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

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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

Open refrigerated display cabinets (ORDC) used to expose perishable food for sale in convenience stores and supermarkets are subject to human interference. Consumers and repositories pass in front of the ORDC and frequently remove or place food products on the shelves depending on sales volume. This movement is part of the trade; however, it has consequences on the thermal performance of the ORDC. Each interference drags or breaks the air curtain resulting in the modification of air flow and promoting the ambient air thermal entrainment that consequently change the equipment's working conditions.

ASHRAE (2010) indicates that the percentage of the energy consumed in a typical supermarket due to the refrigeration systems reaches 50%. Compressors, refrigerated display cases, walk-ins and condensers consume this energy. The vertical open refrigerated display cases (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. This condition results from the low efficacy of the air curtain in separating (thermal and mass) two contiguous spaces with different thermal environments, whose access must be kept open for operational and/or commercial reasons. The application of air curtains results from the need of a non-physical sealing between the food products stored in cold and the consumer, so that he can see and handle without constrains the food product to purchase, and thus increasing the sales potential.

The effectiveness of this aerothermodynamics sealing is highly dependent on ambient air conditions, i.e. its temperature (T_{amb}), relative humidity ($\o_{\text{amb}}$) and velocity - module (v_{amb}) and direction (θ_{amb}). The thermal entrainment is associated with the variation of these parameters, which impact on the overall performance of the equipment is significant and differentiated 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). The combined analysis of these data confirms the need to evaluate the influence of ambient air conditions 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 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.*, 2014a).

This work, experimental and numerical, aims to quantify the increase of thermal load of cooling and the temperature increase of the products inside 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 $\text{m}\cdot\text{s}^{-1}$ to 0.8 $\text{m}\cdot\text{s}^{-1}$ with 0.2 $\text{m}\cdot\text{s}^{-1}$ 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. All tests are performed in an ORDC with two configurations: single and double air curtain.

2. STATE OF THE ART

The work developed by various researchers has focused, for this type of equipment, in qualifying and quantifying the perceptible thermo-physical properties of the jet that provides a cold air curtain. Hayes & Stoecker (1969) developed a correlation that describes the ability of the air curtain to provide a proper separation between environments. The correlation is given by a dimensionless parameter named as deflection modulus, D_{m}, which is the ratio between the air curtain momentum and the modulus of the transverse forces caused by temperature difference between the contiguous environments. Faramarzi (1999) determined the relative weight of the cooling load components for VORDC, composed by thermal loads from infiltration, radiation, conduction, product pull-down cooling, devices (lights and fans), defrost and anti-sweat heaters, and product respiration. According to EN-ISO 23953 (2005), the total cooling load can be determined by eq. (1).

