2016

Experimental Evaluation of the Influence of Consumers' Passing Velocity on the Thermal Performance of Open Refrigerated Display Cabinets

Samuel Mariano Nascimento
Eletrofrio Refrigeração, Brazil, samuel@eletrofrio.com.br

Gustavo Galdi Heidinger
Eletrofrio Refrigeração, Brazil, gustavo@eletrofrio.com.br

Pedro Dinis Gaspar
University of Beira Interior, Portugal, dinis@ubi.pt

Pedro Dinho Silva
University of Beira Interior, Portugal, dinho@ubi.pt

Experimental Evaluation of the Influence of Consumers' passing Velocity on the Thermal Performance of Open Refrigerated Display Cabinets

Samuel M. NASCIMENTO[1], Gustavo G. HEIDINGER[1], Pedro D. GASPAR[2,*], Pedro D. SILVA[2]

[1]Eletrofrio Refrigeração Ltda, r João Chede, 1599, Cidade Industrial,
Curitiba - PR, 81170-220, Brazil,
+55 (41) 2105-6097, samuel@eletrofrio.com.br; gustavo@eletrofrio.com.br

[2] University of Beira Interior, Engineering Faculty, Dept. of Electromechanical Engineering,
Rua Marquês d'Ávila e Bolama, 6201-001, Covilhã, Portugal,
+351 275 329 759, * dinis@ubi.pt; dinho@ubi.pt

* Corresponding Author

ABSTRACT

Vertical open refrigerated display cabinets (VORDC) used to display perishable food for sale in convenience stores and supermarkets are subject to human interference. Consumers and repository personnel pass in front of the VORDC and frequently remove or place food products on shelves. This movement affects the thermal performance of the VORDC. Each interference drags or breaks the air curtain resulting in the modification of the air flow and promoting the ambient air thermal entrainment that consequently changes the VORDC working conditions. This experimental study quantifies the products temperature and the energy consumption of the VORDC when there is an interference due to consumers passing in front of the VORDC. The tests were performed in a test room according to ISO 23953 using a robotic mannequin (MARIA - Mannequin for Automatic Replication of the Interference in the Air curtain) that systematically passes in front of the VORDC. Experimental tests are performed for translational velocity from 0.2 ms-1 to 0.8 ms-1, with 0.2 ms-1 steps and considering two conditions: mannequin moving towards and against the air flow of the test room. The results quantify the influence of MARIA's translational velocity in front of the VORDC on the products temperature and energy consumption. These results are part of a more complex evaluation of the air curtain interference by humans to be used in the development of new products on an industrial scale.

1. INTRODUCTION

Part of the refrigeration equipment installed in supermarkets are vertical open refrigerated display cabinets (VORDC). The frontal opening to the environment allows consumer to see and handle the product that intends to acquire without inconvenience. The absence of this physical restriction for the consumer is accomplished by an air curtain that establishes an aerothermodynamics barrier between the conservation space, where the food products are located, and the external surroundings. However, this merchandising solution contributes to the largest part of electrical energy consumption among refrigeration equipment installed in a typical supermarket (Westphalen, 1996). The energy spent during the commercialisation of refrigerated food products is about 50% of the supermarket's total energy consumption ASHRAE (2010). The VORDC are the cabinet type that consumes more energy. According to Faramarzi (1999), ASHRAE (2010) and Gaspar *et al.* (2011), the thermal load due to ambient air infiltration in a VORDC corresponds 67% to 81% of the total thermal load. Consider the sketch of a VORDC as shown in Fig. 1. The air is drawn by the fans located in front of the evaporator. The air passing through the evaporator is cooled below the conservation temperature of the perishable products exposed in the shelves of the equipment. This air mass flow rate is conducted to the rear duct, where part of it is discharged inside the conservation space at low velocity across the back panel perforation (PBP). The other part of this air mass flow rate supplies the air curtain, which develops vertically between the discharge (DAG) and return (RAG) air grilles. The air curtain reduces the external infiltration of air from outside at higher dry temperature and specific humidity. The effectiveness of this aerothermodynamics barrier varies due to thermal and mass diffusive effects that affect the thermal entrainment. The thermal entrainment is associated with the air temperature and velocity gradient between the still ambient air and the air curtain, as well as flow instabilities and boundary effects. All these effects impact the overall performance of the equipment as shown by Gaspar *et al.* (2010a, 2010b). The global demand for commercial refrigeration equipment is forecast to rise 4.7% per year through 2018 to $36.5 billion (Freedonia, 2014). An updated report covering the USA indicates that the demand for commercial refrigeration equipment is expected to increase 3.1% per year through 2020 to $11.3 billion, being the display cases one of the fastest growing types (Freedonia, 2016). The combined analysis of these data confirms the need to evaluate the influence of the abovementioned parameters on the stability of the air curtain of VORDC to develop methodologies and procedures that may promote the reduction of energy consumption, improve the thermal performance and consequently ensure the food safety. There is a world trend to retrofit the VORDC into vertical closed refrigerated display cabinets (VCRDC) by installing glass doors in order to reduce the thermal entrainment of ambient air and consequently to reduce the energy consumption. However, in countries of Latin America most equipment is of open-type. In Brazil are manufactured about 30,000 refrigerated equipment, of these 30% is of closed type, 65% are open and 5% are combined (Nascimento *et al.*, 2015; Heidinger *et al.*, 2014).

