DOI: 10.5897/AJAR2013.6983

academicJournals

Vol. 9(1), pp. 1-7, 2 January, 2014
DOI: 10.5897/AJAR2013.6983
ISSN 1991-637X ©2014 Academic Journals
http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Simulation of air flow in cold chambers using the openfoam® computational fluid dynamics (CFD) software

Jose de Castro Silva, Barbara Janet Teruel Mederos* and Luiz Antonio Rossi

School of Agricultural Engineering, University of Campinas - UNICAMP, SP, Brazil.

Accepted 30 October, 2013

This work applied the mathematical models already implemented in the OpenFOAM® computational fluid dynamics (CFD) software, to simulate two proposed air distributions inside cold chambers. The OpenFOAM® software was chosen because of the absence of licensing costs associated with its use, compared to the major commercial CFDsoftwares available. In the pre-processing phase, we used the free Google SketchUp® software for the virtual design of the prototypes, and the free enGrid® software for the discretization of these virtual prototypes; later the resulting grids were used, by the OpenFOAM®, in the post-processing phase.

Key words: Air flow distribution, refrigeration, foods.

INTRODUCTION

The refrigerated storage, using vapor compression refrigeratedchambers, which causes a decrease in both the air and products temperature, is the most commonly used method for preserving food with their desirable characteristics; thus, reducing the loss of quality, and increasing the their shelf life (Ashrae, 2009). The best results from a proper preservation are obtained when the recommended temperature for each vegetable is maintained with fewer fluctuations, as well as the appropriate distribution of cooling air. Moreover, there must be adequate dimensioning of the cooling systems; thus, avoiding the risk of decreasing the life of the equipment (Furlan and Marques, 2007; Flores-Cantillano, 2011).

The proper design and operation of a cold chamber can represent a significant improvement in the reduction of costs, resulting in profits for the producer. Besides the temperature and relative humidity, distribution and air velocity of the cold air also have a direct effect on the heat transfer rates; directly affecting the cooling time, which in turn affects the quality and shelf life of the produce. Within a refrigerated environment, the temperature levels and their uniformity are directly governed by the airflow patterns. The temperature maintenance is essential during the transport and storage of a refrigerated cargo in order to preserve the shelf life, safety, and quality of perishable food products (Moureh et al., 2009). The computational fluid dynamics or CFD began in the late 1970s and early 1980s, where the flows with warlike interests were the primary focus, in particular, the displacement of air around aircraft and projectiles. For the flow of fluids (gases and liquids), the mathematical models are established based on partial differential equations of conservation of momentum,

*Corresponding author E-mail: barbarat@feagri.unicamp.br

mass and energy (Souza, 2011). The use of computers in conjunction with the experimental facilities, are an ideal interaction, which enhances the analysis of fluid dynamics (Krause, 1985).

The use of simulation software allows the solution of many scientific projects and operational problems without either stopping machinery or causing production losses. The reduction of time and number of experiments on test benches allows for considerable savings in developing new projects or updating the ones already in operation. Therefore, to ensure consistent simulation results, it is necessary to validate them with experimental ones (Souza, 2011). According to Djunaedy et al. (2003) and Luo and Roux (2004), with the advancements in computer technology, the use of simulation in fluid dynamics promoted a reduction in cost during the project analysis phase of research.

The CFD techniques are helpful in obtaining predictions of velocity and temperature distribution of indoor air, having an important role in improving designs of ventilation systems (Awbi, 1989). Gan (1995) compared heating and cooling systems for air conditioners, the simulations showed that the floor vent is more efficient than the conventional systems with outlets for ceiling diffusers. The CFD tools have been used for many years in the analysis of ventilation systems designs for buildings, and in assessing ventilation parameters and environmental settings for the air flow in air conditioning systems with floor vents (Nielsen, 2004). According to Fortuna (2000), it is a mistake to think that the CFD will replace experimental techniques and theoretical analysis. The CFD is an assisting tool in the understanding of the phenomena.