$$\dot{Q}_{tot} = \dot{m}_{ref} \cdot \Delta i \tag{1}$$

Chen *et al.* (2005, 2009, 2011) developed studies using Computational Fluid Dynamics (CFD) codes to evaluate the thermo-physical parameters of the air curtain in VORDC. The performance of the air curtain was evaluated by the variation of Reynolds number, Grashof number, Richardson number and dimensionless temperature. The results provided the following conclusions: There is a range of values of Reynolds number, dependent of the height/width ratio of the air jet, that provide an optimal thermal insulation of the cold air curtain jet; The Grashof number provides the fluctuation proportion of the buoyancy force that acts on a viscous fluid in situations involving heat transfer by natural convection while the Richardson number is related to the influence of natural convection in relation to forced convection It can be stated that air curtains with small height/width ratio provide a good thermal performance. Navaz *et al.* (2005) developed studies using Digital Particle Image Velocimetry (DPIV) focusing mainly in studying the effectiveness of the air curtain and maintaining the temperature of food products to a predetermined value. The results evaluation indicates that the Reynolds number has direct effect on the ambient air entrainment due to its role in the turbulence development. According to Navaz *et al.* (2005), the best range of values for Reynolds number in the discharge air grille (DAG) is about 3200-3400. In that study, the authors defined the Thermal Entrainment Factor, TEF, to quantify the thermal entrainment of the air curtain with the ambient air, varying $0 < \text{TEF} < 1$. The analysis of the correlation shows that a TEF close to 0 provides a low thermal entrainment with the ambient air. The correlation described by Navaz *et al.* (2005) does not take into account the air flow through the perforated back panel (PBP). Yu *et al.* (2009) developed the TEF equation considering this air flow. The results obtained by Yu *et al.* (2009) show a good approximation for TEF and temperature value at the return air grille (RAG) with deviations of 0.9% and 0.1 °C respectively. These deviations indicate that the correlation has a good approximation at the engineering level and can be applied in the design of VORDC. 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 $\theta_{\mathrm{amb}} = 45°$. In the case study, TEF = 0.25, 0.32, 0.3 for $\theta_{\mathrm{amb}} = 0°, 45°, 90°$ respectively. However, the majority of studies abovementioned were based in VORDC with a single jet in DAG. This paper presents the initial calibration for experimental studies in a VORDC with double jet in DAG. This kind of equipment is used when is needed a "stiffer" aerothermodynamics sealing to separate the contiguous spaces. Nascimento *et al.* (2013b, 2013c) developed experimental fieldwork to assess the energy consumption of VORDC in stores during open and close periods. The results showed that the VORDC consume on average during the open period 18% more energy than in close period. This increase of the energy consumption is due, in part, to the consumers' movement inside the store that affects the performance of the air curtain. In that study was not possible to quantify the thermal load increase due to movement inside the store, because the equipment was also subject to variations of the environment air temperature and humidity. Based on this constrain, it was recommended the development of experimental and numerical studies in which thermal effect due to the external environment can be considered constant, to thereby quantify only the effect of consumers' movement in front of the VORDC. 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. To pursuit this objective, several experimental and numerical studies were developed by Nascimento *et al.* (2015), Heidinger *et al.* (2014a, 2014b, 2015a, 2015b) and Carneiro *et al.* (2015) to evaluate the influence of the test procedure for setting the external air movement on the thermal performance of the VORDC and its evaporator. Experimental tests and simulation models were developed to analyse the thermal performance by varying the width of the discharge air grille and the perforation density of the back panel, since they have a significant effect on the thermal entrainment factor and the energy consumption of the equipment. Kaffel *et al.* (2016) developed experimental tests 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 comparison of the experimental results obtained with and without external perturbation allow quantifying the effect of the perturbation on the time-averaged wall jet characteristics. The results of the application of the proper orthogonal decomposition technique illustrate the strong effect induced by the ELS in reducing the jet entrainment at the jet nozzle vicinity which in turn lowers the mean jet flow.

The results described on this review of studies covering this topic along with the results shown in this paper provide valuable information based on in-store environmental conditions and airflow efficiency for the air curtain and heat exchanger design as well as the control, regulation and command system of the refrigeration system.

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 device 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.

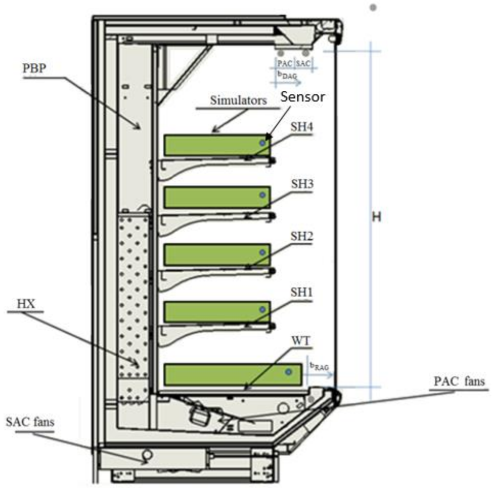

Figure 1: Vertical open refrigerated display cabinet and sensors location (Legend: Temperature sensors: ●; Temperature and humidity sensors: ●).

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).


(b)

(a) (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, $v_{\text{MARIA}} = 0\ m \cdot s^{-1}$), 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.

