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Experimental study of airflow and heat transfer above a hot liquid surface simulating a cup of drink

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ABSTRACT

This work was carried out to study the airflow and heat transfer above a cup of hot drink. The experiment was undertaken in a device in which the air temperature and velocity were controlled representing a room condition. The influence of heat exchange by convection and evaporation between the hot drink (at different temperatures) and air on the velocity and temperature fields above the cup is presented. An experimental methodology was developed to evaluate the heat transfer coefficient between the air and hot drink with and without evaporation.

The airflow visualisation by PIV (Particle Imagery Velocimetry) above the cup shows that the flow is complex with unsteady plumes detachment and vortex formation. The combined convection and evaporation lead to upward airflow with temperature fluctuations which become significant for drink temperature above 55 °C. This can be explained by the non-linearity between saturated pressure of water and its temperature. This work could highlight how volatile aromas are released from hot drink.
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1. Introduction

Odour during food consumption largely influences perception of foods and is thus determinant in consumer preference. Food aroma compounds are released to ambient air and are responsible for the ambient smell of the room where the food is consumed. The ambient smell greatly influences food intake and food choice (Stroebele and De Castro, 2004). To be able to better understand the impact of smell ambient due to food on consumer behaviour, it is first necessary to identify key room factors impacting aroma release to ambient air. Aroma release phenomena involve multi-factorial and complex processes. In the case of a cup of hot drink, it consists in aroma diffusion to liquid surface, aroma transportation to the surrounding air due to diffusion, convection and compounds/water mixture evaporation through a boundary layer (located above liquid surface). Then, aroma compounds follow airflow in the room and arrive to the consumer nose. This study focuses only on the airflow, heat and vapour transfer just above the cup. The understanding of these mechanisms is a first step useful for understanding and controlling the aroma perception by consumer.

1.1. Studies on aroma compounds in foods

Aroma, which is one of the key components of food flavour, depends on the type and concentration of volatile compounds present in the air above the food and in the oral cavity during eating, and how they interact with appropriate sensory receptors in nose when they are carried by the breath of the individual (Overbosch et al., 1991; Taylor and Linforth, 1996). Many studies highlighted the influence of physicochemical properties of aroma compounds (volatility, hydrophobicity), the released amounts and kinetics, for model food (Landy et al., 1998; Marin et al., 1999; Carey et al., 2002; Philippe et al., 2003; Rabe et al., 2004; Meynier et al., 2005; Giroux et al., 2007) and real food (Doulia et al., 2000;

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Nomenclature

A	surface area, m^2
D	cylinder diameter, m
L	characteristic length, m
f	frequency of vortex shedding, Hz
g	gravitational acceleration, m s^{-2}
h	convective heat transfer coefficient, W m^{-2} K^{-1}
M	molecular weight, Kg mol^{-1}
Q	heat exchange, W
t	time, s
T	temperature, °C
v	velocity, m s^{-1}
x	molar fraction of water in air
Greek symbols	
β	thermal expansion coefficient, K^{-1}
ρ	density of the fluid, kg m^{-3}
ν	kinematic viscosity, m^2 s^{-1}
α	thermal diffusivity, m^2 s^{-1}

Dimensionless number	
Reynolds number $Re_L = \frac{v_\infty L}{\nu}$	Characterization of flow regimes for forced convection: laminar or turbulent flow
Grashof number $Gr_L = \frac{g\beta(T_w - T_\infty)L^3}{\nu^2}$	Ratio of buoyancy to viscous force acting on a fluid
Prandt number $Pr = \frac{\nu}{\alpha} = 0.71$ for air	Ratio of momentum diffusivity to thermal diffusivity
Rayleigh number $Ra_L = Gr_L.Pr_L$	Characterization of flow regime for natural convection: laminar or turbulent flow
Nusselt number $Nu_L = \frac{h.L}{\lambda_{air}}$	Ratio of convective to conductive heat transfer
Richardson number $Ri_L = \frac{Gr_L}{Re_L^2}$	Characterization of the importance of natural convection relative to forced convection
Strouhal number $St = \frac{fD}{v}$	Dimensionless frequency of oscillating flow

Doyen et al., 2001; Roberts et al., 2003; Relkin et al., 2004; Deleris et al., 2009). In the case of real food, products are generally complex. Thus, global characterization and determination of apparent properties are often the most convenient ways to represent transport properties and explain release profiles. For solid foods, aroma release is often limited by the diffusion inside the food. For liquid foods, especially drinks of low viscosity, release is also controlled by the transport phenomena from the liquid/air interface to surrounding air (Marin et al., 1999).

