Applied Thermal Engineering xxx (2014) 1–15

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Preliminary study of airflow and heat transfer in a cold room filled with apple pallets: Comparison between two modelling approaches and experimental results

Hong-Minh Hoang [a, *], Steven Duret [a, b], Denis Flick [b, c], Onrawee Laguerre [a]

[a] Irstea, UR GPAN, 1 rue Pierre-Gilles de Gennes, 92761 Antony, France
[b] AgroParisTech, UMR 1145-GENIAL, F-91300 Massy, France
[c] INRA, UMR 1145-GENIAL, F-91300 Massy, France

HIGHLIGHTS

- Forced convection in cold room with apple pallets is studied by 2 CFD approaches.
- 1st Approach: each pallet is considered as one porous medium (PM) block.
- 2nd Approach: each pallet is modelled as 8 solid blocks (SB).
- Numerical results show a good agreement with the experimental results.
- PM approach gives good results with mesh numbers 4 times smaller than SB approach.

ARTICLE INFO

Article history:
Received 16 July 2014
Accepted 7 November 2014
Available online xxx

Keywords:
Forced convection
CFD
Cold room
Porous medium

ABSTRACT

Two CFD modelling approaches of transient heat transfer by forced convection in a cold room filled with four apple pallets have been performed and compared with experimental data. For the first approach, each apple pallet is considered as one porous medium block. For the second, each pallet is considered as 8 solid blocks representing the apple bins. The numerical results obtained by these two approaches show a good agreement with the experimental results regarding air velocity and product temperature evolution during cooling process. A better prediction of product temperature evolution is obtained with the solid block approach. The porous medium approach gives a fairly good result with a much smaller mesh numbers (nearly 4 times) than the solid block approach. Four turbulence models (standard $k-\varepsilon$, RNG $k-\varepsilon$, realizable $k-\varepsilon$, and shear stress transport SST $k-\omega$) and two heat transfer models for porous medium (local thermal equilibrium and local thermal non-equilibrium model) are tested to determine the most appropriate ones for the studied configuration.

1. Introduction

Transient heat transfer between product and air often takes place in food process engineering, for example, fruit and vegetables chilled in a cold room, transported in a refrigerated vehicle or stored in a display cabinet. In these processes, the heat transfer phenomenon depends mainly on the airflow pattern (which in turn is influenced by the room/equipment and loading configuration) and the product properties (thermal conductivity, specific heat, density, etc.).

Uniform storage conditions in cold stores are difficult to attain in practice in spite of the ventilation generated by the air supply. Non-uniform airflow and temperature heterogeneity of product and air are observed in ventilated enclosures such as cold room [1,2] or refrigerated vehicle [3]. Variation of heat transfer coefficient between the air and the product at different positions in the cold room is also observed leading to different product cooling rates [4,5]. The product packaging and stacking play an important role in cooling performance [6]. The products, often packed in bins or pallets, can be represented as porous medium [7,8]. A more realistic geometry can also be considered: cylinders [9]; stack of spheres for

* Corresponding author. Tel.: +33 1 40 96 65 02; fax: +33 1 40 96 60 75.
E-mail address: hong-minh.hoang@irstea.fr (H.-M. Hoang).

http://dx.doi.org/10.1016/j.applthermaleng.2014.11.012
1359-4311/

Nomenclature

A_{sf}	specific solid–fluid interface surface area, m^2
C_s	swirling coefficients
Cp	heat capacity at constant pressure, J/(kg K)
D	apple diameter, m
F	Forchheimer coefficient, empirical coefficient depending on porosity and microstructure of porous media
h	convective heat transfer coefficient, W/(m^2 K)
HCT	half cooling time, h
k	turbulence kinetic energy, m^2/s^2
K_i	permeability, m^2
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
MRE	mean relative error
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
PM	porous medium
q	surface – averaged heat flux, W/m^2
R	apple radius, m
RMSE	root-mean-square error
Re	Reynolds number, $Re = \rho_f uD/\mu_f$
R^2	coefficient of determination
S	swirling
S_{PM}	momentum source term in porous medium approach
SB	solid block
t	time, s
T	temperature, K
u	fluid velocity, m/s
Greek symbol	
ρ	density, kg/m^3
ε	dissipation rate, m^2/s^3
ε_p	porosity
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
ω	turbulent frequency, s^{-1}
Subscript	
eff	effective
f	fluid
sf	solid fluid interface

apples [10,11], complex 3D geometry from image analysis for strawberries [12]. Nevertheless, this approach that requires a much more complex meshing with a higher number of cells than the porous medium approach is difficult to be applied to model the airflow and heat transfer in an entire cold room.