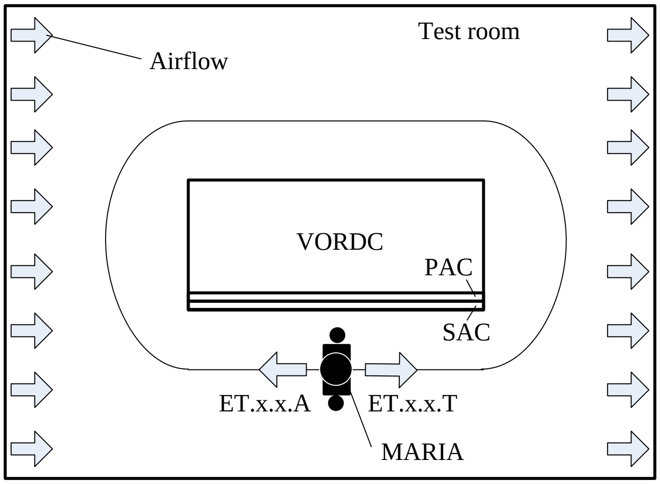

Figure 3: Schematics of experimental tests.

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).

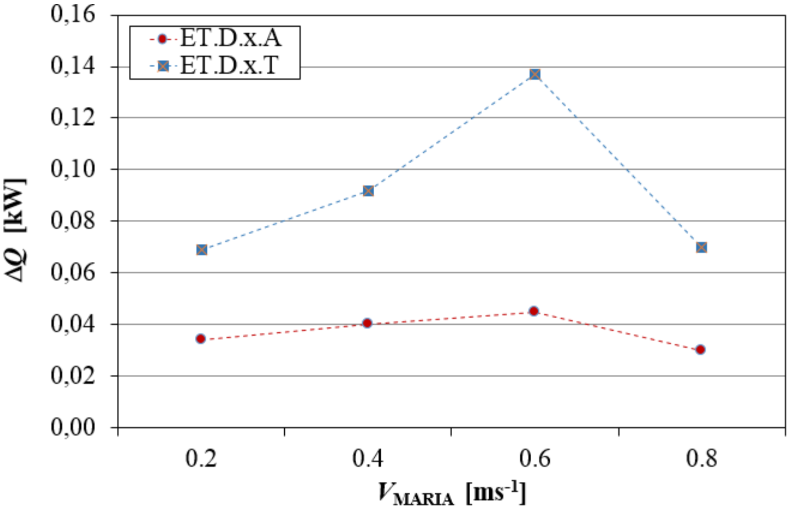

Figure 4: Energy consumption variation for different test setups.

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.

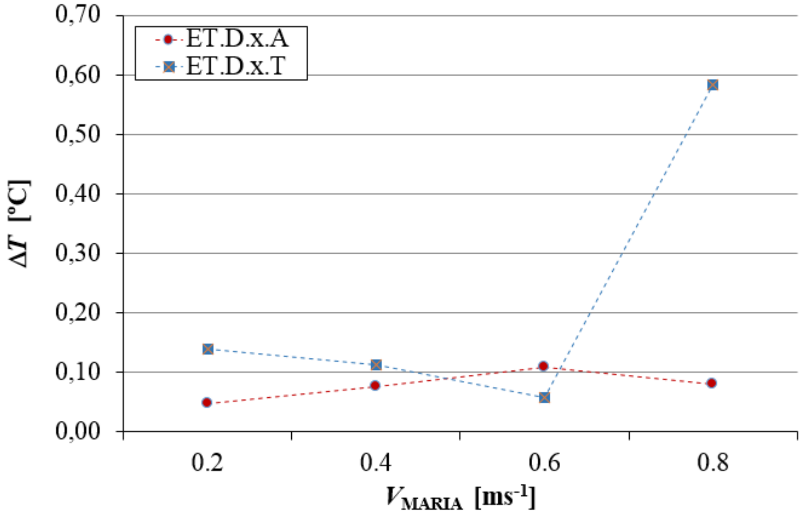

Figure 5: Products temperature variation for different test setups.

With respect to transfer time in front of VORDC, it is possible to observe that the translational velocity of 0.6 m·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·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).