Fukuyo (2004) applied the computational simulation to analyze the relationship between occupations and thermal comfort within working environments. The results have shown that the creation of an automatic control system for the cooling system in conjunction with preventive maintenance scheduled by the technical support would be the ideal way of improving system efficiency. Jian et al. (2006), used computational tools to pre-analyze projects of the entry and exit angles for the air flows inside air conditioned environments,and with the help of a CFD tool, concluded that the elevation of the entry angle and reduction of the exit angle contribute to a better cooling environment, as well as the comfort for the occupants. The application of computational fluid dynamics in the agricultural sector is becoming increasingly important. Over the years, the versatility, ease of use and accuracy offered by the CFD led to its wider acceptance within the agricultural engineering community. Besides the refrigerated storage, the CFD is now regularly used to solve environmental problems in greenhouses and livestock facilities (Norton et al., 2007). Numerous studies have elucidated the benefits associated with the even distribution of air flow in animal and plant systems (Boulard et al., 2002; Gebremedhin and Wu, 2005). In animal production, control over the air flow is needed to remove moisture and gases from manure, and to provide shelterfrom cold temperatures, rain and radiation. These analyzes provide a significant improvement, making the environments healthier and more productive for both the animals and the workers (Spoolder et al., 2000). This shows that in the ambience area as well, the prior knowledge of the principles governing the distribution of internal climate variables through a CFD tool is indispensable for the design of production systems or to optimize its performance.

Tassou and Xiang (1998), Hoang et al. (2000), Nahor et al. (2005) and Xie et al. (2006) performed simulations in cold chambers with the evaporator in the conventional position, showing the existence of areas with stagnant air, and large variations in the air flow. The air flow analysis showed that the CFD can be used in the analysis of designs; however, it did not provide information on how to improve the air distribution within the cold chamber. With the complexity of temperature homogenization, fruits are stored at different stages of maturation, which is very detrimental to their marketing, seeing that they do not follow a maturation pattern.

Ho et al. (2010) who studied the distribution of air pressure and temperature inside a cold chamber concluded that the addition of evaporators, which increase the air flow, will help to minimize the temperature fluctuations. With the complexity of temperature homogenization, fruits are stored at different stages of maturation, which is very detrimental to their marketing, seeing that they do not follow a maturation pattern. Besides the use of CFD tools for the analysis of air flow in air conditioning systems and cold chambers, Cortella et al. (2001), Cortella (2002), Gaspar et al. (2003), Gaspar and Pitarma (2005), D'Agaro et al. (2006), Yan-Li et al. (2007) and Gaspar et al. (2012), all demonstrated the use of CFD software to analyze airflow in refrigerated display cabinets used in supermarkets.

Cortella et al. (2001) performed experimental measurements of temperature and air velocity, in order to validate the numeric model predictions. The goal was to simulate the phenomena of heat and mass transfer in open vertical refrigerated display cabinets; the mathematical model implemented in the CFD software accounted for the turbulent, non-isothermal 2D flow, and for the steady state heat transfer process. According to Cortella (2002) and Lu et al. (2007), the refrigerated display cabinet is the weakest link in the cold chain; therefore, researches seeking to improve this equipment can impact on the efficiency of the whole chain. However, it is important to add that the cold chambers, studied in this article, are connected to all the cold chain stages; thus, making them the most important equipment in the entire chain.

Gaspar et al. (2003) in a comparison between two commercial CFD software's; the PHOENICS® and the FLUENT®, concluded that the PHOENICS® is superior in

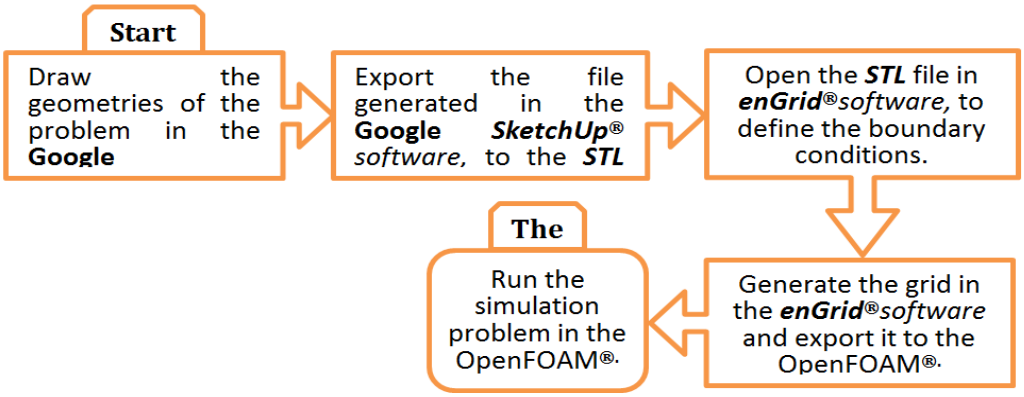

Figure 1. Show the sequence of the simulation process.

the diversity of physical and mathematical models, it presents major facilities in the construction of the computational grid, and in the ability of using larger quantities of mathematical models. Now, the FLUENT® is superior in the ease of use due to the versatility and simplicity of its interface, with higher velocity of convergence of solution, and relatively lower absolute error to the experimental values.

