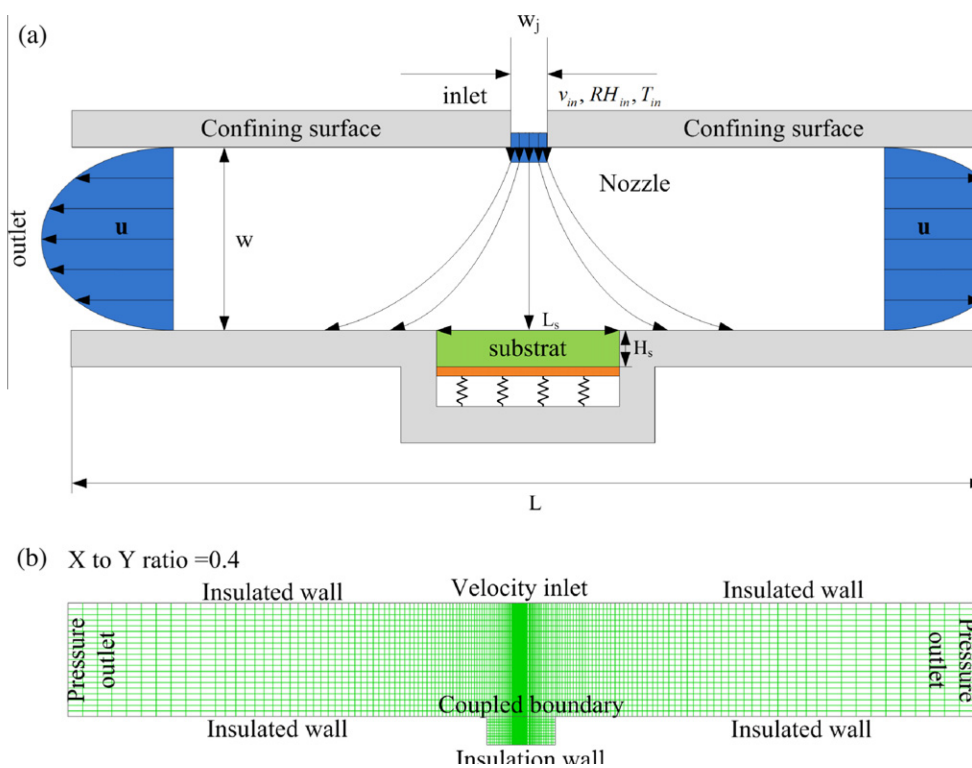

Fig. 1. (a) Schematic and (b) computational domain (mesh) of the impinging-jet dryer arrangement.

Table 1
Thermophysical and transport properties.

Properties	Function	References
ρ_{air}	$1.076 \times 10^{-5} T_{air}^2 - 1.039 \times 10^{-2} T_{air} + 3.326$	Kays et al. (2005), Kurnia et al. (2011)
μ_{air}	$5.21 \times 10^{-15} T_{air}^3 - 4.077 \times 10^{-11} T_{air}^2 + 7.039 \times 10^{-8} T_{air} + 9.19 \times 10^{-7}$	Kays et al. (2005), Kurnia et al. (2011)
k_{air}	$4.084 \times 10^{-10} T_{air}^3 - 4.519 \times 10^{-7} T_{air}^2 + 2.35 \times 10^{-4} T_{air} - 0.0147$	Kays et al. (2005), Kurnia et al. (2011)
$c_{p,air}$	$-4.647 \times 10^{-6} T_{air}^3 + 4.837 \times 10^{-3} T_{air}^2 - 1.599 T_{air} + 1175$	Kays et al. (2005), Kurnia et al. (2011)
ρ_b	$\frac{\rho_{b,ref}(1+X)}{1+SbX}$	Srikiatden and Roberts (2008)
k_b	$\frac{0.049}{1+X} \exp\left[-\frac{47}{8.3143\times10^{-3}}\left(\frac{1}{T_s+273.15} - \frac{1}{335.15}\right)\right] + \frac{0.611X}{1+X}$	Srikiatden and Roberts (2008)
$c_{p,b}$	$1750 + 2345\left(\frac{X}{1+X}\right)$	Srikiatden and Roberts (2008)
$D_{vb} = D_{lb}$	$1.29 \times 10^{-6} \exp\left(\frac{-0.0725}{X}\right) \exp\left(\frac{-2044}{T_s+273.15}\right)$	Srikiatden and Roberts (2008)
D_{va}	$-2.775 \times 10^{-6} + 4.479 \times 10^{-8} T + 1.656 \times 10^{-10} T^2$	Nellis and Klein (2009)