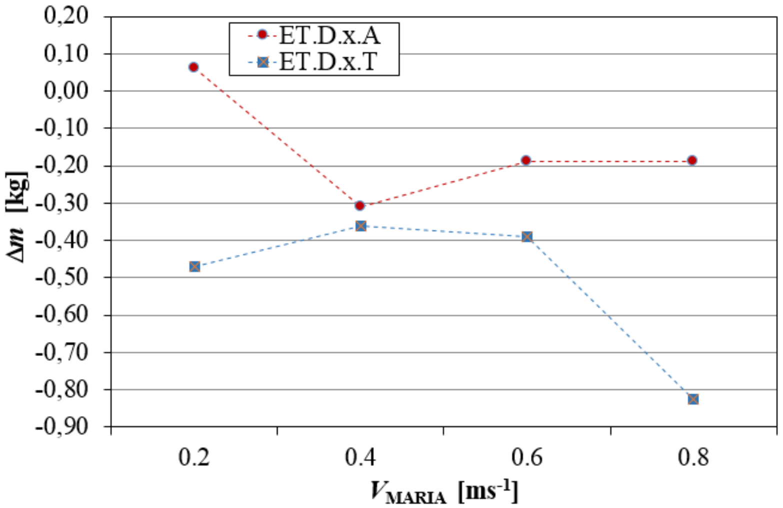

Figure 6: Condensate mass variation during defrost period.

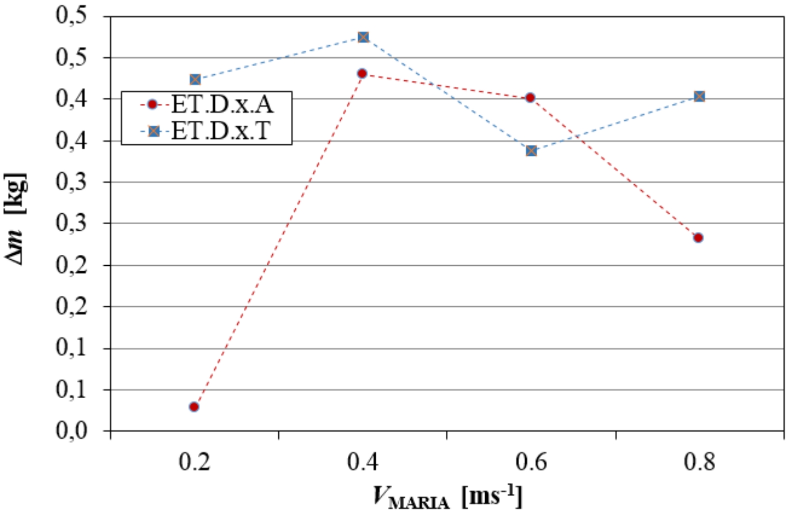

Figure 7: Condensate mass variation during refrigeration period.

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

CFD	Computational Fluid Dynamics

DAG	Discharge Air Grille	
DPIV	Digital Particle Image Velocimetry	
HX	heat exchanger	
MARIA	Mannequin for Automatic Replication of the Interference in the Air curtain	
ORDC	Open Refrigerated Display Cabinets	
PAC	Primary Air Curtain	
PBP	Perforated Back Panel	
PLC	Programmable Logic Controller	
RAG	Return Air Grille	
SAC	Secondary Air Curtain	
TEF	Thermal Entrainment Factor	
VCRDC	Vertical Closed Refrigerated Display Cases	
VORDC	Vertical Open Refrigerated Display Cases	
WT	Well Tray	
b	width	(m)
T	air temperature	(ºC)
$\o$	relative humidity	(%)
v	velocity	$(\mathrm{m{\cdot}s^{-1}})$
θ	direction	(º)
D_{m}	deflection modulus	(-)
$\dot{Q}_{tot}$	total cooling load	(W)
$\dot{m}_{ref}$	refrigerant mass flow	(kg/s)
Δi	enthalpy difference	(kJ/kg)

Subscript

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

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