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Enhancing impinging jet heat or mass transfer by fluidically generated flow pulsation

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ABSTRACT

Periodic pulsation of high intensity generated by a no-moving-part fluidic oscillator located upstream from jet generating nozzles was demonstrated to enhance heating (or cooling and, because of the analogy of governing equations, also drying) by impinging hybrid-synthetic jets. The test setup was built for an envisaged application in food processing by baking or roasting. It has two nozzles, each connected to one of the two outlets of the diverter-type oscillator. The nozzles were of annular exit cross-section and operated in anti-parallel (outflow from one nozzle simultaneous with suction into the other nozzle). The investigation, focused on study of the temperature fields on a plane impingement wall visualised by thermochromic liquid crystals, revealed some unexpected effects.

Keywords: Heat transfer; Mass transfer; Pulsation; Fluidics; Impinging jet; Hybrid-synthetic jet

1. Introduction

Convective heating, cooling, and drying by fluids is an essential operation in a large number of technological processes. Effectiveness of these processes is limited by the very thin near-stagnant fluid layer held by viscosity at the surface of the heated (or cooled) body (Fig. 1). The transport has to cross this layer by conduction. This is, especially in gases, far less effective – by several orders of magnitude – than convection. Even if sometimes extremely thin, the stagnant layer thus represents the basic constraint to the whole transport process.

To minimise the conduction transport distance, the moving fluid has to get as near to the surface as possible. Turbulence, useful for moving the fluid towards the wall by the vortical motions, is damped in the viscosity-dominated region near the wall. Simple flow parallel to the wall in Fig. 1 is inefficient from this point of view, since the conduction layer there is usually thick. If the highest possible transfer rates are desired, the most efficient solution is to force the fluid as a jet oriented perpendicularly to the wall (Fig. 2). The impinging jets gets very near to the wall and as a result, are known to achieve the highest transfer rates among all convective transfer methods. An authoritative review of impinging jet heat and mass transfer, still unsurpassed for its depth, is Martin (1977). More recent surveys are Jambunathan et al. (1992) and Viskanta (1993).

One idea how to suppress the insulating effect of the stagnant layer is to oscillate the flow. The effect is particularly pronounced at low *Re* (e.g. in microdevices) where it can substitute the weak or absent turbulent fluctuation. The idea is not new and has been already tried in other convective heat transfer situations. Early objections to it were the complexity of the additional machinery required for modulating the nozzle flow and also the necessary power to drive it. A piston pulsator or mechanically driven valves are indeed too expensive considering the usually not significant achieved improvement. Fortunately, the recent progress of fluidics, the technique of fluid flow control without moving mechanical devices, e.g. Tesař (2004) or Tesař (2007b), offers a simple and reliable solution, needing no external driving power (such as e.g. an electric input).

Tesař and Marvan (1989), may be cited as providing an example of the heat transfer improvement, in a simple heat exchanger, by a pulsation produced by a no-moving-part fluidic oscillator. The enhancement reported there characteristically exhibited resonant peaks to which the driving frequency has to be tuned. Apart from selection of the proper frequency there are other parameters the adjustment of which

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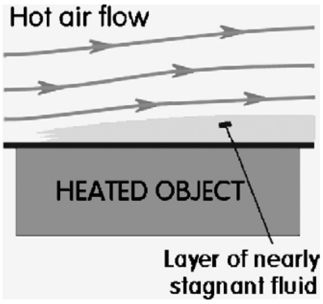

Fig. 1 – The effect limiting convective transport between a fluid and a solid object is the near-stagnant fluid layer at the surface, as is here schematically represented. Heat and/or mass transport across this layer is by much less effective conduction mechanism.

for obtaining a significant improvement is a rather difficult task. If the conditions are not properly adjusted, the pulsation may be quite useless. The near-wall layer, responsible for most of the thermal resistance, exhibits a strong and selective damping capability (Tesař, 1998a,b; Tesař and Trávníček, 2005a,b) enabling it to absorb improperly adjusted oscillation without any enhancement effect. The pulsation energy may be also uselessly spent on formation of vortical structures near the nozzle exit (Tesař and Ho, 1998; Tesař, 1998b). In fact, Vejrazka et al. (2005), in studies of the vortical structures in impinging jets, demonstrated that improperly adjusted excitation can even decrease the transfer rate. Hwang and Cho (2003) have shown that the intensification by superimposed pulsation is most pronounced if the separations between the nozzle and impingement surface is large. Indeed, in the related case of a planar jet issuing from a slot, Camci and Herr (2002) found Nusslet number increase as large as 20% and 70% for the separations between 24 and 60 slot widths, respectively. Of course, this is not very helpful for most applications because at these large nozzle distances the transfer rates are weak (Jiang et al., 2006).