Gaspar and Pitarma (2005) used the PHOENICS® to simulate and visualize the flow and heat transfer in the refrigerated space from the refrigerated display cabinet, testing alternative configurations corresponding to a preliminary study of optimization. By comparing the numerical and experimental results for the temperature, it can be concluded that the simulation model can predict, with appropriate accuracy, the thermal performance of this equipment. It is noteworthy that Gaspar et al. (2003) and Gaspar and Pitarma (2005), used the same type of equipment (refrigerated display cabinets) for the experimental analyzes.

The comparison between the CFD results and the experimental data, performed by D'Agaro et al. (2006), and Gaspar et al. (2012), demonstrate that a 2D computer simulation is totally inadequate for such configurations, while the 3D simulations are closer to the real phenomena; therefore, the 3D simulation is a far better option for analyzing the engineering design in refrigerated display cabinets. The work assumes that the use of a new configuration for the distribution of air through the evaporator in the cold chamber makes it possible to minimize temperature differences between the hot and cold zones.

MATERIALS AND METHODS

OpenFOAM®Applications

The OpenFOAM® is basically a set of C++ libraries using the finite volume method (FVM) developed on the Linux platform, allowing elements to simulate 3D geometries, unstructured grids with an arbitrary number of faces and turbulence models. The OpenFOAM® was chosen because it is free, while the major commercial CFDsoftwares such as the FLUENT® and the CFX® owned by ANSYS® and the PHOENICS owned by CHAM carry licensing fees.

Simulation steps

In the pre-processing step, we used the free Google SketchUp® software for the virtual design of the prototypes, and the free enGrid® software (Figure 2) for the discretization of these virtual prototypes and to generate the grids; later the resulting grids were used in the post-processing phase by the OpenFOAM®(Figure 3). Figure 1 shows the sequence of the simulation process.

Directory of structures and files

Figure 4 shows the folders directory for the simulation setup used by the OpenFOAM®, and Figure 5 shows the directory of a problem with the three folders (5000, constant and system). The directory name <time>will be the number of programmed iterations; this directory contains the files with the field variables (RH, T, P, etc.), 5000 iterations were programmed for the simulations. The system directory contains the simulation configuration files (control Dict, fv Solution, fv Schemes, sample Dict, and decompose Part Dict). The constant directory contains the polyMesh directory, the files with the physical and thermodynamic proprieties, (g and thermo physical Properties), and the turbulence files (RAS Properties). The poly Mesh directory also contains the grid structure files (cells, faces and points), and the boundary conditions files.

Numerical simulations

Under the assumption that a gas flow is incompressible, turbulent, with constant viscosity, in steady state, and with no heat transfer through the walls of the chamber, the OpenFOAM® used the following equations: mass conservation, momentum, and energy. Such equations, mainly due to non-linearity associated with them, are complex, and to date, their analytical solutions were only achieved in a simplified manner. To develop a discrete approximation of the original equations, the OpenFOAM® simulation uses the numerical method of finite volumes to solve them. In turn, these discretized equations comprise a system of differential equations that are numerically solved at the same time.

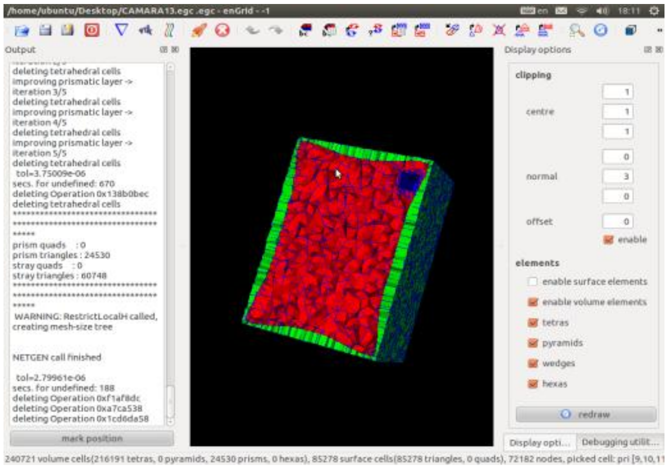

Figure 2. Show the ***enGrid***® window during the grid generation.

