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CFD model of the airflow, heat and mass transfer in cool stores

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Abstract

A transient three-dimensional CFD model was developed to calculate the velocity, temperature and moisture distribution in an existing empty and loaded cool store. The dynamic behaviour of the fan and cooler was modelled. The model accounted for turbulence by means of the standard k-ε model with standard wall profiles. The model was validated by means of velocity, air and product temperature. An average accuracy of 22% on the velocity magnitudes inside the empty cold store was achieved and the predicted temperature distribution was more uniform than predicted. In the loaded cold store, an average accuracy of 20% on the velocity magnitudes was observed. The model was capable of predicting both the air and product temperature with reasonable accuracy.

Keywords: Cold store; Modelling; CFD; Heat transfer; Mass transfer; Speed; Air; Temperature; Humidity

Modélisation par dynamique des fluides numérisée de l'écoulement de l'air et du transfert de chaleur et de masse dans les entrepôts frigorifiques

Mots clés : Entrepôt frigorifique ; Modélisation ; Dynamique des fluides ; Transfert de chaleur ; Transfert de masse ; Vitesse ; Air ; Température ; Humidité

1. Introduction

Agricultural products are subjected to heat and mass transfer during cooling and storage. Uniform cooling and storage of fresh product is difficult to attain in industrial cooling rooms, owing to the existence of an uneven distribution of the airflow [1,2], which affects the product quality, especially during long-term storage. Heat and mass transfer inside bins of products, particularly, becomes very important in maintaining good quality of stored products,

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Nomenclature

A_c	heat transfer area of the cooler (m^2)
A_{spec}	specific area ($m^2\ m^{-3}$)
a	ratio of transversal pitch to pipe diameter (–)
C	constant (–)
c_p	heat capacity of product ($J\ kg^{-1}\ °C^{-1}$)
D	diffusivity ($m^2\ s^{-1}$)
E	Error (–)
f_e	external force ($N\ m^{-3}$)
f_{RES}	resistance of product in bins ($N\ m^{-3}$)
g	gravity vector component ($m\ s^{-2}$)
H	enthalpy ($J\ kg^{-1}$)
h_c	heat transfer coefficient at cooler ($W\ m^{-2}\ °C^{-1}$)
h_m	mass transfer coefficient ($m\ s^{-1}$)
h_T	heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
h_{fg}	heat of evaporation/condensation ($J\ kg^{-1}$)
k	geometry parameter (–)
l	cooler length (m)
m	moisture evaporation or condensation ($kg\ m^{-3}\ s^{-1}$)
p	static pressure (Pa)
p'	$p+\rho_0 g_j x_j$ (Pa)
Q_V	heat removed (W)
q	heat of respiration ($W\ m^{-3}$)
r	volume fraction (–)
T	temperature (°C)
t	time (s)
u	velocity component ($m\ s^{-1}$)
$\mathbf{u}$	velocity vector ($m\ s^{-1}$)
x	Cartesian coordinate (m)
X	product moisture content ($kg_w\ m^{-3}$)
Y	humidity ratio ($kg_w\ kg_{air}^{-1}$)
z	number of tube rows in the cooler (–)
β	thermal expansion coefficient ($°C^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
μ	viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)

Sub and super-scripts

a	Air
i,j	index of Cartesian components
f	mixture, fan
o	reference value
p	Product
sat	Saturation
v	Vapor
w	Water

and is mainly dependent on the interaction between the supply airflow and the bulk products. The variability of the cooling rate as well as the temperature of the product inside a cool store causes the product quality to deteriorate through either increased respiration at higher temperature or by chilling or freezing injury at lower temperature.

One of the main aims in designing storage enclosures is to ensure a uniform targeted temperature and humidity in the stored bulk products. The intricate transport mechanics and the complex geometry of a fully loaded cool store make it difficult to determine the optimal configuration and operation parameters of the store in an empirical way. A model-based approach can prove to be advantageous for design purposes with small added cost. With the increasing availability and power of computers together with efficient solution algorithms and processing facilities, the technique of Computational Fluid Dynamics (CFD) can be used to solve the governing fluid flow equations numerically.

A first step towards modelling cool stores loaded with agricultural products is representation of the heat and mass transfer inside bulk storages of agricultural products. Many models have been proposed with different levels of complexity such as uniform air-product temperature [3,4], thermal equilibrium [3–7] and internal temperature gradient [3] with mass transfer incorporated [8,9]. Airflow has been studied in ventilated enclosures for food preservation and processing [10–12]. To study the non-uniform temperature and moisture of a loaded cool store, only a few models have been proposed in the last 10 years. These models are limited to a two-dimensional one-phase model [13], or distributed dynamic model with only validation for temperature at two locations in the cool store [2]. Van Gerwen and Van Oort [14] used CFD to model 3D airflow and heat transfer in a refrigerated room for agricultural products and studied the effect of different configurations on the cooling effectiveness. However, no detailed information of the model, or the validation was reported. Mass transfer was not modelled in most of the cases. Hoang et al. [15] used CFD to model 3D airflow, heat and mass transfer in an industrial cool store for chicory roots. The latter was validated for the air temperature only (air velocity and product temperature were not validated).

The main objective of the present work was to model the transient three-dimensional airflow, heat and mass transfer in an empty and loaded cool store. The model was then validated using experimental data for velocity and temperature distributions of both air and product phases.

2. Method

2.1. Model formulation

A transient two-phase model of heat and mass transfer in a cool store was proposed. The governing equation