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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.

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 such 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 Hanjalić [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

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Nomenclature

A	pre-exponential factor, 1/s
c	species concentration, mol/m^3
$c_{1\varepsilon}$	model parameter in Eq. (11)
$c_{2\varepsilon}$	model parameter in Eq. (11)
c_μ	model parameter in Eqs. (12), (20) and (21)
c^+	model parameter in Eq. (21)
c_p	constant pressure specific heat, J/kg K
D	mass diffusivity, m^2/s
E_a	activation energy, J/mol
H	height, thickness, m
k	turbulent kinetic energy, m^2/s^2
K	rate of evaporation, 1/s
L	length, m
M	molecular weight, g/mol
$\mathbf{n}$	normal versor
p	pressure, Pa
Q_{EV}	latent cooling flux, W/m^3
r	radial coordinate, m
R	universal gas constant, J/mol K
Re	Reynolds number
t	time, s
T	temperature, K
U	moisture content, wet basis (kg liquid water/kg substrate)
$\mathbf{v}$	velocity vector, m/s
v	velocity component, m/s
z	vertical coordinate, m

Greek

δ_w	distance from surface, m
δ_w^+	dimensionless distance from surface
Δh_{EV}	latent heat of evaporation, J/kg
Δt	process duration, s
ε	turbulent energy dissipation rate, m^2/s^3
κ	Von Kàrmàn's constant
λ	thermal conductivity, W/mK
μ	dynamic viscosity, Pa s
ξ	curvilinear coordinate, m
ρ	density, kg/m^3
σ_k	model parameter in Eq. (11)
σ_ε	model parameter in Eq. (11)
ω	air absolute humidity (kg water vapor/kg air)

Superscripts

f	fluid side
s	solid side

Subscripts

0	nominal, initial, reference
a	air
j	jet
l	liquid water
p	plate, process
r	radial component
s	substrate, solid
t	turbulent
v	water vapor
z	vertical component

were found in the available literature concerning coupled heat and mass transfer from a protrusion impinged normally.

The present work is aimed to investigate on JI-enhanced heat and mass transfer from a realistic biomaterial. Initially laminar or moderately turbulent air flows are impinged normally to upright cylinder protrusions. Air velocity, residual moisture and temperature fields can be computed by a conjugate model complemented by a custom evaporation kinetics. Temperature and moisture can be described within the target substrate and along its exposed surface, to speculate on the potential of process finishing and optimization by JI.

2. Analysis

2.1. Flow topology and alteration

A JI configuration over a liquid-saturated protrusion consists in a hot jet flow directed from a round nozzle to the cylindrical target, in a space confined by two parallel plates (Fig. 1). Upon recognition of the nozzle internal geometry, a velocity distribution $v_z(r)$ can be inferred. The configurations at stake in this study consider jet flows that are initially laminar at nozzle, or moderately turbulent. In this case, the impinging flow structure can be summarized into three characteristic regions: the free jet region formed as jet exits, the stagnation (impingement) flow region formed upon jet impact and deflection on protrusion top, and the perturbed boundary layer, along with its recirculation (secondary) pattern, formed upon re-direction of the flow past and along the protrusion. The perturbed boundary layer patterns depend on protrusion height and extension relative to the free jet.

Due to JI, then, large heat and mass transfers are attainable in the vicinity of the stagnation region, but the perturbed boundary layer may contribute to lateral surfaces. At the end, a highly non-uniform drying can result at the exposed surface, with possible local overheating or incomplete evaporation.

2.2. Driving assumptions

Moisture can convert into vapor depending on the heat perturbation front within the substrate. There, liquid moves due to capillarity and solute concentration difference, while vapor moves within the air spaces due to vapor pressure gradients,

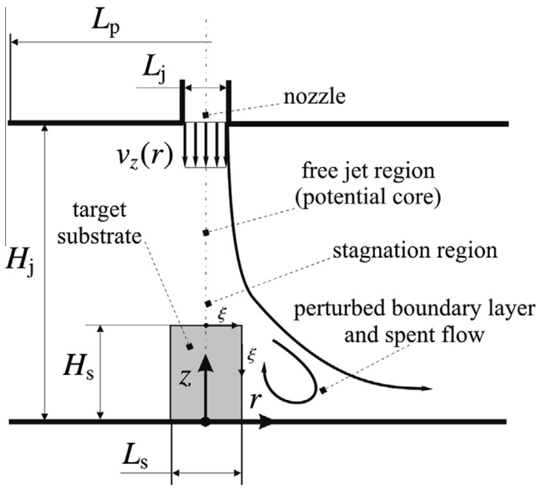

Fig. 1. The adopted geometry and nomenclature, with indication of characteristic flow regions, process coordinates r and z, and curvilinear coordinate ξ.