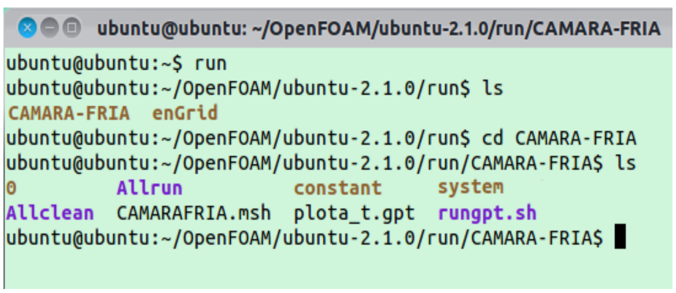

Figure 3. show the command terminal window in the Ubuntu Linux®.

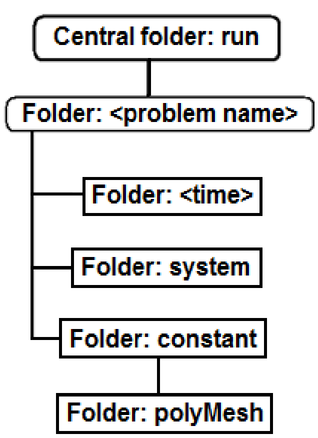

Figure 4. Structure of the OpenFOAM® directories.

This transformation procedure of the continuous equations into a system of discrete differential equations is called discretization. The main boundary conditions for analysis of all simulations were the air flow volumes, and the fluid temperatures at the entry and exit of the simulated geometries. The exit temperature of the cooled air from

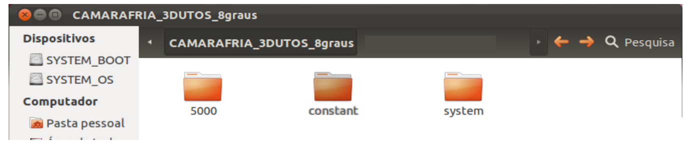

Figure 5. Directory of a simulated problem performed on the Ubuntu Linux®.

the evaporator was considered to be at 8°C, and the return temperature at 12°C; these reference values are used for the cold storage of fruits such as the Tommy Atkins mangoes (ASSIS, 2004). For the simulation of the chamber walls and the remaining surfaces, it was used the zero temperature gradient, that is, dT/dn = 0. The no-slip condition was imposed to the refrigerated chamber walls, that is, zero velocity on the surfaces. Slipping walls were assigned to the evaporators and ducts, considering that the velocities in these regions are sufficiently low, and that the boundary layer effects can be ignored; thus, facilitating the grid generation, since, in this situation, it is not necessary to build a more detailed layer such as the prism. Constant and normal surface velocities, calculated from the flow rates and intake areas, were considered at the ducts opening. For the first proposal (evaporator with ductwork) was considered the velocity of v = 12.6 ms$^{-1,}$ and for the second proposal (central evaporator), the velocity was of v = 2.98 ms^{-1}. The simulations were performed considering the atmospheric pressure of 1,0 atm at sea level.

Turbulence model

The k-ε, the most widely used model is robust and economical, with a wide range of applications. It provides good results for flows with high Reynolds numbers. It is the most used model in simulations of environments receiving mechanical ventilation (Zhao et al., 2003). We used this model of turbulence in the OpenFOAM® because of its ability to simulate a wide range of flows with minimal adjustment of the coefficients, the simplicity of formulation, and hardware availability. According to Xie et al. (2006), the model can be used to predict the behavior of air flows in cold chambers. Details regarding the implementation and validation of the k-ε turbulence model can be found in the works by Launder and Spalding (1974), Rodi (1980), and Chandrasekharan and Bullard (2005).

Suggestion of settings for the air distribution

The projects and installations of cool chambers for the cooling and preservation of fruits, vegetables and foods in general, are still performed with the evaporator positioned in the so called "conventional position". The following proposals were simulated in the OpenFOAM® according to the theoretical basis described above.

