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Conjugate heat and mass transfer in drying: A modeling review

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ABSTRACT

Coupled transfer mechanisms are common in a variety of industrial operations, as in food drying, and their virtualization is becoming indispensable. In this paper one such situation, a rectangular food chunk exposed to heat and mass transfer by a turbulent cross flow of air in a channel (Re $\simeq 1{\cdot}10^4$), is investigated by modeling the transfer mechanisms (linked each other by evaporation) in conjunction with the inherent flow transport. This formulation is referred to as a conjugate problem.

In the present model, the most limiting parameters that commonly are employed in such studies can be disregarded, i.e. the empirical heat and mass transfer coefficients at the auxiliary air/substrate interface: they refer to unrealistical average conditions and unspecified geometry variations.

After proper literature evaluation, the solution of a benchmark drying problem is discussed by assessing the conjugate and coupled features of the analytical development, focusing on some transfer phenomena loci on the sample's exposed surface. It is shown that, in case of a finite protrusion with a unitary form factor (height equals streamwise thickness) the average Nusselt number of about 25 (resumed from associated literature) greatly overestimates the one computed based on the model, everywhere along the exposed surface and during process time: varying up to 6 times along the lateral edges and dropping down to an average value of about 6 after less than 2 h of treatment.

1. Introduction

Many processes involve simultaneous heating and drying of given 3D moist substrates placed in a bulk flow of working air, generally in the turbulent regime. In the process industry, one of the simplest configuration is with the substrates protruding in the flow, therefore altering (and partially blocking) the boundary layer. But in this case, strong finishing effects in drying and thermization are produced, that can be reflected even within the substrate itself. These effects are impossible to study by analytical methods, and prohibitive to attack with experimental procedures. That is why numerical computations of such complex processes, or virtualization, come into play.

This classical problem of momentum transfer over protrusions has been treated numerically by Shah and Ferziger (1997), for example. Coherent horseshoe vortices, separations and wakes are created that affect the other transfer phenomena (Fiebig, 1998). Even during steady flows, nonuniform variable thermal and moisture driving forces are therefore determined over, through and along the exposed surfaces, depending on the altered flow field, yielding for complex distributions of temperature and residual moisture. This situation, referred to as a conjugate problem, is reviewed in the present paper.

The quantitative study of the heat transfer has clearly preceded the one on moisture transfer. External flows have drawn considerable attention over the years. The protrusion geometry exploited in this paper also differs from other classical arrangement, as the so-called immersed body (Knudsen et al., 1997; Culham et al., 2001). Average heat transfer for isoflux rectangular semi-cylinders (sitting on the floor, with their axis normal to the flow) was experimentally performed first by Roeller et al. (1991), in the $\overline{\mathrm{Nu}} = a\mathrm{Re}^b$ form, accounting for flow three-dimensionality and blockage.

A conjugate heat transfer is the one that analyzes the heat transfer simultaneously in both solid and fluid phases (Joshi and Nakayama, 2003), and the solution for temperature is determined with no need for empirical assumptions at the interface: isothermal or isoflux assumptions are no longer needed. In other words, the

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solution for temperature is shared seamlessly through the phases interface. One such work was first proposed by Davalath and Bayazitoglu (1987), for the case of laminar flow past protruding block arrays. Within this topic, the advent of vast computational power and the spread of knowledge and availability of realizable Computational Fluid Dynamics (CFD) modeling, has given way to more speculative insights. Sometime efforts were performed both by experiments and with numerical modeling, as with Meinders et al. (1999) and Popovac and Hanjalić (2009) who focussed on surface heat transfer from protrusions exposed to cross flow (with Reynolds numbers less than 5000), but without digging in conjugate effects. However, with the above-mentioned finishing effects in mind, it is now clear that the CFD offers the potential to virtualize the process and product conditioning in their essence, even yielding for local heat transfer description. Conjugate modeling in food heat transfer under a localized flow was performed for the first time by Dirita et al. (2007), who proposed as accurate evaluation of the local dimensionless heat flux across the food interface.

Water and its phase change are commonly found in many engineering and biotechnical applications in which the heat and mass transfers are inevitably intertwined, i.e. coupled and competing. This is the case with moisture drying: partial evaporation of the liquid phase occurs within substrate and at its exposed surface, producing a vapor phase which is removed from it. The need of drying is common, as an example, when seeking bio-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.

