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Heat transfer coefficients measurement in industrial freezing equipment by using heat flux sensors

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Abstract

Heat transfer coefficients, either for convection or conduction mechanisms were determined by using heat flux sensors coupled to temperature measurement devices. Three distinct pieces of equipment were assessed with respect to their heat transfer capabilities. The dynamic variability of heat transfer coefficients was determined along the processing length of a conduction–convection SuperContact® tunnel and a fluidized bed freezer. The main sources of heat transfer inefficiency were uneven air speed profiles for convection and high thermal contact resistance for conduction mechanisms. Fluctuation of coolant temperature was determined to be the limiting factor in a plate freezer. Simulations either with Tylose® gel (SuperContact® tunnel) or with mashed carrot (plate freezer) were carried out to predict improvement in heat transfer coefficients.

Keywords: Heat flux; Heat transfer coefficient; Heat flux sensor; Freezing

1. Introduction

The simulation of the performance of a freezing system is required for its design, adaptation and operation. For this, the accurate knowledge of the heat transfer coefficients is essential in order to obtain a reliable prediction. Heat transfer coefficients and refrigeration loads, however, are often complex to be estimated in industrial processing conditions. Uncertainty in the order of 10–30% is commonly reported in the literature (Becker & Fricke, 2003; Cleland & Özilgen, 1998).

It is still common practice to collect product temperature–time data and apply regression analysis using different models to derive the heat transfer coefficients. Analytical modeling is difficult due to the discontinuity inherent to phase change and to unsteady conditions (Heldman & Taylor, 1997). Numerical modeling, although accurate, is strongly dependent on the thermophysical properties of the product undergoing freezing, and results in an average value for the heat transfer coefficient during the entire processing cycle (Cleland, 1990). The dynamic variation of coefficients in function of time and in different locations in the equipment can be modeled by using CFD techniques (Verboven, Nicolaï, Scheerlinck, & De Baerdemaeker, 1997), but again the complexity of realistic problem formulation and the intensive calculation required still keep this method of little use for practitioners. Experimentally calculated heat transfer coefficients for food products were systematically collected in the form of dimensionless correlations by different authors (Arce & Sweat, 1980; Fricke & Becker, 2002; Stewart, Becker, Greer, & Stickler, 1990), frequently in the form of $Nu = f(Re, Pr)$. These correlations are useful for a first approach, but their use in real engineering problems finds limitations due to the specific configuration used in the experiments or partially available information. Moreover, information about heat transfer coefficients in industrial scale equipment is scarce in the literature.

Recent research work (Harris, Lovatt, & Willix, 1999; Harris, Willix, & Lovatt, 2003) has presented a customized sensor for local heat transfer coefficient determination. A good accuracy was achieved, but the system needs further development for other applications, particularly for reduced geometries and unsteady processing conditions.

The aim of this work is to present the use of heat flux sensors coupled to a plastic support in order to map heat

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Nomenclature

Bi	Biot Number; dimensionless
e	thickness (m)
F	temperature correction factor; dimensionless
h	surface heat transfer coefficient (W m^{-2} °C^{-1})
H	volumetric enthalpy (J m^{-3})
m	number of thermocouple locations
n	nth node in a grid
Nu	Nusselt number; dimensionless
Pr	Prandtl number; dimensionless
q	heat flux (W m^{-2})
R	thermal resistance (m^2 °C W^{-1})
Re	Reynolds number; dimensionless
S	sensitivity (V m^2 W^{-1})
SSQ	sum of squared residuals
t	time (s)
T	temperature (°C)
T^*	dimensionless temperature
U	global heat transfer coefficient (W m^{-2} °C^{-1})
V	electromotive force (mV)
x	space coordinate (m)
x^*	space coordinate; dimensionless ($x^* = x/e$)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
λ	thermal conductivity (W m^{-2} °C^{-1})

Subscripts and superscripts

a	ambient
air	air-exposed surface
cool	coolant
hs	heat sink compound
i	initial
j	jth thermal resistance
k	kth time interval
l	lth thermocouple position
n	node at the air-exposed surface
0	node at the isolated surface
p	predicted
pl	plastic
q	heat flux
sole	related to the sole
steel	related to the sole material
T	temperature

transfer in industrial scale freezing equipment. The simplicity of the method has a great potential to provide practitioners with a simple tool to estimate the heat transfer coefficients and rates in real processing situations, in an on-line basis, and without any knowledge of the thermophysical properties of the product or extensive calculation. The mechanisms of heat conduction and convection were analyzed in three different pieces of equipment: a fluidized bed tunnel, a contact plate freezer and a conduction–convection SuperContact® tunnel.

The heat flux sensor consists of a serial array of very small thermocouples embedded in a substrate material. The thin flat sensor formed has the thermocouple junctions distributed symmetrically along both plane surfaces and works as a differential thermocouple. It is designed to be attached to the surface of the material that exchanges heat with the environment. The instantaneous heat flux (W m^{-2}) traversing the surface of the sensor is calculated by dividing the measured electromotive force (μV) by the sensitivity (μV m^2 W^{-1}) of the instrument. Flux sensors, although used regularly in other fields like pipe insulation testing or building thermal comfort assessment (Langley, Barnes, Matijasevic, & Gandhi, 1999), still find little use in food engineering. The main reasons are the difficulty of reliable calibration procedures, proper selection of sensor's size and sensitivity, and of finding suitable attachment methods to the food surface. These topics were presented in a previous work (Amarante, Lanoisellé, & Ramirez, 2003a).

2. Materials and methods

2.1. Instruments and data acquisition

By selecting flux sensors, a small ratio of thickness to radius of the sensor is a general guideline in order to reduce the protrusion caused by the instrument's implantation on the surface of the substrate to be measured (Barnes, 1999). This is important to reduce the disruption of fluid flow lines on the surface of the system, which could disturb the convection mechanism. On the other hand small surface areas help in reducing the physical barrier imposed to the system by the sensor, and consequently minimizes the effects of different thermal conductivities (conduction disturbance) and emissivities (radiation disturbance) between the sensor and the substrate. Thus, heat flux sensors RdF 27036-3 (RdF Corp., USA) were chosen for their small surface area (6.0 mm width × 16.0 mm length) and thickness (0.30 mm), and high nominal sensitivity (0.36 μV m^2 W^{-1}). The flux sensors were connected to a SRMini data acquisition System (13-bit conversion, TCSA, France), which allowed a resolution of 2 μV for the signal delivered by the instrument. Complementarity to the flux sensors, 10 wire thermocouples (T type, diameter 1.0 and 0.5 mm), two low thermal mass foil thermocouples (Ref. 20117, type T, foil thickness 5×10^{-3} mm, surface area 63.0 mm^2, RdF Corp., USA) and a propeller anemometer (Miniair 64, range 0.3–20.0