Proposal #1

In this first proposal, the air volumetric flow of 1800 m³ h^{-1} was used for the conventional evaporator. The designed ductwork (Figure 6) is composed of three air distribution branches, with 600 m³ h^{-1} in each extension; with the following equation it was possible to tailor each with three 75 mm outputs with 200 m³ h^{-1}in each exit.

$$Q = v.\ A \quad (1)$$

Where Q is the volumetric flow rate (m³ h^{-1}), V is the average

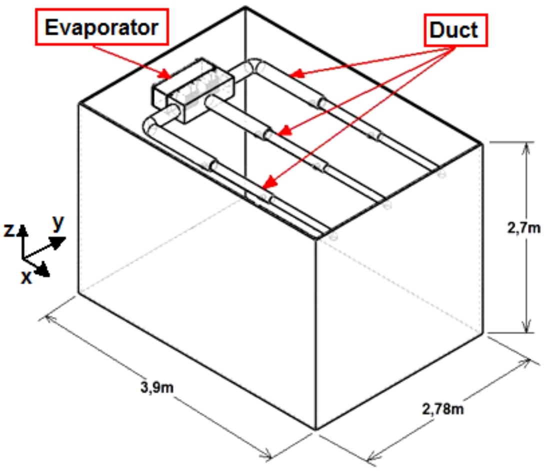

Figure 6. Proposed air distribution using a ductwork.

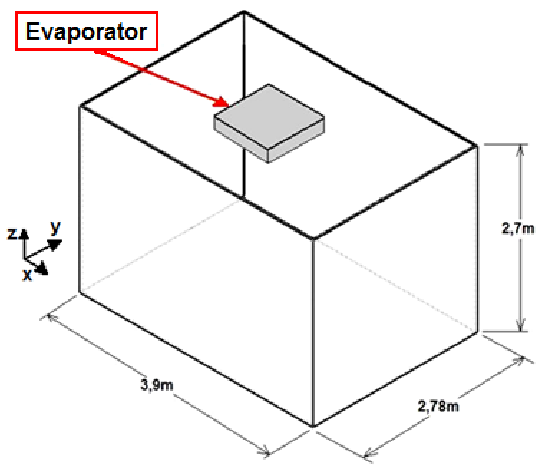

Figure 7. Ilustration of the cassette evaporator placed at the center of the cold chamber.

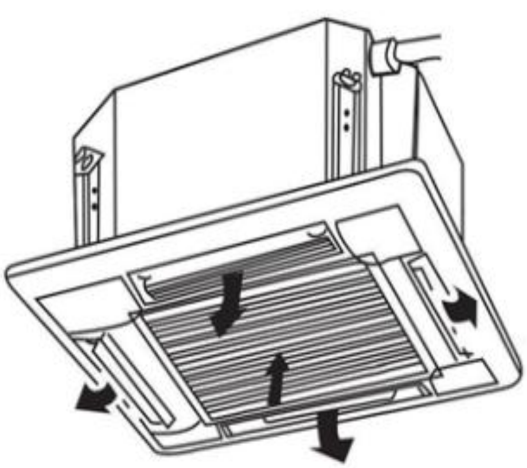

Figure 8. Cassette evaporator.

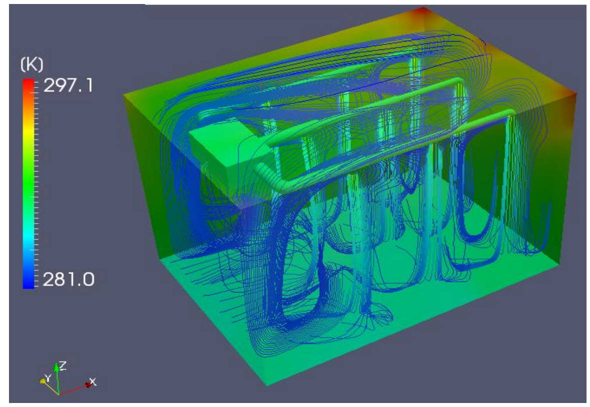

Figure 9. Air ductwork distribution showing air flow patterns

velocity of the section (ms^{-1}), and A is the sectional area (m^2).

Proposal #2

In this second proposal, we placed an evaporator, commercially known as cassette, in the center of the cold room (Figures 7 and 8). Currently, this evaporator is used exclusively in air conditioners; it is square-shaped with four air outlets, and a volumetric flow of 1800 m^3h^{-1}.

