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Research Paper

Heat transfer finite element model of fresh fruit salad insulating packages in non-refrigerated conditions

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The quality of many foods is significantly affected by temperature fluctuations that can occur during distribution and transport. Packaging materials can help to shield the product from temperature variation by increasing the heat transfer resistance. Thermal insulation power is influenced by several factors, such as material, geometry, and degree of contact between materials. To maintain the cool chain of fruit salad with syrup during the transportation (temperature less than 5 °C), thermal insulation effect of different packaging materials was investigated. A parametric analysis using a finite element model able to describe the heat transfer inside the containers, on varying packaging material (expanded polystyrene: EPS, and air), geometry, dimension, and boundary conditions, was developed and validated. Good agreement was obtained between numerical and experimental results (R^2 up to 0.98). The effectiveness of the insulation configurations was evaluated by determining the time taken for the temperature to rise the critical value of 5 °C. Results showed that insulating performance of the air is better than EPS. This is realistic only taking into account insulation layer less than 0.013 m. From a practical point of view, an EPS packaging could result stronger compared to a packaging characterised by an insulating air layer. For the same EPS insulation thickness, product temperature exponentially decreases with the volumetric capacity ($R^2 = 0.99$).

1. Introduction

The quality of frozen and chilled foods, in terms of microbiological grown, chemical, physical and nutritional properties, is significantly affected by temperature fluctuations (Erickson & Hung, 1997; Gospavic, Margeirsson, & Popov, 2012). During food distribution and transportation, the products may be exposed to non-refrigerated environment conditions (Sun, 2011). Transportation is consequently a crucial phase for the perishable food, such as vegetables, fruits, fish and meats (Pathare & Opara, 2014). The relative loss of perishable foods through a lack of refrigeration has been estimated equal to 20% worldwide and about 9% for developed countries (IIR, 2009).

By reducing heat transfer from the outside environment, packaging can help to shield the product from temperature variation in the storage and transport. Temperature stability can be improved by increasing the packaging heat transfer

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Nomenclature

d	Thickness (m)
h	Heat transfer coefficient (W m^{-2} K^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
q	Heat flux (W m^{-2})
t	Time (s)
Cp	Specific heat (J kg^{-1} K^{-1})
L	Characteristic length (m)
R	Heat transfer resistance (m^2 K W^{-1})
T	Temperature (°C)
Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
α	Thermal diffusivity (m^2 s^{-1})
β	Air thermal expansion (K^{-1})
ε	Fraction
μ	Dynamic viscosity (Pas)
ρ	Density (kg m^{-3})

Subscripts

a	Air
bot	Packaging bottom
c	Continuous phase
cn	Contact
d	Dispersed phase
ext	Packaging surface
m	Maxwell
p	Parallel
s	Series
top	Packaging top
tot	Total
$side$	Packaging sides
C	Convective
∞	Environment

resistance (Choi & Burgess, 2007; Zuritz & Sastry, 1986). Several factors such as material, geometry and degree of contact between product and package, affect the insulating power. Furthermore, due to small opening, the air currents can flow in and out from the package, carrying heat with them to render even the best insulator ineffective. Accordingly, sealing the package plays a fundamental role in product temperature control (Choi & Burgess, 2007). Concerning the geometry, the wall thickness controls the heat transfer by conduction, meanwhile the surface area guides the heat transfer by convection and radiation (Singh, Burgess, & Singh, 2008). Thicker walls have a better insulation power, but in many cases, trapped air spaces between thinner multilayer, can make better insulators than one thick wall. The material used for packaging is another important aspect to consider (Carlos & Sudhir, 1988). Plastic foam, particularly expanded polystyrene (EPS), is the most common and economical insulating material used to preserve the refrigeration temperature of food product during the transport (Burgess, 1999; Stubbs, Pulko, & Wilkinson, 2004). Low thermal conductivity of this material is imputed to the low thermal conductivity of the air enclosed within the cells and the relatively small amount of solid material through which heat may be conducted. Accordingly, about 98% of the volume of an EPS box consists of air pores (Margeirsson, Gospavic, Pálsson, Arason, & Popov, 2011).

To improve the design and the capability of the insulating packaging, several mathematical, analytical and numerical models, are reported in literature (Almonacid-Merino & Torres, 1993; Choi & Burgess, 2007; Qian & Zhao, 2013; Ge, Cheng, & Li, 2014; Singh et al., 2008). Moreover, numerical heat transfer modelling is a valuable tool to predict temperature food change under thermal fluctuations (Norton & Sun, 2006; Scott & Richardson, 1997; Wang & Sun, 2003). Nevertheless, few studies are based on the finite element technique and focused on the preservation of perishable food products during transport.

The main advantages of the numerical models over analytical models are related to the possibility of considering complex geometries, materials and boundary conditions. Moreover, the possibility to predict the temperature distribution inside the whole package and not only the mean product temperature is an advantage.

Gospavic et al. (2012) proposed a mathematical model for the heat transfer from surrounding environment to a single food package. A simplified analytical solution for 3D unsteady temperature distribution in the food package, was obtained. Margeirsson et al. (2012) developed a finite volume heat transfer model of temperature fluctuations of chilled cod fillets packaged in EPS stored under dynamic temperature. In general, a good agreement between numerical and experimental results was reported. To study the thermal protection of an insulated pallet cover during logistic operations in uncontrolled environments, a 3D finite volume heat transfer model, was developed by Moureh, Laguerette, Flick, and Commere (2002). The model considered the thermal characteristics of the cover and products, the pallets arrangement in the canvas and the external ambient temperature. Regarding perishable fruits, Marai, Ferrai, and Civelli (2012) proposed a 3D heat transfer model to study a possible optimisation of the postharvest transport in cold chain of blueberries by using EPS box and ice slab. Results seem to be encouraging, nevertheless future improvements of the model were required.

The aim of this study was to investigate the possibility to maintain the cool chain of fruit salad with syrup by improving the thermal insulation of a specific plastic container. A parametric analysis using a finite element model able to describe the heat transfer inside the container, by varying the material (EPS and air), geometry and dimension of the insulation packaging and the environment temperature, was developed and validated.

2. Materials and methods

To preserve the optimal chemical, physical and microbiological characteristics of fruit salad, its temperature should be maintained below 5 °C. Due to the recurring opening of the track doors, especially in summer, the transport temperatures can frequently reach 15 °C. The fruit salads are often packaged in simple small containers made of polypropylene (PP). In this study, fruit salad packaged in 4.6-l containers was considered.

To improve the thermal insulation and maintain the cool chain of fruit salad during the transport, several material,