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Numerical simulation of simultaneous heat and moisture transfer in a domestic refrigerator

O. Laguerre[a,*], S. Benamara[a], D. Flick[b]

[a] Cemagref, Refrigeration Process Engineering, Cemagref, BP. 44, 92163 Antony Cedex, France
[b] AgroParisTech, UMR 1145 Génie Industriel Alimentaire, F-91300 Massy, France

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ABSTRACT

This study was carried out in order to gain a better insight into evaporation and condensation phenomena due to natural convection in a domestic refrigerator without a fan. A model refrigerator loaded with moist cylinders was studied initially. CFD simulations took into account air flow, heat transfer (convection, conduction and radiation) and mass transfer (water evaporation and condensation). The numerical results were compared with the experimental values. The position where evaporation and condensation occur was generally well predicted in spite of the fact that simulation underestimates the experimental values. The numerical methodology developed was then applied to a real refrigerator loaded with unpackaged products (susceptible to dehydration). The same phenomena as those in the model refrigerator were observed: condensation on the product located near to the evaporator, dehydration of the products located near the door and at the top.

Simulation numérique du transfert de chaleur et d'humidité dans un réfrigérateur domestique

Mots clés : Réfrigérateur domestique ; Transfert de chaleur ; Transfert de masse ; Condensation ; Évaporation

1. Introduction

When fruit and vegetables are preserved in a domestic refrigerator, dehydration occurs gradually due to water evaporation. For products with a high water activity (~1), this phenomenon takes place when the product surface temperature is higher than the dew point temperature of the surrounding air. The water loss from fresh produce causes shrinkage and accelerates deterioration of product quality degradation (texture, colour, destruction of ascorbic acid, etc.). On the contrary, when the surface temperature (of the product or the refrigerator) is lower than the dew point temperature of surrounding air, water condensation takes place on the surface, which enhances microbial growth. Therefore,

* Corresponding author. Tel.: +33 1 40 96 61 21; fax: +33 1 40 96 60 75.
E-mail address: onrawee.laguerre@cemagref.fr (O. Laguerre).
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Nomenclature

a_w	water activity
C_p	thermal capacity of the product, $J\,kg^{-1}\,K^{-1}$
D	relative diffusivity of water and air, $m^2\,s^{-1}$
e_w	thickness of the wall of cavity, m
g	acceleration due to gravity = $9.81\,m\,s^{-2}$
h_{glob}	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
ΔH_v	latent heat of evaporation (or condensation), $J\,mol^{-1}$
I	directional intensity of radiation, $W\,m^{-2}\,srd^{-1}$
k	mass transfer coefficient, $mol\,s^{-1}\,m^{-2}\,Pa^{-1}$.
M_a	air molecular weight = $29 \times 10^{-3}\,kg\,mol^{-1}$
M_w	water molecular weight = $18 \times 10^{-3}\,kg\,mol^{-1}$
$\vec{n}$	normal vector
p	pressure, Pa
p_w	water vapor pressure in air, Pa
P_{sat}	vapor pressure at saturation, Pa
T	temperature, K
T_{amb}	room temperature, K
T_c	temperature of cold wall, K
T_{dew}	dew point temperature, K
T_i	temperature at the air/water interface, K
T_p	temperature of cylinder (product), K
t	time, s
x	mass fraction of water in air
v	air velocity, $m\,s^{-1}$

Greek symbol

λ_a	thermal conductivity of air, $W\,m^{-1}\,K^{-1}$
λ_p	thermal conductivity of the product, $W\,m^{-1}\,K^{-1}$
λ_w	thermal conductivity of the wall, $W\,m^{-1}\,K^{-1}$
ρ	density, $kg\,m^{-3}$
ρ_0	density at reference condition, $kg\,m^{-3}$
μ	viscosity, Pa s
ϕ_{in}	incident radiation flux, $W\,m^{-2}$
$\phi_{net,rad}$	net radiation flux, $W\,m^{-2}$
$\omega_{net.cond}$	net condensation flux, $mol\,m^{-2}\,s^{-1}$
ε_r	wall emissivity

limiting evaporation and condensation in order to maintain the product quality and hygiene in a domestic refrigerator is a technological challenge. Humidity control in the refrigerator is also important from an energy consumption point of view. The humidity in a refrigerator may not be derived from the food alone: it may also come from door openings. Several studies demonstrate the impact of door openings on the energy consumption of appliances because of frost formation on the evaporator (Meier, 1993; Meier and Jansky, 1993; Meier and Heinemeier, 1988; Alissi et al., 1988; Stein et al., 2002).

For a static refrigerator (without a fan), heat is transferred mainly by natural convection and airflow is due to the variations in air density. These variations are mainly related to the temperature and humidity gradients. The vertical force which results from air weight and buoyancy is upward if the air is locally lighter than the average and downward where the opposite is true (hot and/or humid air is lighter than cold and/or dry air).

Several studies have investigated heat transfer and airflow in empty refrigerators. Pereira and Nieckele (1997) studied heat exchange by natural convection between the air and the evaporator. Silva and Melo (1998) experimentally characterized a static refrigerator by temperature cartography and local flux on the walls and on the evaporator. Deschamps et al. (1999) carried out a numerical study to predict air velocity and temperature distribution. In our previous experimental and numerical studies, the air temperature, velocity, and humidity in a loaded model refrigerator were presented (Laguerre et al., 2009a,b). To complete our investigation, a study on evaporation and condensation in a refrigerator is presented here. The first objective was to gain a better insight into heat, mass (water) and momentum transfer through natural convection in a domestic refrigerator. The second objective was to develop a numerical tool to predict the warm and humid positions susceptible to lead to deterioration in the quality of foodstuffs. There are few studies taking into account not only heat and water transfer and but also the combined effects of natural convection and radiation in a loaded refrigerator. A specific methodology of CFD simulation was developed in this study to calculate the water evaporation or condensation rate on product surfaces.

In a real refrigerator, there are numerous food dimensions, shapes, arrangements and occupied volumes. There are also temperature variations in appliances due to the "on" and "off" compressor cycles. To avoid such complex conditions, a simplified configuration was studied initially: a model refrigerator equipped with a cold wall maintained at a constant temperature and filled with arranged moist cylinders. A comparison between experimental and numerical results was undertaken in order to validate the numerical methodology. Then, the numerical model was applied to the case of a real refrigerator loaded with products without packaging (susceptible to dehydration) which is often the case of fruit and vegetables. This study is a stepping stone towards real use conditions.

2. Materials and methods

2.1. Model refrigerator

The internal dimensions of the model refrigerator (Fig. 1) are: 0.5 – 0.5 – 1 m (length – width – height). It is composed of 3 vertical double glass walls (glass thickness of 6 mm and air thickness between glass walls of 10 mm) and one vertical aluminum wall (thickness of 2 cm, containing a coil). A low-temperature water-glycol mixture was prepared in a thermostatically controlled cooling bath to maintain a constant temperature in this aluminum wall. The top and bottom horizontal walls are made of PVC (thickness: 2 cm). The two side walls are insulated using expanded polystyrene plates (thickness: 4 cm) so that 2D air flow and heat transfer can be ensured (Laguerre et al., 2009a). The model refrigerator was placed in a test chamber in which the ambient temperature was regulated at 20 °C. The cold wall temperature was regulated at −-2.5 °C (mean value of 5 measurement points). Moist