This experimental work aims to quantify the increase of the thermal cooling load and the temperature increase of the products inside the VORDC due to the interference of consumers passing in front of the VORDC. The tests were performed in a test room according to ISO 23953 and using a robotic mannequin (MARIA - *Mannequin for Automatic Replication of the Interference in the Air curtain*) that systematically passes in front of the VORDC. Experimental tests are performed for translational velocity from 0.2 $m \cdot s^{-1}$ to 0.8 $m \cdot s^{-1}$ with 0.2 $m \cdot s^{-1}$ steps and considering a cycle time of 150 sec. These experimental tests are performed for two conditions: mannequin moving in the same direction or against the air flow of the test room.

2. STATE OF THE ART

Several methods, experimental and numerical, are adopted by many researchers to evaluate the thermal performance of VORDC, and particularly of the air curtain. Some researchers carried out Computational Fluid Dynamics (CFD) parametric studies based on two- and three-dimensional models. Cortella *et al.* (2001) and Navaz *et al.* (2002) evaluated the influence of DAG velocity in thermal performance, quantifying the air infiltration through the frontal opening. Ge and Tassou (2001), developed correlations for the heat transfer across air curtain with reasonable agreement with experimental data at steady state conditions, based on results obtained from a finite difference model. Axell and Fahlén (2003) developed a CFD parametric study to evaluate the influence on the thermal performance of air curtain height/width ratio and inlet velocity. Navaz *et al.* (2005), calculated the amount of entrained air as a function of Reynolds number, based on jet width and velocity and inlet turbulence intensity, to evaluate the optimum operating conditions. Foster *et al.* (2005) developed 3D CFD models to analyse the effect of changing the size and position of the evaporator coil, the width and angle of DAG and inserting baffle plates into the upper duct. D'Agaro *et al.* (2006) carried out 2D and 3D CFD parametric studies to evaluate the influence of: longitudinal ambient air movement; display cabinet length, and air curtain temperature on the extremity effects and how it reflects in the ORDC performance. Chen (2009) developed a CFD parametric study of length/width ratio and discharge angle of air curtains, height/depth ratio of the cavity and dimension and position of the inside shelves on thermal barrier performance of air curtains.

Other research works were just experimental, such as the study developed by Chen and Yuan (2005) to evaluate the ambient air temperature and relative humidity; indoor air flow; DAG velocity; PBP air flow; and night covers application, on the performance of a VORDC. Gray *et al.* (2008) conducted an experimental study to evaluate the effect of the perforation pattern of PBP on the distribution of airflow. Among the experimental techniques used by the researchers are thermocouple thermometry, hot wire/film anemometry, laser Doppler anemometry, DPIV, hygrometry, tracer gases, and infrared thermography. Although these experimental techniques are reliable and provide a high degree of confidence in the CFD modelling approaches, its use involves a high cost and results are dependent on the VORDC geometry, DAG parameters and ambient air conditions. Other method that can be used to evaluate the thermal performance of a VORDC considering the thermal barrier provided by the air curtain is the thermal entrainment factor (TEF) calculation as proposed by Navaz *et al.* (2005), D'Agaro *et al.* (2006), Chen and Yuan (2005), without PBP airflow or as proposed by Yu *et al.* (2009) to consider the PBP airflow on the calculations.

Gaspar *et al.* (2009, 2010a, 2011) evaluated the stability of the air curtain for climatic classes according to EN-ISO 23953 (2005) and other classes beyond the standard. The evaluation was made by experimental testing and numerically using CFD models. The results showed that the VORDC performance strongly depends on the ambient air conditions such as temperature, humidity, velocity and direction of ambient air flow in relation to the VORDC's frontal opening. These authors showed that (1) the cooling load increases with the air temperature and relative humidity of the external environment, (2) the increase of the ambient air velocity increases more significantly the power consumption of the

VORDC than the airflow direction change from parallel to perpendicular in relation the frontal opening of the VORDC, (3) the magnitude of deflection modulus D_m related with minimum momentum required to maintain a stable curtain of air is between 0.12 and 0.25; (4) the cooling load due to air infiltration is 78% - 81%, which is range closer to the value obtained by Faramarzi (1999) and (5) TEF is not constant along the length of the equipment for parallel air flow. Furthermore, the TEF value increases when the ambient air flow goes from parallel to perpendicular, being the worst case for $\theta_{amb} = 45°$. In the case study, TEF = 0.25, 0.32, 0.3 for $\theta_{amb} = 0°, 45°, 90°$ respectively. Nascimento *et al.* (2014a) developed experimental work with a VORDC in a climatic room which internal environment was adjusted according to EN ISO 23953-2 (2005) and to ASHRAE Standard 72-2014. The experimental results obtained in each test condition were compared. Additionally, the results were also compared with the tests developed by some manufacturers. The analysis of results showed that the indications provided by the EN ISO standard are stricter than the indication of ASHRAE standard. Thus, tests following the former standard have more energy consumption. The tests produced by manufacturers simulate the internal environment of a store with several equipment connected at the same time in a large room with a traditional air conditioning system with air vents in the ceiling and air return nozzles in the room sides. The results showed that the VORDC consumes on average 17% less energy in non-standardized tests. These results are used by manufacturers as project data and usually do not show operating problems due to the undersizing the mechanical refrigeration system. Nascimento *et al.* (2014a) indicate that further studies are needed to clearly describe the performance differences obtained in standardized laboratory and in field tests. Kaffel *et al.* (2016) developed an experimental investigation using time resolved particle image velocimetry (TR-PIV) to investigate the aerodynamic behavior of a wall jet subjected to external lateral stream (ELS). The experiments are performed on a reduced-scale model representing a generic configuration of a VORDC. The work focus on the near-field region downstream the nozzle exit. Comparisons of experimental data obtained with and without external perturbation allowed to quantify the effect of the perturbation on the time-averaged wall jet characteristics such as airflow patterns, mean velocity and root mean square (RMS) of velocity fluctuations, Reynolds shear stress, space correlations and the development of primary and secondary instabilities. The aerodynamic interaction between the ELS and the wall jet gives rise to an external circulation loop located at the bottom of the wall jet. This recirculation strongly affects the wall jet characteristics yielding a significant decrease in the jet entrainment, higher velocity fluctuations and lower jet expansion. The ELS reduces the jet entrainment at the jet nozzle vicinity which in turn lowers the mean jet flow rate. Additionally, Moureh and Yataghene (2016a, 2016b) investigated experimentally and numerically the aerodynamic behavior and the effectiveness of an air curtain confining cavity and subjected to external lateral stream. Experiments were carried out on a VORDC reduced-scale model using LDV and PIV techniques. A CFD model was developed to better understand the local air flow characteristics. A good agreement between CFD and experimental results was found. Comparisons of experimental and numerical data obtained with and without external perturbation make allow to quantify the effect of the perturbation on the air curtain characteristics such as airflow patterns, velocity profiles, maximum velocity decay, half-width jet growth and its stability as well as those related to the global fluxes exchanged between the air curtain and its surroundings. The sealing performance of the air curtain with and without external perturbation was evaluated through dimensionless parameters related to air tightness, thermal entrainment and thermal confinement efficiency. It was showed that for higher values of external lateral velocity, the performance of the air curtain was reduced. Thus, although there have been developed experimental studies concerning the air curtain performance due to external perturbations, none of these evaluate the influence of consumers, which reveals the significance of the present work.