1.2. Airflow and heat transfer between object and air

The exchange between the hot drink and the ambient air can be due to natural or forced convection. To understand the airflow, heat and water transfer between a cup of hot drink and air, the simplest way is to consider the similar phenomena occurring above a heated horizontal flat plate. Another way is to consider the cup as a cylindrical obstacle of airflow. A literature review of air flows over a flat plate and around a cylinder is, thus, presented below.

Over an isothermal flat plate, a laminar flow is first observed, then after a certain flow length (called critical length) the flow becomes unstable and turbulent. This instability occurs usually when $Re \approx 3.10^5$ (Incropera and Dewitt, 1996).

Different flow patterns occur around a cylinder in function of air velocity. For $Re \ll 1$, the flow smoothly divides and reunites around the cylinder. For $Re \approx 10$, the flow separates in the downstream and the wake is formed by two symmetric eddies. The eddies remain steady and symmetrical but grow in size up to a Reynolds number of about 90. At $Re \geq 90$, the symmetry between the two eddies is broken. The downstream vortices become unstable, separate from the body and are alternately shed downstream for $90 \leq Re \leq 10^4$. The alternate shedding is called the Karman vortex street. This type of flow is unsteady but repeats itself at some time interval.

For natural convection, the driving force is the temperature difference between the drink and air, the flow regime is characterised by the Rayleigh number: Ra (warm air flows upward from the drink surface and this air is replaced by cooler air flowing downward from the ambient). For forced convection which may occur in ventilated room, the driving force is air velocity, the flow regime is characterised by the Reynolds number Re. The intensity of heat exchange is characterised by Nusselt number (Nu) which can be related to mass exchange by Lewis analogy.

Incropera and DeWitt (1996) proposed the following correlations of the mean Nusselt number (Nu_L) for airflow over a horizontal flat plate of characteristic length L.

Natural convection, here L is the surface area divided by the perimeter:

$$Nu_L = 0.54 Ra_L^{1/4} \quad 10^4 \leq Ra_L \leq 10^7 \quad \text{Laminar flow} \tag{1}$$

Forced convection, here L is the length of the plate in the flow direction:

$$Nu_L = 0.664 Re_L^{1/2} Pr^{1/3} \quad Re_L \leq 2500 \quad \text{Laminar flow} \tag{2}$$

The Richardson number ($Ri = Gr/Re^2$) indicates the importance of natural convection relative to the forced convection. Typically, the natural convection is considered when $Ri > 10$ (negligible forced convection), mixed convection when $0.1 < Ri < 10$ and forced convection is considered when $Ri < 0.1$ (negligible natural convection) (Incropera and DeWitt, 1996).

Most of the studies found in the literature about fluid flow and heat transfer around complex obstacles are applied to building air conditioning, heat exchangers and electronic equipment cooling. In these applications, various obstacles are employed to alter the flow pattern which leads to locally increase or decrease heat exchange. The experimental studies are rare in comparison with the numerical ones because of the metrology difficulties and cost. Several authors reported that the fluid flow over blocks is complicated unsteady motion and the average flow often looks very different from the instantaneous flow (Rahman et al., 2008, 2009; Chyu and Natarajan, 1996). Although the geometry has a symmetry plane, the instantaneous velocity field is not symmetric while the time average flow must be symmetric. The changes in obstacle size or shape can lead to Nusselt number increases as high as 40% (Jubran et al., 1996) and mass transfer enhancements up to two times (Sparrow et al., 1982, 1984). Heat transfer and airflow by mixed

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