Conjugate heat and mass transfer by jet impingement over a moist protrusion

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ABSTRACT

Biosubstrates drying can be intensified, controlled and optimized, even in blunt shapes, by providing exposure to air jet impingement. In this paper round air jet impingement on cylinder protrusions of a model substrate is investigated, for moderate Reynolds numbers and various geometry arrangements.

A comprehensive numerical model featuring conjugate interface transport (local fluid dynamic effects), multiphase coupling (local surface evaporation) and moisture diffusion notations, is first validated with the corresponding experimental results. Then quantitative distributions of temperature and moisture within the protrusion and along its exposed surface are presented, focussing on the dependence of surface heat and mass transfer on geometry arrangement and fluid dynamic regime. Two values of Reynolds number, two jet heights and two protrusion/jet diameter ratio combinations are investigated.

It is pointed out that, within the investigated range of variables, a protrusion/jet diameter ratio equal to 1 allows for flow patterns that foster process enhancement, but at the expenses of treatment uniformity: after 15 min of treatment the 10% of protrusion only is still relatively moist, but with a strong internal non-uniformity, whereas with a protrusion/jet diameter ratio equal to 3 the untreated part accounts to the 85%, with a smoother internal distribution.

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1. Introduction

Most bio-substrate heating is inevitably coupled and intertwined with mass transfer (drying). The most common liquid fraction being water or moisture, evaporation occurs within substrate and at its exposed surface producing vapor which is removed from it. The need of drying is common when seeking substrate stability: by lowering moisture, handling is promoted and microbial spoilage is prevented, enhancing quality and commercial value. But uncontrolled drying leads to undesired changes in bioactive molecules with their valuable features.

Modeling coupled heat and mass transfer is therefore necessary in these cases, and to ensure approach generality the problem must be attacked simultaneously in both fluid and solid phases. This approach is referred to as the conjugate problem; in this way the heat and mass fluxes vary seamlessly, in space and time, as the solution of field variables. Therefore, no limiting empiricism at phase interface (heat and mass transfer coefficients), usually referring to average conditions and unspecified geometry variations, is introduced.

Jet impingement (JI) has long been recognized for its superior transport characteristics, which can be useful in process intensification, control and optimization. Frequently the involved geometry is more complex than a planar one. Much of the gas JI heat transfer research has been motivated by the need for enhanced cooling of extended surfaces (or blunt corrugations) in limited spaces, as with gas turbine blades or high power CPUs [1]. Reviews on conjugate heat transfer that evidences in a JI configuration can be found in Sarghini and Ruocco [2] (laminar flows) and Yang and Tsai [3] (turbulent flows). Heat transfer was first coupled to mass transfer in conjugate drying due to JI by De Bonis and Ruocco [4] (for a semi-infinite plate) and then by De Bonis and Ruocco [5] and Kurnia et al. [6] (for a flushed substrate): it was evidenced that the drying treatment may be non-uniform, depending on the wall boundary layer that develops locally.

As bio-substrates are often encountered as protrusions, JI can be profitably supplemented to process control and enhancement, and induce a desired superficial finish. In the present framework, a protrusion is a floor or wall-mounted solid with the prevailing length coincident to jet axis. Merci et al. [7] modified the turbulence paradigm to account for the peculiarities of the boundary layer around an impinged blunt cylinder, similar to the geometry speculated in the present paper. Popovac and Hanjalic [8] offered a thorough example of perturbed JI flow and heat transfer around and over a cube protrusion. JI over smooth protrusions have been also studied, as lately by Zhang et al. [9]. Finally, multiple physics effects have even been studied, as the enhancement of heat transfer due to the electromagnetic exposure during JI [10,11]. However, no hints