3. MATERIALS AND METHODS

3.1 Experimental apparatus

The VORDC provided by Eletrofrio Refrigeration LTDA - Brazil has 2.5x1.1x2.1 m^3. It comprises (1) an insulating body (IB) surrounding all the equipment; (2) tube and fins heat exchanger (HX); (3) discharge air grille (DAG); (4) return air grille (RAG); (5) perforated back panel (PBP) and shelves (SH) as shown in Figure 1. The temperature of the refrigerated compartment is provided by the cold air mass flow that exits DAG and PBP and returns to RAG to be cooled again in the HX. The air flow exiting DAG forms an air curtain which protects the inner refrigerated compartment. Note that this equipment has a primary air curtain (PAC) and a secondary air curtain (SAC) in order to promote a more effective aerothermodynamics sealing. The air for SAC is collected from the bottom front of the VORDC. An electronic expansion valve in mounted in the HX to control the refrigerant superheat, maintaining it at the temperature of 7 °C. The VORDC has four fans with 53 W each to supply a flow rate of 0.4 $m^3 \cdot s^{-1}$ to DAG and PBP. The air, before reaching the DAG, passes through an evaporator with dimensions 2.20x0.13x0.35 m^3 constituted by 222 fins and three rows of tubes in the air flow direction and 8 rows of tubes perpendicular to it. The DAG has a total width, *b*, of 140 mm, which is equally distributed to form the PAC (b_{PAC} = 70 mm) and SAC (b_{SAC} = 70 mm). This equipment is used to display products with temperature class M1 (-1 °C to +5 °C). It was installed a remote mechanical system with a compressor Octagon 2DC-3.2 and water condenser. The measuring instruments were selected in order to obtain reliable measurements of the relevant physical properties variation collected every minute during the experimental test. The experimental tests (ET) followed EN ISO 23953 (2005) and were performed in a climatic chamber designed in accordance to the standard. Figure 1 shows the location of the test probes inside the VORDC. Air temperature and humidity sensors Super MT 530 were placed in DAG, RAG and ambient. Temperature sensors type PT1000 were placed in the test M-packages (product simulators). A Coriolis flow meter MASSFLO 2100 DI 6 was installed at the liquid refrigerant line.