RESULTS AND DISCUSSION

In the first simulationanairflow pipeline network connected to the original evaporator of the refrigerator was used, but it was not a satisfactory alternative to reduce the temperature differential. The simulation showed that the temperature differential (ΔT) had a value of approximately 16°C higher than the differential (ΔT) of 14°C with the same evaporator without ductwork (Figures 9, 10 and 11). The temperature differential (ΔT) used in this analysis is the difference between the value of the lowest temperature and thehighest air inside the cold chamber.

In simulation # 2, the cassete evaporator originally designed for split system air conditioners, proved to be an alternative to reduce the temperature differential. In this problem simulated (Figures 12, 13 and 14), the temperature differential was worth approximately 7°C, and the same difference found in the work of Ho et al. (2010). It is observed in Figure 12, an ordering of the lines of current, different from Figure 9. Figure 14 shows a larger, more symmetrical filling of the air inside the chamber which differs from that observed in simulation No. 1 (Figure 11).

Conclusions

The OpenFOAM® tool proved to be useful in the

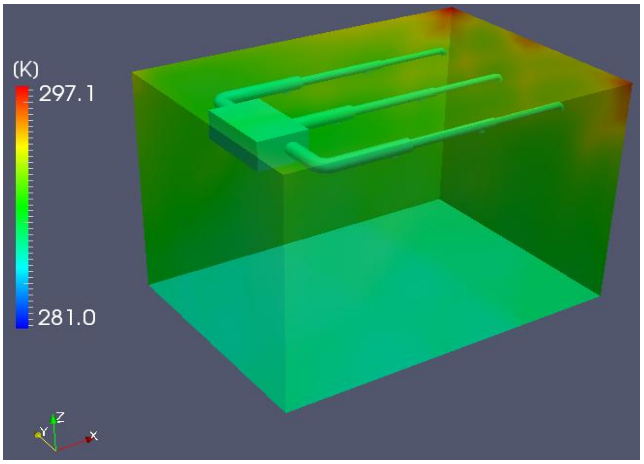

Figure 10. Distribution of air temperature in the network of ducts.

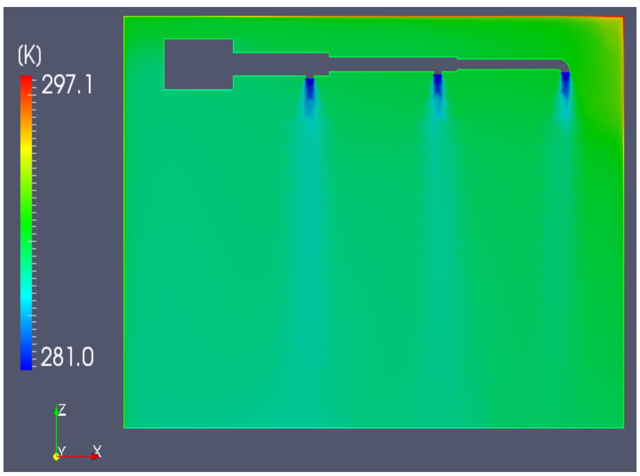

Figure 11. Distribution of air temperature in the center of the Y plan with a network of ducts.

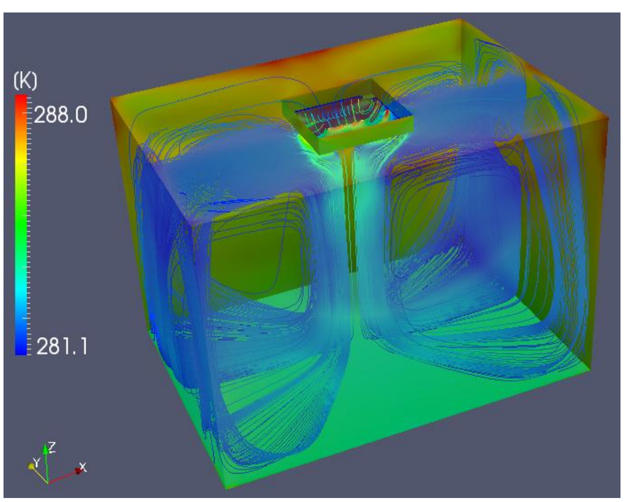

Figure 12. Temperature distribution and streamlines of the air with the evaporator model cassete.

