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Experimental characterization of airflow, heat and mass transfer in a cold room filled with food products

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A R T I C L E I N F O

Article history:
Received 27 January 2014
Received in revised form
1 July 2014
Accepted 12 July 2014
Available online 19 July 2014

Keywords:
Cold room
Airflow
Temperature
Humidity
Weight loss

A B S T R A C T

Temperature and moisture heterogeneity, with non-uniform airflow in cold rooms was observed in several studies. This heterogeneity can lead to a deterioration of food quality and safety. Heat and mass transfer in cold rooms is a complex phenomenon because of the presence of the product (airflow modification, heat of respiration…) and the coupling between heat transfer and airflow. Temperature, velocity, humidity and heat transfer coefficient measurements were carried out in a ventilated cold room filled with four apple pallets. The front pallets near the cooling unit were submitted to higher air temperatures compared to the rear ones, leading to product cooling rate and temperature heterogeneity. The experimental results allow the understanding of mechanism of airflow as well as heat and water exchanges between product and air.

Caractérisation expérimentale de l'écoulement d'air, du transfert de chaleur et de masse dans une chambre froide remplie de produits alimentaires

Mots clés : Chambre froide ; Ecoulement d'air ; Température ; Humidité ; Perte de masse

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http://dx.doi.org/10.1016/j.ijrefrig.2014.07.008

Nomenclature

A	product surface, m^2
A_{cr}	surface of the cold room walls, m^2
Bi	Biot number $Bi = h \cdot R_p/\lambda$
C	heat capacity, $J\ kg^{-1}\ K^{-1}$
α	thermal diffusivity, $m^2\ s^{-1}$
h	convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
H_{resp}	apple heat of respiration, $W\ kg^{-1}$
k_{ta}	moisture transfer coefficient of the apple skin, $m\ s^{-1}$
K	global heat transfer coefficient of the walls of the cold room, $W\ m^{-2}\ K^{-1}$
T_0	product initial temperature, °C
T_{air}	air temperature, °C
T_{avg}	product average temperature, °C
T_c	product core temperature, °C
T_{eq}	product equilibrium temperature, °C
T_{ext}	external temperature, °C
T_{inlet}	air inlet temperature, °C
T_{int}	air temperature in the cold room, °C
T_{outlet}	air outlet temperature, °C
T_s	product surface temperature, °C
T_w	wall temperature, °C
T^*	dimensionless temperature $T^* = (T - T_{eq})/(T_0 - T_{eq})$
M	mass, kg
M_{H_2O}	molar mass of water, $kg\ mol^{-1}$
$\dot{m}$	air mass flow rate, $kg\ s^{-1}$
$\dot{m}_{inf}$	mass flow rate of air infiltration, $kg\ s^{-1}$
R	universal gas constant, 8.314 $J\ mol^{-1}\ K^{-1}$
R_p	product radius, m
RH	relative humidity, %
ρ_w	vapour density of the apple surface, kg water m^{-3}
$\rho_{w,\infty}$	vapour density of the surrounding air, kg water m^{-3}
t	time, s
V	air velocity, $m\ s^{-1}$
V_p	product volume, m^3
a_w	water activity of the apple
w	water content in air
ε	emissivity
σ	Boltzmann constant, $5.67 \cdot 10^{-8}\ W\ m^{-2}\ K^{-4}$
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
τ	characteristic time, s

1. Introduction

In order to provide food products of high organoleptic quality and safety, attention must be paid to every aspect during the cooling process and storage. However, uniform storage conditions in cold stores are difficult to attain in practice. Several studies have shown temperature or moisture heterogeneity, with non-uniform airflow in cold rooms (Mirade and Daudin, 2006; Chourasia and Goswami, 2007; Kolodziejczyk and Butrymowicz, 2011), in refrigerated trucks (Moureh et al., 2009), in display cabinets (Cortella, 2007; Laguerre et al., 2011; Laguerre et al., 2012) or in domestic refrigerators (Laguerre et al., 2002, 2010a, 2010b). This uneven distribution of airflow is related to the presence of the product and the cooling equipment (Ho et al., 2010). Variation of heat transfer coefficient between the air and the product at different positions in the cold room was also observed by Flick et al. (1999) and Mirade (2007), leading to different product cooling rates. The heat transfer phenomena involved during product cooling and storage are conduction within the product, convection (between cold air and product surface) and radiation (between product surface and cold room walls) (Hu and Sun, 2000). Another source of temperature heterogeneity is the heat of respiration of the product (Ben Amara, 2005). Simultaneously, moisture evaporation from the product surface can be significant which causes product weight loss. In the case of beef carcasses for example, this loss is around 1.5–2.3% by weight and represents around 20 times the cost of the process function (Gigiel and Collett, 1989). In a cheese ripening room, Mirade et al. (2006) observed that the characteristics of the blowing duct could greatly influence the product weight losses. Both the heat and moisture transfers are influenced by flow characteristics (such as cooling air temperature and velocity), air properties (viscosity, density, conductivity and specific heat), product properties, shape, dimension and arrangement of the load.

The comprehension of the heat/mass transfer and airflow in cold stores is a complex task because of several interdependent factors acting simultaneously (Smale et al., 2006). Failure to understand the phenomena taking place in the equipment results in excessive weight loss, reduced shelf life or deterioration in product quality (James, 1996). This deterioration rate is more significant in the case of high product respiration rate at warm zone or by chilling injury at cold zone (James, 1996).

Computational Fluid Dynamic (CFD) models can confirm experimental results and help correct a dysfunction revealed in the experimental diagnosis as shown in the study of industrial chillers of beef carcass carried out by Mirade and Picgirard (2001). CFD which can be used to study different cooling conditions and package designs can be very useful to understand and improve cooling processes (Ambaw et al., 2013; Defraeye et al., 2013) and reduce energy consumption (Defraeye et al., 2014). CFD models (Nahor et al., 2005; Mirade and Daudin, 2006) or simplified models (Wang and Touber, 1990) were developed to predict temperature, humidity and air velocity in refrigerated cold rooms. However, in most of the cases, only experimental temperatures were used to compare with the numerical values. The interacting aspects of airflow direction, air velocity, air and product temperature, heat transfer coefficients, product cooling rates and product quality evolution (weight losses) are rarely studied simultaneously. Concretely, the objective of our study is to understand the transfer phenomena in a ventilated cavity filled with food products of a complex configuration (stack of food in pallets) that exchange both heat and water with air in the room. The experimental results will be used for the validation of future models (CFD and simplified).