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Numerical prediction of the unsteady temperature distribution in a cooling cabinet

J. Arturo Alfaro-Ayala *, Agustín R. Uribe-Ramírez, J. Isaac Minchaca-Mojica, J. de J. Ramírez-Minguela, B. Uciel Alvarado-Alcalá, Oscar A. López-Núñez.

Department of Chemical Engineering, DCNE, University of Guanajuato, Col. Noria Alta s/n, C. P. 36050, Guanajuato, Gto, Mexico

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ABSTRACT

An unsteady state numerical study of a small cooling cabinet, using Computational Fluid Dynamics (CFD), is presented in this work. Three different cooling levels are simulated until 3.5 h of operational time is reached. The prediction of the temperature and the velocity distributions of the air inside the cooling cabinet is obtained using three different models: a) the use of constant properties (CP), b) the approximation of all the properties fitted to temperature polynomials (PFTP) and c) the variation of the density with temperature according to the Boussinesq approximation (BA). The CFD numerical results were validated against experimental data. It was concluded that both PFTP and BA models are good approaches to predict the unsteady temperature inside the cooling cabinet.

Prévision numérique portant sur la répartition irrégulière des températures dans une armoire de refroidissement

Mots clés : Armoire de refroidissement ; Approximation de Boussinesq ; Polynômes de températures ; Régime variable ; Simulations par MFN ; Froid

1. Introduction

The refrigeration systems are regarded as significant indirect contributors for carbon emissions due to the high electrical energy consumption. About 30% of the final energy consumed worldwide is for the refrigeration Belman et al. (2010). In the refrigeration field, it is important to analyze the cooling cabinet in order to achieve the storage quality of products. Cooling cabinets are designed to keep food, medicines and

* *Corresponding author.* Department of Chemical Engineering, DCNE, University of Guanajuato, Col. Noria Alta s/n, C. P. 36050, Guanajuato, Gto, Mexico. Fax: +52 473 7320006 ext. 8108.
E-mail address: ja.alfaroayala@ugto.mx (J.A. Alfaro-Ayala).
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Nomenclature

c	specific heat [J kg^{-1} K^{-1}]
g	gravity [m s^{-2}]
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
k	conductivity [W m^{-1} K^{-1}]
P	pressure [Pa]
T	temperature [°C or K]
t	time [s]
u	velocity [m s^{-1}]

Greek letters

β	volumetric thermal expansion coefficient [K^{-1}]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]

Superscripts and subscripts

BA	Boussinesq approximation
CC	cooling cabinet
CP	constant properties
ENV	environment
EVA	evaporator
EXP	experiment
PFTP	properties fitted to temperature polynomial
x, y, z	component

biological matter at specific temperatures to ensure optimal freshness, quality, safety and shelf life. Beside these applications of refrigeration, Zhang et al. (2014) found that the use of refrigeration in cooling cabinets for data centers are increasing, thus important strategies for energy savings in the refrigeration field are great challenges.

Yusufoglu et al. (2015) showed that a configuration of a cooling cabinet with a phase change material (PCM) reduced the number of ON/OFF stages. Marques et al. (2014) demonstrated that the use of PCM into a cooling cabinet achieved longer periods of continuous autonomous operation (without power supply). Alzuwaid et al. (2015) concluded that the use of PCM saved up to 5% of energy with lower cabinet temperatures. Gaspar et al. (2011) and Ke-zhi et al. (2009) studied the air curtain in a vertical open display cabinet for different ambient air conditions, it was concluded that the discharge air curtain velocity was important for improving the overall performance of the equipment, ensuring a higher food safety and, thus, reducing its energy consumption.

Recent advances in hardware and software have made more attractive the CFD numerical methods to investigate a vast amount of phenomena, such as in this paper, the unsteady state CFD numerical study of the thermal and hydraulic performance of a cooling cabinet that uses the diffusion-absorption refrigeration (DAR) technology. Laguerre et al. (2015) specified two main advantages in using the CFD numerical approaches. Firstly, it enables the knowledge of local parameters that allows the understanding of the phenomena. Secondly, it permits the prediction of the operating conditions and the equipment design (which very often is expensive or impossible to undertake via experiments).

Laguerre et al. (2014) showed a simplified CFD numerical model in steady state to assess the influence of operational conditions for a domestic refrigerator, a refrigerated vehicle and a display cabinet. Temperature stratification was observed due to the variation of air density, the cold zone is located at the bottom and the warm zone is located at the top of the naturally-cooled cabinet. Belman-Flores et al. (2014a) studied a domestic refrigerator via CFD numerical simulations using the commercial code ANSYS-Fluent®. It was found that the original design of the cooling cabinet revealed an inadequate thermal operational profile, thus a new design was proposed showing a better distribution of the air flow and temperature in the fresh food compartment. Experimentally, the new design represents less ON/OFF stages compared with those of the original refrigerator under the same operational conditions. Fakhim et al. (2011) studied a data center room in order to evaluate the thermal behavior using CFD numerical techniques. They found undesirable hot spots and remedial solutions for improving the cooling effectiveness allowing a reduction of air-conditioning power consumption. Wang et al. (2015) showed a steady-state CFD numerical study of the air flow and temperature in a cooling cabinet using a 3D model. They considered the variation of the air density according to the ideal gas law. The boundary condition of the evaporator wall was set as a constant temperature, during the ON/OFF stages, and the boundary conditions of the cooling cabinet walls were defined as adiabatic. However, robust numerical simulations are needed to predict the performance during the ON/OFF stages, and also it is required avoiding oversimplified assumptions in the models, such as it is shown in this work.

Lari et al. (2011) numerically analyzed the effect of thermal radiation in a cooling cabinet under ambient conditions. They showed that the contribution of radiation is almost constant over a wide range of operation. Laguerre and Flick (2004) showed an experimental and theoretical study of the heat transfer in a typical domestic cooling cabinet. The results indicated that the radiative heat transfer coefficient is in the same order as the natural convective coefficient. However, their findings were obtained under many assumptions, between them, a constant temperature on the evaporator (it is well known that it varies within a range during the ON/OFF stages) and the use of constant properties.

Laguerre et al. (2008) studied the air flow by natural convection in a closed cabinet of a domestic refrigerator via particle image velocimetry (PIV), focusing mainly in the evaporator wall. They found that the cold temperature of the evaporator plate had larger influence than the surface area of the evaporator plate on the performance of the cooling cabinet. Belman-Flores and Gallegos-Muñoz (2016) studied, via CFD numerical simulation, the evaporator plate with/without extended surfaces and the wired shelf location inside a cooling cabinet under steady-state conditions. They concluded that the evaporator plate with/without extended surfaces have little affects on the thermal and energy performance of the cooling cabinet. On the other hand, the wired shelf position over the thermal behavior did not have a great influence in the energy consumption.

Shortcoming of the literature in the CFD numerical simulations of cooling cabinets was observed, the works are mainly focused in the steady state natural convection with simplified