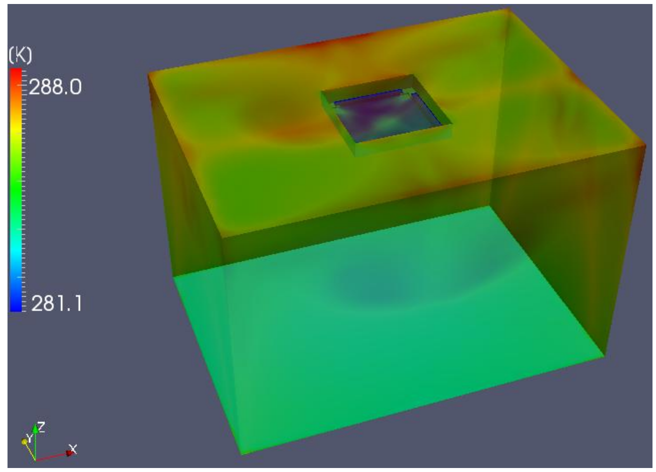

Figure 13. Temperature distribution with the evaporator model cassete.

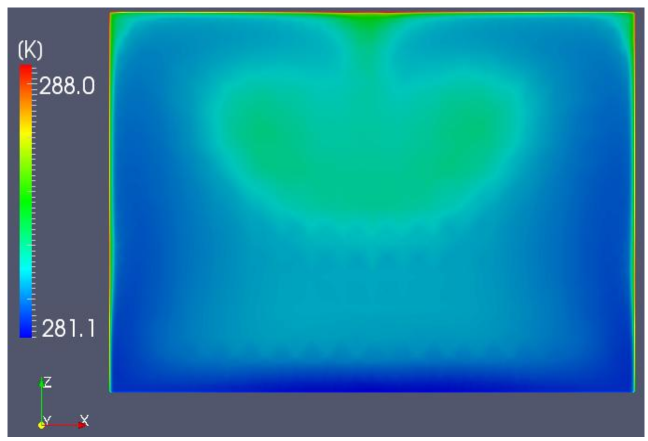

Figure 14. Temperature distribution evaporator model cassete in the center of the Y plan.

simulation, and analysis of the studies presented here. The proposed simulated in OpenFOAM® using a network of ducts connected to the original evaporator of the refrigerator, was not a good alternative to reduce the temperature differences, the maximum differential temperature remained at a value higher than that with the original evaporator configuration (no ductwork). To improve the circulation of air inside cold rooms and minimize temperature differentials, the simulation OpenFOAM® pointed out that the use of cassette model evaporators and air flow in four directions, currently only used in Spilt type air conditioners is an engineering solution for reducing temperature differentials in chambers.

REFERENCES

Awbi HB (1989). Application of Computational Fluid Dynamics in Room Ventilation, Build. Enrwon. 24:73-84.

Assis JS (2004). Colheita e pós-colheita da mangueira. Embrapa Semi-Árido Sistemas de Produção.

ASHRAE (2009). Fundamental handbook. Atlanta, Georgia, USA: American Society of Heating, Refrigerating and Air Conditioning Engineers.

Boulard T, Kittas C, Roy JC, Wang S (2002). Convective and ventilation transfers in greenhouses, part 2: determination of the distributed greenhouse climate. Biosyst. Eng. 83:129-147.

Chandrasekharan R, Bullard C (2005). Design tool for display case evaporators. ASHRAE Trans. 111:1071-1082.

Cortella G (2002). CFD-aided retail cabinets design. Comput. Electr. Agric. 34:43-66.

Cortella G, Manzan M, Comini G (2001). CFD simulation of refrigerated display cabinets. Int. J. Refrig. 24:250-260.

D'Agaro P, Cortella G, Croce G (2006). Two and three dimensional CFD applied to vertical display cabinets simulation. Int. J. Refrig. 29:178-190.

Djunaedy E, Hensen JLM, Loomans MGLC (2003). Development of a guideline for selecting a simulation tool for airflow prediction. Eighth International IBPSA Conference. pp. 267-274.

Flores-Cantillano RF (2011). A cadeia do frio e a qualidade das frutas e hortaliças. Disponívelem: <http://www.infobibos.com/Artigos/2011_1/CadeiaFrio/index.htm>. Acesso em: 14 set 2011.

Furlan EF, Marques D (2007). Refrigeração x Energia elétrica. Frigorífico 139:30-35.