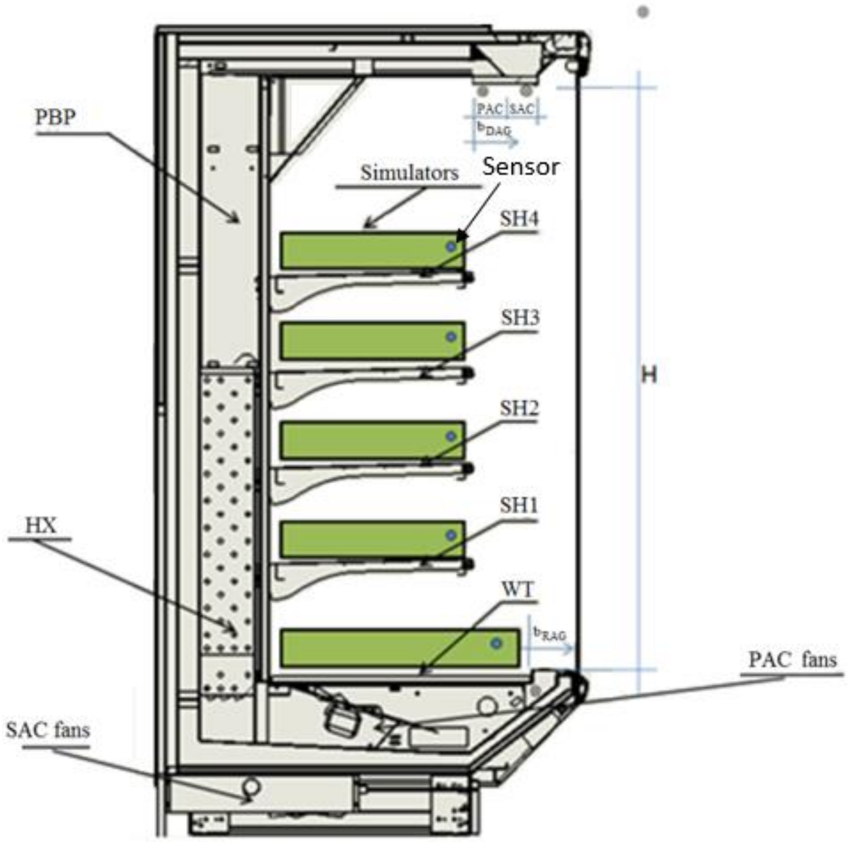


Figure 1: Vertical open refrigerated display cabinet and sensors location (Legend: Temperature sensors: ●; Temperature and humidity sensors: ●).

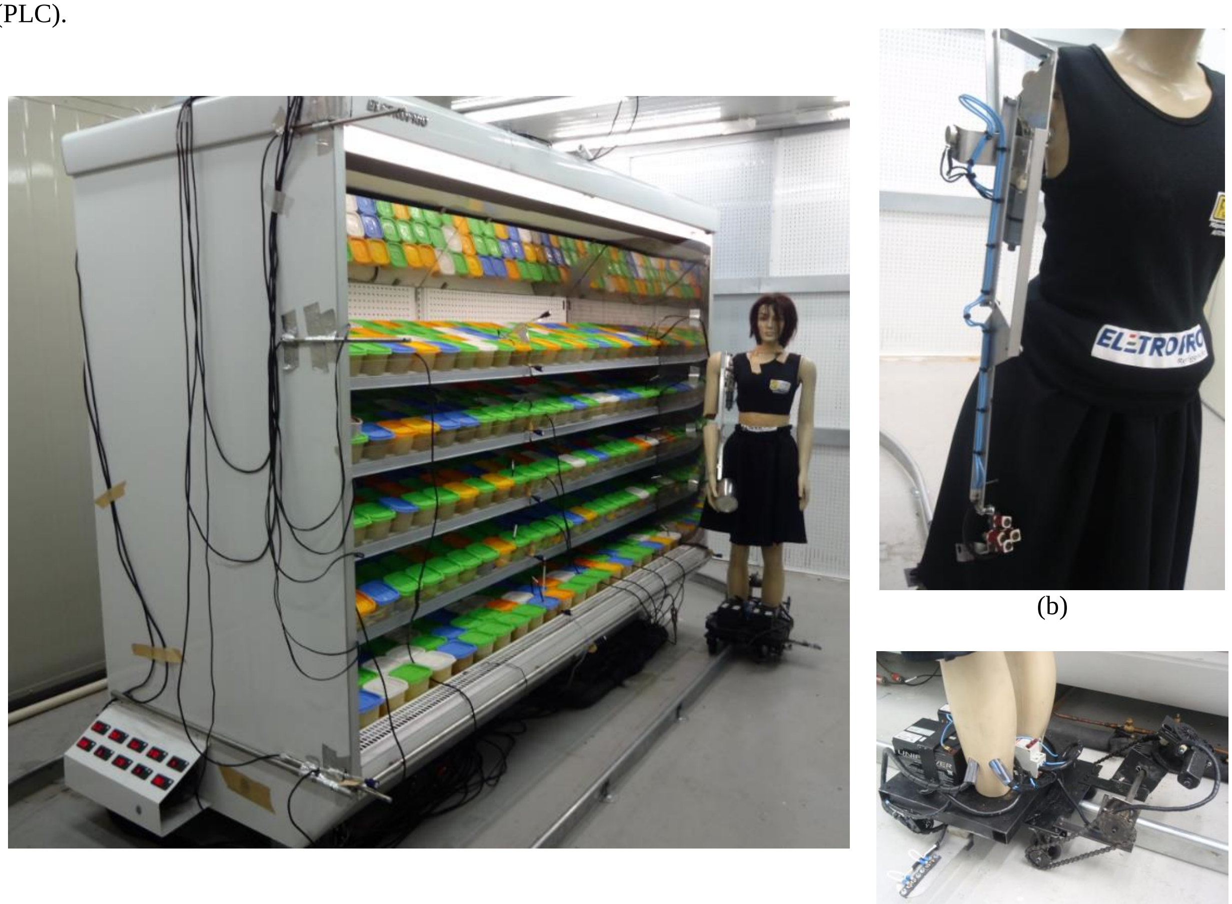
Table 1 shows the experimental techniques and probes/experimental measuring devices used to collect the relevant physical properties.

Table 1: Experimental techniques and probes/experimental measuring devices.

Experimental technique	Model	Measuring range	Accuracy
Thermometry	PT 1000	-40°C to +80°C	± 0.3 °C
	MT 530 Super	-10°C to 70°C	± 1.5 °C
Hygrometry	MT 530 Super	20% to 85%	± 5%
Anemometry	HD2903TC3.2	0.05 $m \cdot s^{-1}$ to 1 $m \cdot s^{-1}$	± 2%
Flowmetry	MASSFLO 2100	0 to 1000 $kg \cdot h^{-1}$	± 0.1%
Barometry	AKS 32	0 to 200 psig	± 0.3%

3.2 Robotic mannequin MARIA

A robotic mannequin, MARIA (*Mannequin for Automatic Replication of the Interference in the Air curtain*), shown in Figure 2, was designed and constructed for the experimental study. The robot is composed by an electrical locomotion system that runs on a rail that goes around the VORDC (see Figure 2 a) and c). MARIA has a robotic arm that was built to simulate the movement performed by a consumer arm when is taking out a food product from the VORDC (see Figure 2 b). MARIA locomotion and movements were programmed in a Programmable Logic Controller (PLC).