Generally more likely to succeed, even with the nozzle nearer to the surface, is pulsation of a large velocity amplitude relative to the time-mean velocity. This may even result in temporary stopping the flow at some instant in each period or even flow reversal. In an unsteady flow starting from rest, the wall layer grows in proportion to square root of time. If the growth stops and then begins to grow anew in each period, chances are it will never reach its steady-state thickness. The extreme case is synthetic jet—Glezer and Amitay (2002), Holman et al. (2005), Crittenden and Glezer (2006), Baydar and Ozmen (2006). Its characteristic feature is zero time-mean nozzle flow rate (Tesař, 1984, 1991; Tesař and Zhong, 2003). Studies of synthetic jets originated from the idea of no-moving-part fluidic rectification (Tesař, 1982, 1984). The name “synthetic” jets, conveying the idea of their being synthesized from a succession of individual vortex rings (which is actually true only for some regimes, Tesař and Zhong, 2003), was introduced later by prof. Glezer (Glezer and Amitay, 2002; Crittenden and Glezer, 2006). Typical uses are flow control in external aerodynamics (e.g., Tesař, 2006). When applied to heat and mass transfer (Trávníček and Tesař, 2003; Tesař and Trávníček, 2005b; Kercher et al., 2003), synthetic jets are capable of achieving exceptionally high transfer rates—but their zero time-mean nozzle flow rate makes them impractical for continuous operation. Re-ingesting the same fluid finally removes the temperature gradients driving the transfer.

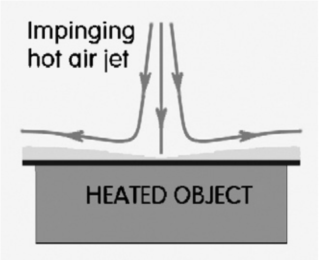

Fig. 2 – The insulating stagnant layer is thinnest – and heat or mass transfer therefore most intensive – under an impinging jet.

The solution are hybrid-synthetic jets (Trávníček et al., 2005, 2006; Tesař et al., 2006, 2007; Tesař, 2007a), essentially a superposition of a synthetic jet and a steady outflow from the nozzle. The time-mean flow rate is non-zero, so that e.g. some cold air is always supplied into the impingement cooling region. There are two versions of the actuators used for producing it. In the first one (Trávníček et al., 2005), the actuator essentially contains a no-moving-part fluidic pump and needs no fluid supply. The other version (Tesař et al., 2006; Tesař, 2007a), uses a supply-flow-driven fluidic no-moving-part oscillator, usually consisting of a diverter jet-type amplifier and a feedback loop.

2. Application to roasting and baking

This paper describes a recent project inspired by a prospective application of impinging jet heating to thermal processing of food. The idea was to apply it as a parallel additional heating method for improving the food processing properties of microwave ovens. To operate together with the fast microwaving, the thermal power transfer of the impinging jets had to be exceptionally effective—but at the same time spread over the food product surface rather than concentrated in the small stagnation region, where it would cause thermal decomposition of the food. A unit capable of meeting this requirement, small enough for being built into the available space in microwave ovens, was designed and laboratory tested. The high performance was achieved by applying the hybrid-synthetic jet principle, using the oscillator actuator version. The oscillator is a simple fluidic hot-air-driven device, small, reliable and inexpensive.

The impinging jets unit was tested in comparison-type experiments. The improvement in heat transfer was evaluated relative to steady-flow impinging jets. The fluidic oscillator was used alternatively with a simple flow-distributing manifold, the latter producing no oscillation but exhibiting the same hydraulic loss. The performance was evaluated by processing the data on the generated temperature distribution on a flat impingement surface, obtained by means of thermochromic liquid crystals.

The importance of the project rests on the popularity microwave ovens as thermal food processors. Estimated 95% of Americans own one and 75% of them use it every day (Parker and Vollmer, 2004). In Europe at the beginning of the new millennium, its sales outstripped those of both DVD players and refrigerators, and are currently still rising. The popularity is due to saving time. The heating is fast because it acts instantly inside the food rather than acting from outside and progressing inwards as was the case in all earlier food processing methods. The internal action, however, has its disadvantages. It fails to produce the attractive qualities traditionally asso-