Coupled heat and mass transfer was addressed by De Vries (1958), Luikov et al. (1971) and Whitaker (1977), in the first place, by means of porous media formulations. Their analysis were adopted by many in the available literature, but only few implemented the additional notations for conjugate transfer, following the indications by Dolinskiy et al. (1991) on the discrepancies between conjugate and non-conjugate computations. In the present context, the same line than presented above is speculated: the heat and mass transfer are analyzed simultaneously in both solid and fluid phases. Oliveira and Haghighi (1998) obtained the temperature and the moisture contours during wood drying, but their work was limited due to the boundary layer assumption over the substrate. This approach was then overcome by Murugesan et al. (2001) and Suresh et al. (2001) for brick blocks, using a laminar 2D Navier–Stokes formulation (therefore with inherent limitations on geometry and flow regime), and focusing on the effect of buoyancy. Nonetheless those works correctly emphasized over average and local heat and mass transfer on the exposed substrate surface. Erriguible et al. (2006) solved for such a problem on a 2D porous block in a laminar flow. They did not reported for the experimental validation of the code, which was arranged in two parts, one dealing with the transport in the porous medium, the other solving for the flow field. A first model on conjugate drying in foods was proposed by De Bonis and Ruocco (2007), while applying localized convection. Food drying modeling can be attacked by rigorous porous media formulations, as reviewed by Datta (2007), but still appealing to empirical exchange coefficients. Curcio et al. (2008) showed how to avoid their use in modeling drying, but simplistic fluid dynamics (uniform velocity at inlet and turbulence in 2D geometry) and redundant boundary conditions (mixed scalar/vector continuity at interface, with different temperature solutions in both phases) were applied. De Bonis and Ruocco (2008) attacked the conjugate problem by imposing numerically-sound interface conditions instead, and by employing a drying kinetics in order to overcome the difficulties of the porous media formulation, but the substrate thinness posed no opportunity to dig into fluid flow effects. More details on this side were then reported by Lamnatou et al. (2009) for a square cylinder of a model food substrate, focusing upon the flow blockage and its influence over heat and mass transfer. Their work, nonetheless, did not account for turbulence effects and realistic geometries.

Except these few contributions, very little can be found in the available literature on coupled and conjugated transfer phenomena. Nowadays, the advantage of conjugate modeling is recognized to perform realistic studies (Defraeye et al., 2012), and conjugate experiments are still sought and speculated upon (Loiola and Altemani, 2014). De Bonis and Ruocco (2014) recently described the application of a moderately turbulent jet impingement, to treat a finite moist substrate within this line of speculation. With these deductions in mind, much of the available literature and results of multidimensional drying, which depend on empirical heat and mass transfer coefficients, can be referred to qualitatively, only (as for example in Kaya et al. (2006); Chandra Mohan and Talukdar (2010)). A round-up was tried by Dorfman (2010) on conjugate modeling, but unfortunately the few examples included therein were related to very simple geometries and laminar airflow, only. Once again, the CFD can be enforced to extract all of the information needed without recurring to the heat transfer/mass transfer analogy, but using directly the solutions for local energy and mass budgets to the coupled and conjugate local transfer descriptions.

In this paper, light is shed on such an implementation: a finite food chunk interacts with a developed turbulent air flow in a channel, allowing for a realistic treatment of the boundary layer. Therefore temperature, water vapor and residual moisture can be computed locally in a conjugate configuration based on the flow field interaction, over the exposed surface and beneath it, and the effect of flow disturbance, stagnation and wake are scrutinized. The dimensionless heat rate (that can be related then to the rate of moisture depletion) is analytically formulated and numerically solved, and compared to the available literature notations, emphasizing on its non-uniformity in space and time.

2. Problem formulation

Convection heat and mass transfer by a bulk, hot air draft is assumed to a generic 3D substrate protrusion, of finite size (Fig. 1), or a rectangular semi-cylinder, sitting on the drier floor with its main axis normal to the flow. The same lines of De Bonis and Ruocco (2008) are speculated: heat is transferred by convection from air to the protrusion's exposed surface, and by conduction from the surface toward the substrate interior. Meanwhile, moisture is converted into vapor or diffuses outward to the surface, where is vaporized.

The present study stems from the considering the actual flow field peculiarities which form when a bulk flow's boundary layer is perturbed by a relatively obstructive protrusion. Experimental

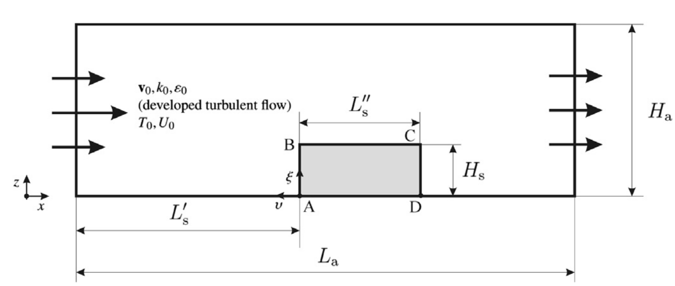

Fig. 1. A median section ($y = 0$) of channel and substrate sub-domains: geometry nomenclature. Channel and protrusion have width W_a and W_s, respectively. Global x, z and local ξ, υ coordinate systems are provided.

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