(a) (b) (c)

Figure 2: MARIA (Mannequin for Automatic Replication of the Interference in the Air curtain).

3.3 Experimental testing procedure

This work starts from the results obtained by Nascimento *et al.* (2013, 2014a, 2014b) through the development of experimental studies aimed to optimize the thermal performance with adjustment of the air flow between the DAG and PBP. The best configuration lead to tests carried out with MARIA moving in the front of the VORDC in order to determine the thermal performance when subjected to the transfer of an object (MARIA) in the frontal opening.

The results showed that: (1) adjusting the proportion of air flow between the DAG and PBP improved the VORDC performance by 10%. (2) the movement of MARIA in front of the VORDC at a velocity of 0.6 $m \cdot s^{-1}$ increased energy consumption by 4.6%. These results are part of a more detailed study of the interference on the air curtain triggered by consumers. These results are to be used in the development of new products on an industrial scale. This experimental study is part of that study since it was designed to evaluate the influence of the systematic passage of consumers in front of the VORDC on the perturbation of the air curtain and consequently on its performance.

Experimental tests (ET) were performed with a double air curtain, D, constituted by PAC and SAC. The tests were referenced as ET.D.x.x. For each case, MARIA was programmed to move in front of VORDC with different velocities. Each passage in front of the VORDC was set to a period of 150 sec. Besides the case where MARIA is stopped (Reference case, $v_{MARIA} = 0\ m \cdot s^{-1}$), velocities from 0.2 $m \cdot s^{-1}$ to 0.8 $m \cdot s^{-1}$ with steps of 0.2 $m \cdot s^{-1}$ were considered. These ET were named sequentially, that is, ET.x.0.x to ET.x.4.x. This velocity value was obtained with fieldwork analysis and corresponds to the average velocity of people in a supermarket moving in front of a VORDC in the butchery section. Each test lasted 24 hours Additionally, tests were conducted in which MARIA, moves itself toward, T, and against, A, the airflow of the test room. These ET were respectively named ET.x.x.T and ET.x.x.A. The experimental tests were conducted under the same climate condition and air velocity in the test room. Figure 3 shows a schematic of the test room with the VORDC and MARIA moving around it.

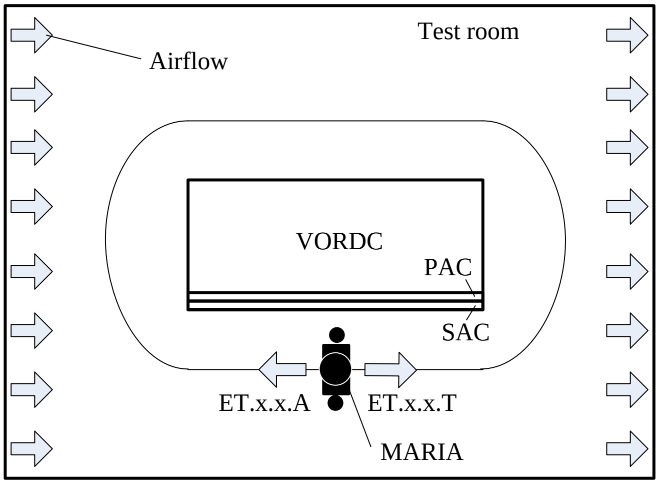


Figure 3: Schematics of experimental tests.

4. RESULTS ANALYSIS AND DISCUSSION

This section includes the analysis of test results for the different MARIA translational velocities. It is assumed as reference case the experimental test, ET.D.0.Stop, when MARIA is stopped in front of the VORDC frontal opening. Figure 4 shows the power consumption for different test setups. Figure 5 shows the average temperature of product simulators for each shelve from the well tray (WT) to the upper shelf (SH4) (see Figure 1 for details about the location of the shelves). Figure 6 shows the average condensate mass during defrost and refrigeration periods. Figures 4 to 7 represent the variation of the parameters (increase or decrease) in relation to the reference case (ET.D.0.Stop).

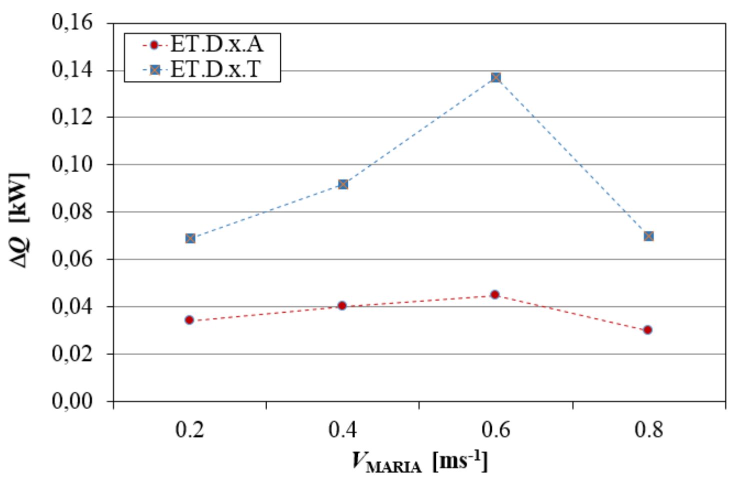


Figure 4: Energy consumption variation for different test setups.

