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Review Article

A review on surface heat and mass transfer coefficients during air chilling and storage of food products

Alain Kondjoyan*

Transfer & Quality Modelling Team, Laboratory of Animal Products Quality, QuaPA, INRA, 63122 St Genès Champanelle, France

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Abstract

Heat and mass transfer coefficients are needed for the mathematical simulation of air chilling and storage of solid food products. Average transfer coefficient values and distributions around cylinders are now quite well known while it is not the case for solids of more complex shapes. CFD models are more and more often used to calculate transfer coefficient values on a single food product or packaging. Experimental knowledge is reviewed and the way it can be used by scientists and engineers to determine their own transfer coefficient values is illustrated. The potentials and limitations of present CFD models are illustrated and future improvements are also discussed.

Keywords: Food; Chilling; Refrigerated storage; Survey; Heat transfer; Mass transfer; Coefficient

Coefficients de transfert de chaleur et de masse lors de la réfrigération et de l'entreposage des produits alimentaires

Mots clés : Produit alimentaire ; Réfrigération ; Entreposage frigorifique ; Enquête ; Transfert de chaleur ; Transfert de masse ; Coefficient

1. Introduction

In Europe, chilling of solid foods is most often achieved in an air stream. Airflow is also used to maintain a low temperature and/or high humidity ambience during storage. Heat/mass transfer modelling is needed to improve chilling/storage processes and functioning of industrial plants. In models, fluxes exchanged at the surface of products are mathematically described by Newton's law of convection which is very simple but requires the knowledge of the heat and the mass transfer coefficients. These coefficient values can be fitted against measurements but this procedure leads to inaccurate results, especially when evaporation is not taken into account and when measurements are taken under industrial conditions [1]. Introducing wrong coefficient values in models leads to calculated results which are erroneous. This paper reviews what is known about heat and mass transfer coefficients under air chilling and storage conditions.

* Tel.: +33 4 73624492; fax: +33 4 73624089.
E-mail address: alain.kondjoyan@clermont.inra.fr

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Nomenclature

Latin symbols

A	constant
a	major axis of an elliptical cylinder (m)
a_w	water activity
B	constant
b	the minor axis of an elliptical cylinder (m)
D	cylinder diameter (m)
F	view factor
H	cylinder height (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{eff}	effective heat transfer coefficient (W m^{-2} K^{-1})
L	distance between objects in flow direction (arrangement) (m)
L_{car}	characteristic length of a solid (m)
Re	Reynolds number
P_T	partial pressure of vapour at temperature T (Pa)
r	ratio of the major to the minor axis (elliptical cylinders)
T	cross-flow distance between objects (arrangement) (m)
T_{air}	air temperature (°C or K)
T_d	dew point temperature (°C or K)
T_{max}	greatest of T_{air} or T_{rad} (°C or K)
T_{rad}	temperature used to calculate radiant exchange (°C or K)
T_s	temperature at the surface of the cylinder (°C or K)
Tu	free-stream turbulence intensity (flow direction): $\sqrt{\overline{u^2}}/U$ (%)
Nu	Nusselt number $= hL_{car}/\lambda$
Nu_{car}	characteristic Nusselt number $= Nu/\sqrt{Re}$
u	velocity fluctuation around U (m s^{-1})
U	mean air velocity in the flow direction (m s^{-1})
x	curvilinear coordinate on the rim of an elliptical cylinder (m)

Greek symbols

ε	emissivity of the solid surface
θ	Angle from the stagnation point of a cylinder (degree)
λ	thermal conductivity of the air (W m^{-1} K^{-1})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})

Mean

$\overline{x}$	mean of x

2. What is a transfer coefficient and how accurately shall it be known?

When airflow makes contact with a solid food product, heat is exchanged by convection. As biological products are full of water, this water evaporates if the product is unwrapped. Energy can also been exchanged by radiation when product is totally or partly surrounded by walls whose temperatures are different from its own surface temperature. Very often the total energy exchanged at the surface of the food product by convection, radiation and evaporation is described using an effective transfer coefficient [2,3]:

$$h_{eff} = \underset{\text{convection}}{h\frac{T_{air}-T_s}{T_{max}-T_s}} \; \rightarrow \; + \underset{\text{radiation}}{F\varepsilon\sigma\frac{T_{rad}^4-T_s^4}{T_{max}-T_s}} \; \rightarrow \; + \underset{\text{evaporation}}{k\Delta H\frac{P_{T_d}-a_{ws}P_{T_s}}{T_{max}-T_s}} \tag{1}$$

During storage of stacks of products under free convection or mixed convection conditions, the energy exchanged by conduction between products in contact with each other can be of importance [4,5]. However, this is not the case under most industrial chilling-storage conditions. Under classical chilling conditions the energy exchanged by radiation is much lower than that exchanged by convection. It has been shown by Kuitche et al. [6] that neglecting radiation leads to an overestimation of 0.7 °C of the temperature at the core, and 1.0 °C at the surface, of a single plaster cylinder subjected to an airflow with a velocity of 1.0 m s^{-1}. The effect of radiation is much smaller for a product surrounded by others at similar temperatures. Thus the exact knowledge of ε which is between 0.9 and 1.0 for food products, is not needed, and the variation of the energy exchanged by radiation is mostly due the view factor F which can be determined analytically or numerically.

The energy exchanged by evaporation at the surface of unwrapped products is very important, especially at the beginning of chilling. It is about three times the energy exchanged by convection at the beginning of the chilling of a meat carcass from 40 to 7 °C under normal airflow conditions [6]. Under normal chilling and storage conditions the water activity of unwrapped fresh foods is always very close to one. Thus the uncertainty in energy exchanged by evaporation is directly related to the uncertainty on the value of the mass transfer coefficient. Heat and mass transfer coefficients are related to one another by the Lewis relation. This relation can be theoretically proved for a flat plate subjected to a laminar flow of air. It has also been experimentally validated for turbulent flows and products of complex shapes as well as under mixed convection conditions [7–9].

Finally, under usual chilling and storage conditions, the accuracy of calculated results relies mainly on the accuracy of the convective heat transfer coefficient value used in the model (mass transfer coefficient being deduced from this value). It was shown that during meat chilling a variation of 30% of the transfer coefficient value leads to a variation of 1.2–1.8 °C of the temperature at the centre of a cylinder, 7 cm in diameter and of 1.9–2.6 °C at its surface. The effect