Computational Fluid Dynamics (CFD) is a performant tool to characterize the temperature and air velocity fields in refrigerated enclosures. This tool allows the solving of coupled partial differential equations, such as the Navier–Stokes equations, in which the mass, momentum and energy transfers between air and products are described. However, the accuracy of CFD simulations depends largely on the choice of the turbulence and boundary-layer modelling approach [13]. This choice has to be taken by considering the studied configuration and flow behaviour. For example, the realizable $k-\varepsilon$ model is likely to provide superior performance for flows with boundary layers under strong adverse pressure gradients [14] while the shear stress transport SST $k-\omega$ model shows good results with complex swirling flow [15]. The performance of different turbulence models can be evaluated by comparing the numerical results with experimental data; for studies that involve flow and heat transfer phenomena, the Nusselt number is often used for this comparison [16,17]. Various turbulence closure models including the high and low Reynolds number forms of the two-equation $k-\varepsilon$ model and the more advanced Reynolds stress model (RSM) were used to investigate the airflow pattern inside a long ventilated enclosure [18]. This study showed that only the RSM model was able to predict the separation of the jet from the wall and the general behaviour of airflow patterns. However, the RSM, being computationally expensive, is not usually applied in this field of applications [13]. The airflow pattern in cold room was predicted by Delele et al. [19] using different two-equation eddy-viscosity turbulence models (standard $k-\varepsilon$, RNG $k-\varepsilon$, realizable $k-\varepsilon$, standard $k-\omega$ and shear stress transport SST $k-\omega$). The SST $k-\omega$ model was found to produce the smallest error in air velocity prediction compared to others.

The objective of the present work is to study the airflow and the heat transfer between air and products during cooling of apple pallets in a cold room. Experimental data [20] has shown that there is a great difference in cooling time (7 times) between quick cooling zones (at the top of the pallet where the heat transfer between air and apple is significant) and slow cooling zones (at the pallet center). So, the question is: “Is CFD modelling able to reproduce and explain this phenomenon?” To answer this question, different turbulence models (standard $k-\varepsilon$, RNG $k-\varepsilon$, realizable $k-\varepsilon$, and shear stress transport SST $k-\omega$) have been tested and the choice of the final model has been made by comparing the calculated Nusselt number with the experimental results. The originality of the present numerical study can be summarized in 2 points. The first one is the consideration of the swirling effect of the ventilator which allows the simulation condition to be close to the experimental one. Indeed, the rotation direction of both fans in the studied cold room is clockwise creating a dissymmetric airflow pattern. The comparison between the result of simulations with and without the swirling effect is carried out. The second one concerns the apple pallet modelling. Two approaches have been performed: for the first approach, each apple pallet is considered as one porous medium block and for the second – more “realistic” approach, the pallets are considered as 8 solid blocks representing the apple bins. Moreover, both local thermal equilibrium and non-equilibrium models are tested for the porous medium approach. The comparison between the numerical and the experimental results is performed to evaluate the performance of these approaches and to choose the one which is appropriate for the studied configuration.

2. Numerical models

2.1. Computational domain

The cold room is 3.4 m long, 3.4 m wide and 2.5 m high (volume: 29 m^3). Four pallets are loaded in the room; position and dimensions of pallets and cooling unit are presented in Fig. 1a; one pallet is composed of 64 bins (Fig. 1b). Each bin (Fig. 1c) is filled with 34 apples placed in two layers separated by a paper sheet, the vent hole ratio of the bin is 33%. The total weight of apples is about 2560 kg. The cooling unit (mass flow rate 2450 m^3 h^{-1}) is at the ceiling of the room; it includes two axial fans of 30 cm of diameter

Please cite this article in press as: H.-M. Hoang, et al., Preliminary study of airflow and heat transfer in a cold room filled with apple pallets: Comparison between two modelling approaches and experimental results, Applied Thermal Engineering (2014), http://dx.doi.org/10.1016/j.applthermaleng.2014.11.012