The power consumption of the VORDC in the reference test (Double air curtain with MARIA stopped) was $Q = 4.82$ kW. As shown in Figure 4, the power consumption increases with the velocity of MARIA movement, reaching $Q = 4.97$ kW when the movement is performed at a velocity of 0.6 $m \cdot s^{-1}$ towards the climate room air flow. At a higher translational velocity of 0.8 $m \cdot s^{-1}$, the power consumption reduced in both directions (towards or against the airflow of the test room). The highest power consumption is determined when the movement is performed towards the air flow of the test room. Thus, the increase of the amount and translational velocity of consumers in front VORDC has a significant impact on the disturbance of the air curtain and consequently on the thermal infiltration, this is reflected in an increased power consumption. Figure 4 shows that the performance of the curtain is affected by the direction of movement. The perturbation of the air curtain is higher when the movement is in the same direction of the test room air flow. This condition occurs due to the sum of drag forces in the same direction turning the cold air flow more turbulent in the frontal region of the VORDC.

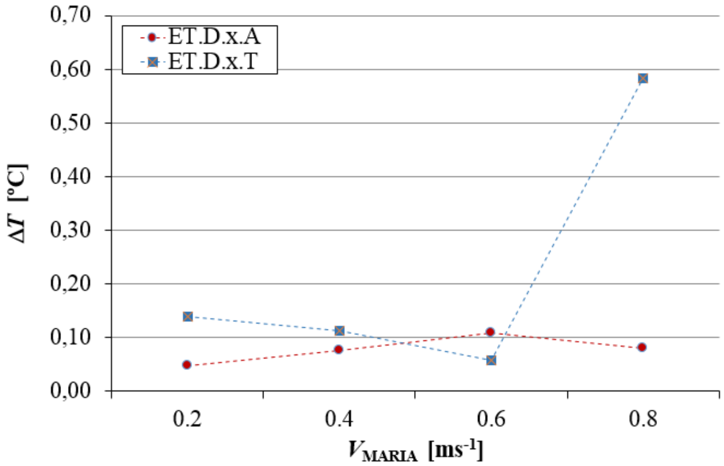


Figure 5: Products temperature variation for different test setups.

With respect to transfer time in front of VORDC, it is possible to observe that the translational velocity of 0.6 $m{\cdot}s^{-1}$ has a larger negative effect on the performance of the air curtain. This velocity value triggers more thermal entrainment and drag between the air masses of the air curtain and ambient air. For the translational velocity of 0.8 $m{\cdot}s^{-1}$, it is possible to observe a significant reduction of the energy consumption. However, Figure 5 shows that the average simulators temperature in this ET increases significantly, approximately 0.6 °C. By other side, Figure 6 shows a reduction on the amount of water collected during defrost period while Figure 7 shows the variation of this parameter during the refrigeration period. The analysis of these conditions indicates that the VORDC performance was impaired by translational velocity at higher velocity. The reduction of the heat load is due to stabilization of the air temperature inside the VORDC at a temperature level above the reference ET. As the HX uses an EEV to control the refrigerant superheating, when there is ice formation on the HX surface, the superheating reduces and the EEV works restraining the refrigerant mass flow. Thereby, the capacity of the HX is reduced which in turns reduces the energy consumption since it depends on the amount of fluid flowing into the HX. This condition is quantified by Eq. (1).

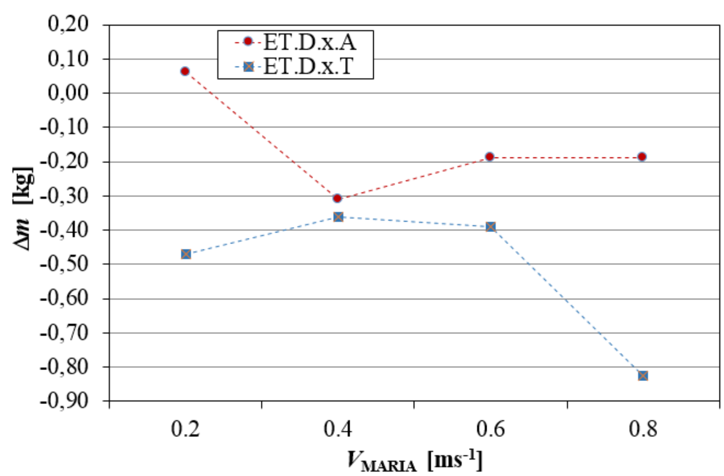


Figure 6: Condensate mass variation during defrost period.

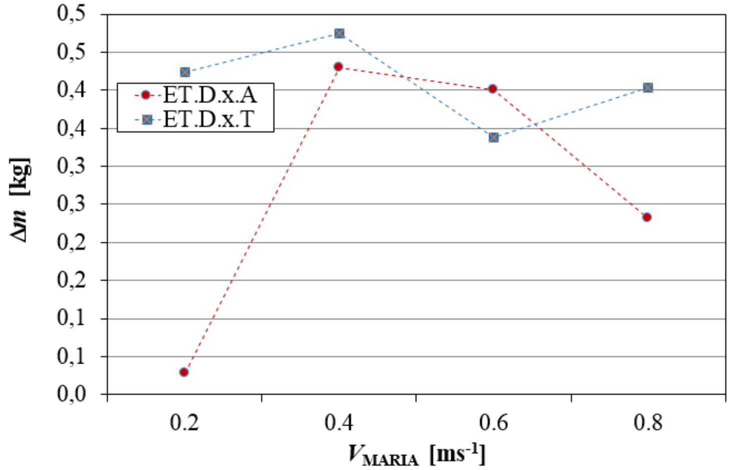


Figure 7: Condensate mass variation during refrigeration period.