Fukuyo K (2004). Simulations of Task-Ambient Air-Conditioning Systems by Computational Fluid Dynamics, Refrigerating-Cycle Simulator, and Pedestrian-Behavior Model. Int. Refrig. Air Cond. Conf. P. 729.

Fortuna AO (2000). Técnicas computacionais para dinâmica dos fluidos: Conceitos básicos e aplicações. São Paulo: Edusp.

Gan G (1995). Evaluation of room air distribution systems using computational fluid dynamics. Ener. Build. pp. 83-93.

Gaspar PD, Gonçalves LCC, Pitarma RA (2012). Detailed CFD modelling of open refrigerated display cabinets. Hindawi Publishing Corporation - Modelling and Simulation in Engineering.

Gaspar PD, Miranda A, Pitarma RA (2003). Estudo comparativo de desempenho de códigos de DFC na modelação de equipamentos de refrigeração abertos. Universidade de Évora - VII Congresso de Mecânica Aplicada e Computacional.

Gaspar PD, Pitarma RA (2005). Estudo numérico do desempenho térmico de expositores refrigerados abertos. Rev. Iberoam. Ing. Mecánica 9:21-30.

Gebremedhin KG, Wu B (2005). Simulation of flow field of a ventilated and occupied animal space with different inlet and outlet conditions. J. Thermal. Biol. 30:343-353.

Ho SH, Rosario L, Rahman M (2010). Numerical simulation of temperature and velocity in a refrigerated warehouse. Int. J. Refrig. 33:1015-1025.

Hoang ML, Verboven P, Baerdemaeker J, Nicoli BM (2000). Analysis of the air flow in a cold store by means of computational fluid dynamics. Int. J. Refrig. 23:127-140.

Jian Y, Li D, Xu H, Ma X (2006). Analysis of cold air distribution system in an office building by the numerical simulation method. Sixth ICEBO-International Conference for Enhanced Building Operations.

Krause E (1985). Computational fluid dynamics: Its presente status and future direction. Computers. Fluids, 13:239-269.

Launder BE, Spalding DB (1974). The numerical computation of turbulent flows. Comput. Methods Appl. Mech. Eng. pp. 269-289

Luo S, Roux B (2004). Modeling of the HESCO nozzle diffuser used in IEA Annex-20 experiment test room. Build. Environ. pp. 367-384.

Lu YL, Zhang WH, Gong Y, Tao WQ (2007). Numerical Simulation of Refrigerated Display Cabinets. BIC-TA (Bio-Inspired Computing: Theories and Applications) Second International Conference. pp. 258-262.

Moureh J, Tapsoba S, Derens E, Flick D (2009). Air velocity characteristics within vented pallets loaded in a refrigerated vehicle with and without air ducts. Int. J. Refrig. 32:220-234.

Nahor HB, Hoang ML, Verboven P, Baelmans M, Nicolai BM (2005). CFD model of the airflow, heat and mass transfer in cool stores. Int. J. Refrig. 28:368-380.

Nielsen PV (2004). Computational fluid dynamics and room air movement. Int. J. Indoor Environ. Health 14:134-143.

Norton T, Sun DW, Grant J, Fallon R, Dodd V (2007). Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review. Bioresour. Technol. 98:2386-2414.

Rodi W (1980). Turbulence models and their application in hydraulics – A state of the art review. International Association for Hydro-Environment Engineering and Research.

Souza Z (2011). Projeto de Máquinas de Fluxo. 1ed. Rio de Janeiro, Editora Interciência.

Spoolder HAM, Edwards SA, Armsby AW, Corning S (2000). A within farm comparison of three different housing systems for finishing pigs. Proceedings of the First International Conference on Swine Housing, Des Moines, Iowa, pp. 40-48.

Tassou SA, Xiang W (1998). Modellingthe environment within a wet air-cooled vegetable store. J. Food Eng. 38:169-187.

Xie J, Qu X, Shi J, Sun DW (2006). Effects of design parameters on flow and temperature fields of a cold store by CFD simulation. J. Food Eng. 77:355-363.

Yan-Li LV, Wen-Hui Z, Yi G, Wen-Quan T (2007). Numerical simulation of refrigerated display cabinets. Bio-Inspired Computing: Theories and Applications. Second International Conference.

Zhao B, Li X, Yan Q (2003). Simplified method for indoor airflow simulation. Build. Environ. 38:543-552.