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Numerical study of the interaction among a pair of blunt plates subject to convective drying – A conjugate approach

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ABSTRACT

The effect of the relative positioning of a pair of porous blunt plates, subject to convective drying, on heat/mass transfer phenomena is investigated numerically based on a combination of a flow-heat transfer simulation with a suitable drying model. The air flow is assumed incompressible, two-dimensional, laminar, confined in a channel and parallel to the plates. The finite volume method is used and the computed temporal and spatial variations of flow parameters, moisture content and temperature for different arrangements are analyzed. Several configurations are studied: Side-by-Side, Staggered and in-Tandem arrangements, in an attempt to find the optimum relative positioning which results in the highest reduction of the mean moisture content of the plates, as well as in a more uniform drying. It was found that the Side-by-Side arrangement shows the best overall drying behaviour among all arrangements considered, owing to the enhancement of heat/mass transfer caused by the blockage effect. The analysis of the parameters affecting the transport rates and the uniformity of drying as well as the discussion of the development of unfavorable aerodynamic or thermal effects due to the interaction of product units, may be valuable in optimizing the arrangement of the products in the dryer.

1. Introduction

Flow and heat/mass transfer over bluff bodies occurs in many engineering applications, such as drying of agricultural products/building materials, cooling of electronic equipment modules etc. Such a configuration usually gives rise to a region of separated flow and an unsteady wake region downstream, both influencing heat and mass transfer. Among the most common configurations encountered in the aforementioned applications is the flow over rectangular cylinders of various aspect ratios. The fundamental fluid dynamical aspects for single rectangular cylinders of low AR (AR = length/height) have been examined extensively for unconfined [1–3] and confined flows [4–6], albeit not so much in conjunction with either heat or mass transfer.

On the other hand, there are several studies on a special type of rectangular cylinders characterized by a high AR (typically higher than 5) for which the term "blunt plate" has prevailed in the literature. Among the most representative experimental studies investigating the flow phenomena for low Reynolds numbers (Re) are those by Lane and Loehrke [7] and Ota et al. [8]. Lane and Loehrke [7] visualized the flow over a blunt plate and a leading edge separation bubble was first observed to form at $Re = 100$. For AR ≥ 8, the bubble grows in size with increasing Re, reaching a maximum streamwise length at $Re = 325$, while with further increase in Re, the separated shear layer becomes unsteady and the bubble shrinks in size. Ota et al. [8] conducted a visualization study for the reattachment length for flow over blunt flat plates, at $Re = 40–2000$. It was also found that the reattachment length increases with the increase of Re, reaches a maximum value and then decreases as the flow enters into a regime of unsteadiness. In addition, Tafti and Vanka [9] conducted two-dimensional (2-D) numerical study of flow separation and reattachment on a blunt plate with AR = 14, for steady ($Re = 150$, 250 and 300) and unsteady ($Re = 1000$) flow regimes. Tafti and Vanka [10] also conducted 3-D numerical study of flow separation and reattachment on a blunt plate and they found that the inclusion of spanwise variations provides superior comparison with experimental data.

Among the earliest of the overall few studies that considered flow over a blunt plate in combination with heat/mass transfer is the one by Sørensen [11], who obtained experimentally mass transfer coefficients on sharp-edged and truncated slabs of various thicknesses. Coincidentally, the motivation for that study was the prediction of heat and mass transfer coefficients from trays with material to be dried in a convective dryer, the topic of interest in the