According to Huzayyin *et al.* (2007), the decrease in the difference in air temperature between the inlet and outlet can be explained by the increase of condensation on the fins and tubes surfaces of the HX, which increases the resistance to heat transfer.
Reindl & Jekel (2009) indicate that there are unfavorable conditions for ice formation that leads to the freezing of ice crystals directly in the air stream. Such crystals adhere to the fins due to the impact creating a lower density ice that blocks faster the air flow through the coil. The unfavorable for icing condition occurs when the air humidity at the evaporator inlet is very high and the dew point temperature of the equipment surfaces is very low. The air becomes saturated with moisture during the cooling process that leads to the formation of ice crystals directly in the air stream. The HX should be studied in more detail to obtain answers more consistent in relation to these ET results. However, it is possible to indicate that the ET that triggered more disturbance in the air curtain, had greater ice formation rate after start working, i.e., after post defrost, which reduced the heat transfer rate, thus the EEV restrained the passage of refrigerant to stabilize the system

5. CONCLUSIONS

This experimental study quantifies the products temperature and the energy consumption due to the air curtain interference by consumers passing in front of a VORDC. The tests were performed on a double air curtain VORDC using a robotic mannequin (MARIA - *Mannequin for Automatic Replication of the Interference in the Air curtain*) that systematically passed in front of it. The movements were set towards and against the air flow of the test room, with translational velocity from 0.2 $m{\cdot}s^{-1}$ to 0.8 $m{\cdot}s^{-1}$, with 0.2 $m{\cdot}s^{-1}$ steps. The analysis of the experimental results provided the following conclusions: (1) This performance is reduced as MARIA translational velocity increases due to larger thermal and mass interactions with the external environment. In this case, the power consumption increases 3% from a stop condition to a translational velocity of 0.6 $m{\cdot}s^{-1}$. Besides the power consumption, also the products temperature and total condensate mass increase.; (2) The increase of MARIA translational velocity causes a reduction of the overall performance of the VORDC
Experimental tests using MARIA will provide additional insights and quantification of the thermal loads in VORDC caused by consumers passing and extracting food products from the VORDC. These results can help manufacturers to develop equipment that able of reducing the negative effects of consumers motion within the store through control, regulation and command techniques applied to it devices such as fans. In countries where most of the equipment are still open to the ambient air this research path can represent a significant energy reduction. These results are part of a more complex evaluation of the air curtain interference by humans to be used in the development of new products on an industrial scale.

NOMENCLATURE

A	Against
CFD	Computational Fluid Dynamics
DAG	Discharge Air Grille

DPIV	Digital Particle Image Velocimetry	
ET	Experimental Tests	
EEV	Electronic Expansion Valves	
HX	heat exchanger	
IB	Insulating Body	
MARIA	Mannequin for Automatic Replication of the Interference in the Air curtain	
ORDC	Open Refrigerated Display Cases	
PAC	Primary Air Curtain	
PBP	Perforated Back Panel	
PLC	Programmable Logic Controller	
RAG	Return Air Grille	
SAC	Secondary Air Curtain	
SH	Shelves	
T	Towards	
TEF	Thermal Entrainment Factor	
VCRDC	Vertical Closed Refrigerated Display Cases	
VORDC	Vertical Open Refrigerated Display Cases	
WT	Well Tray	
b	width	(m)
v	velocity	($m \cdot s^{-1}$)
θ	direction	(º)
D_m	deflection modulus	(-)

Subscript

amb	ambient air
DAG	Discharge Air Grille
MARIA	Mannequin for Automatic Replication of the Interference in the Air curtain
PAC	Primary Air Curtain
RAG	Return Air Grille
SAC	Secondary Air Curtain

REFERENCES

ASHRAE. (2010). ASHRAE *Handbook: Refrigeration*. Atlanta, Ga: American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

Axell, M., & Fahlén, P. (2003). Design criteria for energy efficient vertical air curtains in display cabinets. In: IIR, editor. *Proc. of 21st IIR Int. Congress of Refrigeration*, Washington DC, USA: IIR.

Chen, Y-G. (2009). Parametric evaluation of refrigerated air curtains for thermal insulation, *Int. J. Thermal Sciences*, *48*(10), 1988-96.

Chen, Y-G., & Yuan, X-L. (2005). Experimental study of the performance of single-band air curtains for multi-deck refrigerated display cabinet. *J. Food Engineering 2005*, *69*(3), 261-7.

Cortella, G., Manzan, M., & Comini, G. (2001). CFD simulation of refrigerated display cabinets. *Int. J. Refrig.*, *24*(3), 250-60.

D'Agaro, P., Cortella, G., & Croce, G. (2006). Two- and three-dimensional CFD applied to vertical display cabinets refrigeration. *Int. J. Refrigeration*, *29*(2), 178-19.

Faramarzi, R. (1999). Efficient display case refrigeration. *ASHRAE Journal*, *41*(11), 46–52.

Foster, A.M., Madge, M., & Evans, J.A. (2005). The use of CFD to improve the performance of a chilled multi-deck retail display cabinet. *Int. J. Refrigeration*, *28*(5), 698-705.

Freedonia (2014). *World Commercial Refrigeration Equipment - Industry Study with Forecasts for 2018 & 2023*. Freedonia.

Freedonia (2016). *Commercial Refrigeration Equipment - US Industry Study with Forecasts for 2020 & 2025*. Freedonia.

