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Infrared thermography as a complementary tool for the evaluation of heat transfer in the freezing of fruit juice model solutions

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ABSTRACT

The heat transfer process during the freezing of 600 kg of fruit juice model solutions in common containers (boxes, buckets and metallic drums), and different settings in a freezing tunnel, was studied. The air velocity was measured at several points in the entire tunnel. Thermocouples were installed to monitor the temperature profiles within the solution, at the packaging surface and cooling air. To measure the experimental effective heat transfer coefficients conventional temperature measurements with thermocouples and infrared thermography technology were used to map the distribution of the coefficients throughout the surface. Energy consumption involved in each configuration was evaluated. The higher velocities occurred at greater height (above the stacking and drums), being possible to verify the existence of preferential airflow pathways near the door and at the tunnel bottom. The highest air velocities observed were 2.85 m s^{-1}; 2.72 m s^{-1}, and 2.62 m s^{-1} for drums, boxes and buckets, respectively. The movement of the freezing front has begun from the outermost containers toward those located in the center of the stacks and the average freezing time was 51 h (plastic boxes), 55 h (plastic buckets) and 102 h for metal drums. The energy consumption for drums has been almost the double when comparing with buckets and boxes. The distribution of the local convective heat coefficients throughout the freezing process was not constant. Variations and different intensities of scatter were observed for the different packaging configurations and for the different periods during the freezing process (precooling, phase change and tempering). Thermal imaging technology proved useful in the study of heat transfer coefficients, allowing their complete mapping on the surface of the packaging, without the necessity of direct contact with the product.

1. Introduction

Many industrial processes are based on a simultaneous heat and mass transfer between a solid of complex shape and an air flow. This is what normally occurs in food processing when applying techniques such as refrigeration, freezing, and drying [1]. These processes are considered to be of great interest. Once implemented in an industrial practice, they add value to food, contribute to the reduction of losses, and make it available for longer periods.

A large increase in the production and consumption of fruit pulp, juice, and other fruit products has been recorded over the last decade. Hence, it generates an increasing interest in determining thermal properties, simulation and optimization of processes, as well the development of new systems and equipments in this area [2].

In a freezing system, the simulation of its performance 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. However, this parameter is often complex to be estimated in industrial processing conditions

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Nomenclature

a	Coefficient of equation (5)
A	Heat transfer area m^2
b	Coefficient of equation (5)
Bi	Biot number
c	Coefficient of equation (5)
c_p	Specific heat kJ.kg^{-1}.K^{-1}
d	Coefficient of equation (5)
DSC	Differential scanning calorimeter
e	Coefficient of equation (5)
h	Convective heat transfer coefficient W.m^{-2}.K^{-1}
H	Enthalpy kJ.kg^{-1}
m	Mass kg
T	Temperature °C
t	Time min
x	Depth in the coordinate system cm
y	Height in the coordinate system cm
z	Width in the coordinate system cm
Subscripts	
air	Air
ct	Container
if	Initial freezing
p	Pressure
SC	Subcooling
sol	Solution

such as a freezing tunnel [3].

Researchers have noted that the velocity of fluid through the product is the most significant factor influencing the surface heat transfer coefficient [4] and the air flow is a critical point in the installation. Due to the strong variability of the air velocity in space and time, its measurement is considered a challenge, which often produces unreliable results that are subsequently used in the heat transfer calculations, such as the determination of the heat transfer coefficients [3,5]. Uncertainty in the order of 10%–30% is commonly reported in the literature for this parameter [6,7].

Temperature acquisition at the surface of the sample are needed to determine the local heat transfer coefficients. However, the measurements using conventional experimental methods such as thermometers and thermocouples are done with relative difficulty due to the placement and attachment of sensors. These devices can change the flow properties on the product surface. When the surface format is simple and small, just few thermocouples are needed for the measurement. However, when there are more complex shapes, the number of thermocouples must be increased to adequately describe the distribution of the heat transfer coefficient. This fact can aggravate the changes in air flow properties on the product surface [1].

Within this context, new and innovative technologies have been invested to assist the processes occurring in food industry in order to increase their quality and safety. Among them we can mention the infrared thermography, a powerful experimental tool for non-intrusive measurements of temperature in areas of particular interest in industrial applications such as inspection and quality control, but also in scientific applications such as the local identification of thermophysical parameters [8,9]. There are some potential advantages of the use of infrared thermography in processes involving heat transfer, comparing to tests of invasive sampling with thermocouples and conventional thermometers. Some of them include high-speed, non-intrusive analysis that do not interfere at the flow characteristics and do not bring interference due to the heat conduction through the thermocouple and still avoid contamination by contact with the product [8–10]. Moreover, as a two-dimensional measurement technology, the infrared camera is able to produce a full field of view on the surface of a product, effectively making it possible to measure convective heat flows [8,9].

Since information on heat transfer coefficients in industrial scale equipment is scarce in the literature [3], the objectives of this work were: 1) to study the heat transfer process during the freezing of fruit juice model solution in common containers (boxes, buckets, and metallic drums) and different settings in a freezing tunnel; 2) to measure the experimental effective heat transfer coefficients in these configurations using conventional temperature measurements with thermocouples and infrared thermography technology to map the distribution of the coefficients on the surfaces of packaging, and 3) to evaluate the energy consumption involved in the processing for the three configurations considering a fixed quantity of the product.

2. Material and methods

2.1. Freezing of solution model

A model solution was used to simulate fruit juices, which consisted of 0.5% of k-carrageenan (weight/volume in water) and 10% sucrose (weight/volume in water). The k-carrageenan was added in order to avoid convection processes within the solution. Systems with higher viscosity prevent the formation of natural convective currents, being the most notable effect at low temperatures and under these conditions, the heat transfer by conduction within the solution rules the process [2]. The sucrose was used to simulate the total soluble solids of a fruit juice. According to Saad and Scott [11], sucrose is the regular sugar presents in various food products, including the fruit juices. The fruit juices exhibit a variety of total soluble solids content and the concentration of 10% sucrose was chosen for being a representative average value of the total soluble solids content of various tropical fruit juices [12].

The cooling and freezing of the solution were carried out in an air blast freezer under controlled condition at −25 °C. The load consisted of 3 packing configurations: either 40 of high density polyethylene buckets (HDPE) with 15 kg of solution each, 40 HDPE boxes of 15 kg of solution each or three metal drums with 200 kg of solution each, totaling 600 kg in each case. For the boxes and drums, plastic bags of polyethylene were used for holding the solution. Fig. 1 shows the internal dimensions of the freezing tunnel, the direction of air flow, the positioning of the inspection windows and the rectangular coordinate system (x, y, z) which was used as a reference in all configurations throughout this work. The coordinates x, y and z represent the dimensions of depth, height, and width, respectively.

The positioning of inspection windows were set in (x, y and z) coordinates which were (117.5 cm, 231 cm, 40 cm) - for the window 1 and (117.5 cm, 88.5 cm, 0 cm) - for the window 2.

2.2. Monitoring the temperature of the solution, air and packaging surface

Temperature profiles were obtained with 45 temperature sensors (type T thermocouple copper/constantan AWG-24 and