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Nomenclature

AR	plate aspect ratio, $AR = L_s/H_s$
B	coupling parameter, $B = \Delta c/(\Delta W \rho_s)$
BR	blockage ratio, $BR = (nH_s)/H$, where $n = 1$ or 2 (the number of plates contributing to blockage at each streamwise location)
c, C	dimensional ($kg_{water}\ m^{-3}{}_{moist\ air}$) and dimensionless vapour concentration, $C = (c - c_{min})/\Delta c$, respectively
C_p	thermal capacity ($J\ kg^{-1}\ K^{-1}$)
d^*	dimensionless offset distance of plate
D	moisture diffusivity ($m^2\ s^{-1}$)
D_m	isothermal moisture diffusivity ($m^2\ s^{-1}$)
f	frequency of vortex shedding (s^{-1})
h_c	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$), $h_c = q/(T_w - T_\infty)$
h_m	convective mass transfer coefficient ($m\ s^{-1}$), $h_m = j/(c_w - c_\infty)$
H	height (m)
j	mass flux ($kg\ m^{-2}\ s^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
Ko	Kossovitch number, $Ko = (\Delta H \Delta W)/(C_{ps}\ \Delta T)$
L	length (m)
L_{sc}	length scale (m) for the non-dimensionalization, $L_{sc} = H_s$
Le	Lewis number, $Le = \alpha_f/D_f$
Lu	Luikov number, $Lu = D_m/\alpha_s$
Nu	Nusselt number, $Nu = (h_c L_{sc})/k_f = -(1/(\theta_w - \theta_\infty)) \times (\partial\theta/\partial n)_w$, where $n = X$ or Y (surface normal direction)
P, P_{ws}	total pressure of the humid air and saturation vapour pressure (Pa)
Pn	Posnov number, $Pn = (\delta \Delta T)/\Delta W$
q	heat flux ($W\ m^{-2}$)
R_{cp}	thermal capacity ratio, $R_{cp} = (\rho_s C_{ps})/(\rho_f C_{pf})$
R_{df}	thermal diffusivity ratio, $R_{df} = \alpha_s/\alpha_f$
Re	Reynolds number, $Re = (uL_{sc})/\nu$
S^*	dimensionless distance between the leading edges of the plates
Sc	Schmidt number, $Sc = \nu/D_f$
Sh	Sherwood number, $Sh = (h_m L_{sc})/D_m = -(1/(c_w - c_\infty)) \times (\partial c/\partial n)_w$, where $n = X$ or Y (surface normal direction)
St	Strouhal number, $St = (fL_{sc})/u_i$
t	dimensional time (s)
T	dimensional temperature (K)
U, V	dimensionless velocity components in the x and y directions respectively, $U = \frac{u}{u_i} = \frac{\partial\Psi}{\partial Y}$, $V = \frac{v}{v_i} = -\frac{\partial\Psi}{\partial X}$
u, v	dimensional velocity components in the x and y directions respectively ($m\ s^{-1}$)
W, w^*	dimensional ($kg_{water}\ kg^{-1}{}_{dry\ solid}$) on a dry basis (db) and dimensionless moisture content, $w^* = (W - W_{min})/\Delta W$
x, y	dimensional horizontal and vertical coordinate respectively (m)
X, Y	dimensionless coordinates, $X = x/L_{sc}$, $Y = y/L_{sc}$

Greek symbols

α	thermal diffusivity ($m^2\ s^{-1}$)
δ	thermal gradient coefficient (K^{-1})
Δc	$c_{max} - c_{min}$, where c_{max} the saturation value of vapour concentration at ambient temperature and c_{min} the concentration at wet bulb temperature
ΔH	heat of evaporation ($J\ kg^{-1}$)
ΔT	$T_{max} - T_{min}$, where T_{max}, T_{min} the incoming air dry and wet bulb temperature, respectively
ΔW	$W_{max} - W_{min}$, where W_{max} the initial, and W_{min} the final solid moisture content, respectively
ε	phase conversion coefficient
θ	dimensionless temperature, $\theta = (T - T_{min})/\Delta T$
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
τ	dimensionless time, $\tau = t/(L_{sc}/u_i)$
φ	relative humidity (%)
Ψ	stream function
Ω	vorticity, $\Omega = -\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X}$

Subscripts

∞	ambient
a	air
F	final
f	fluid
i	inlet
l	liquid
o	initial
s	solid (blunt plate)
sc	scale
v	vapor
w	wall (plate surface) value

present work as well. The results showed that mass transfer coefficients do not only depend on the air velocity and distance from the leading edge but the thickness of the slab is also of importance. Kottke et al. [12,13] studied mass transfer for turbulent flow over a thick blunt plate in comparison with thin-plate results. They found that for the thick plate the presence of separation bubble influences the mass transport coefficients. Furthermore, Hwang et al. [14] conducted mass transfer measurements from a blunt-faced flat plate in a uniform flow and found that the point of minimum Sherwood number (Sh) is located at a sort distance behind the leading edge, while the maximum is within the reattachment zone. Similar results for heat transfer were discussed in the numerical study of Kazeminejad et al. [15]. Yanaoka et al. [16] studied numerically the influence of separation, reattachment and vortex shedding on heat transfer for laminar flow over a blunt flat plate mounted inside a channel of square cross-section. Furthermore, Suksangpanomrung et al. [17] conducted a numerical study on heat transfer in pulsating flows through a bluff plate. It was found that pulsating flow introduces instability, the separation bubble decreases in size whereas heat transfer increases. In addition, Marty et al. [18] investigated both numerically and experimentally the heat exchange between a fluid and a blunt flat plate, at $Re = 120{-}500$. It was found that when Re increases, the bulk of the flow becomes unsteady and the leading-edge bubble unsteadiness is responsible for a pseudo-periodic impingement of external fluid on the wall, which locally increases both pressure coefficient and heat transfer.

However, limited results for flows over multiple blunt plates are available, especially for Reynolds numbers less than 1000. Among the few relevant studies is that of Hourigan et al. [19] who