Gaspar, P.D., Gonçalves, L.C.C., & Ge, X. (2010a). CFD parametric study of ambient air velocity magnitude influence in thermal behaviour of open refrigerated display cabinets. *Proceedings of the 5th European Conference on Computational Fluid Dynamics* (ECCOMAS CFD 2010), Lisbon, Portugal.

Gaspar, P.D., Gonçalves, L.C.C., & Ge, X. (2010b). Influence of ambient air velocity orientation in thermal behaviour of open refrigerated display cabinets. *Proceedings of the ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis ESDA 2010* (ASME ESDA 2010), Istanbul, Turkey, July: ASME.

Gaspar, P.D., Gonçalves, L.C.C., & Pitarma, R.A. (2011). Experimental analysis of the thermal entrainment factor of air curtains in vertical open display cabinets for different ambient air conditions. *App. Therm. Eng., 31*(5), 961–969.

Gaspar, P.D., Gonçalves, L.C.C., & Vogeli, A. (2009). Dependency of air curtain performance on discharge air velocity (grille and back panel) in open refrigerated display cabinets. *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Lake Buena Vista, Florida, U.S.A: ASME.

Ge, Y.T., Tassou, S.A. (2001). Simulation of the performance of a single jet air curtains for vertical refrigerated display cabinets. *Int. J. Refrigeration, 21*(2), 201–9.

Gray, I., Luscombe, P., McLean, L., Sarathy, C.S.P., Sheahen, P., & Srinivasan, K. (2008). Improvement of air distribution in refrigerated vertical open front remote supermarket display cases. *Int. J. Refrigeration, 31*(5): 902-10.

Heidinger, G.G., Nascimento, S.M., Gaspar, P.D., & Silva, P.D. (2014). Influence of the test procedure for setting the external air movement on the thermal performance of open multideck display case. *Recent Advances in Mechanical Engineering 11*, 96-104.

Huzayyin, A.S., Nada, S.A., & Elattar, H.F. (2007). Air-side performance of a wavy-finned-tube direct expansion cooling and dehumidifying air coil. *International Journal of Refrigeration, 30*, 230-244.

ISO 23953-2 (2005). *Refrigerated display cabinets - Part 2: Classification, requirements and test conditions*. Geneva, Switzerland: International Organization for Standardization (ISO).

Kaffel, A., Moureh, J., Harion, J-L., & Russeil, S., (2016). TR-PIV measurements and POD analysis of the plane wall jet subjected to lateral perturbation. *Exp. Thermal and Fluid Science, 77*, 71-90.

Moureh, J., & Yataghene, M. (2016a). Numerical and experimental investigations on jet characteristics and airflow patterns related to an air curtain subjected to external lateral flow. *Int. Journal of Refrigeration, 67*, 355-372.

Moureh, J., & Yataghene, M. (2016b). Numerical and experimental study of airflow patterns and global exchanges through an air curtain subjected to external lateral flow. *Exp. Thermal and Fluid Science*, *74*, 308-323.

Nascimento, S.M., Heidinger, G.G., Gaspar, P.D., & Silva P.D. (2014a). Performance variation of vertical refrigerated display case in situ operation and testing according to ISO and ASHRAE STANDARDS. *Proc. of the 3rd IIR Int. Conf. on Sustainability and the Cold Chain* (ICCC 2014), London, United Kingdom: IIF/IIR.

Nascimento, S.M., Heidinger, G.G., Gaspar, P.D., & Silva P.D. (2014b). Experimental study of the interference in air curtains due to the parallel transfer in front of refrigerated display cases. *Proc. of ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis ESDA2014*, Copenhagen, Denmark: ASME.

Nascimento, S.M., Heidinger, G.G., Gaspar, P.D., & Silva P.D., (2013). Thermal insulation by air curtains in open refrigerated display cabinets - Comparison of the thermal performance of tests performed in laboratory, open and closed food shop conditions. *Proc. of the Int. Conference on Engineering* (ICEUBI 2013), Covilhã, Portugal.

Nascimento, S.M., Heidinger, G.G., Gaspar, P.D., & Silva, P.D. (2015). Experimental analysis to optimize the performance of air curtains and heat exchangers: Application to open refrigerated display cases, Ch. 16, pp. 590-640, in Gaspar, P.D., & Silva, P.D. (Eds.), *Handbook of Research on Advances and Applications in Refrigeration Systems and Technologies*, IGI Global.

Navaz, H.K., Faramarzi, R., Gharib, M., Dabiri, D., & Modarress, D. (2002). The application of advanced methods in analyzing the performance of the air curtain in a refrigerated display case. *Trans. ASME J. Fluids Eng., 124*, 756–64.

Navaz, H.K., Henderson, B.S., Faramarzi, R., Pourmovahed, A., & Taugwalder, F. (2005). Jet entrainment rate in air curtain of open refrigerated display cases. *Int. J. Refrigeration, 28*(2):267-75.

Reindl, D.T., & Jekel, T.B. (2009). Frost on air-cooling evaporators. *ASHRAE Journal 51*(2), 27-33.

Westphalen, D., Zogg, R., Varon, A., Foran, M. (1996). *Energy Savings Potential for Commercial Refrigeration Equipment*. In: ADL - Arthur D. Little, editor. Final Report prepared For Building Equipment Division Office of Building Technologies. Cambridge, Mass: U.S. Department of Energy – DOE.

Yu, K-Z., Ding, G-L, & Chen, T-J. (2009). A correlation model of thermal entrainment factor for air curtain in a vertical open display cabinet. *Applied Thermal Engineering*, *29*(14-15), 2904-13.