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Numerical and Experimental Investigation of Air Flow in Refrigerated Display Cabinets

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Abstract

Refrigerated Display Cabinets (RDCs) are used as a means to effectively present the product to the consumer while keeping the product from spoiling. They are run using an air curtain that typically drops from the discharge grill at the top to the return grill at the bottom. These cabinets are inherently inefficient and even a small amount of efficiency increase can save significantly on a supermarkets energy expenditure.

The velocity of the air curtain was determined using Laser Doppler Velocimetry. The flow visualization was also used for the purposes of qualitative analysis. Back panel velocities were also gathered for the use in boundary conditions of a 3D computer simulation of the midsection of the RDC using Computational Fluid Dynamics (CFD) as most CFD to date is 2D in nature.

The RDC was validated against the data and the conditions were compared. The simulation in three dimensions has proven to be a valuable exercise in understanding the complexities of running a full three dimensional flow simulation. It showed us the clearly the how strongly three dimensional flows have on a RDC system. The data has a correlating relationship with the simulation but could improve in accuracy.

Introduction

Refrigerated display cabinets (RDCs) often utilize a cool curtain of air to maintain the quality of the product stored, which includes such food products as milk, dairy, meat and other perishable foods. Air curtains provide no physical wall separating the consumer from the product and as such this approach has better marketing potential in encouraging consumer purchases while preserving the quality of the food (Cortella et al., 2001).

Most open RDCs are designed like normal refrigerators apart from having no door. Instead, there is an air curtain which is typically discharged from the top of the cabinet and falls down to the return grill located at the bottom. The air curtain provides an insulating layer of air that keeps the products at the appropriate temperature while keeping the ambient air and other particulates from reaching the product; the theoretical result is two completely separate temperature regimes inside and outside the cabinet. Practically, however, the air curtains on open RDCs are not completely effective in keeping the products at the appropriate temperature.

The process for bringing produce from the farm to the consumer is called the chill chain with the stages in the chain being primary chilling, spray chilling, chilled storage, secondary chilling, transportation and retail display. Other steps may be present depending on the type of produce in question and in what form it is to be presented to the consumer. RDCs have been identified as the weakest link in the chain (James, 1996). Since this is the case, it is a prudent step to analyze the display process more and to improve the efficiency of the display aspect of the chilled food chain.

Inefficiency can arise from a number of sources. Heat transfer, or entrainment, occurs between the store environment and the air curtain, and increase the temperature of the curtain resulting in a reduction in effectiveness (Foster et al., 2005). This is caused by the air curtain interacting with the store environment. This entrainment takes place and mixes the cool curtain air with the relatively warm store air (Moureh et al., 2009).

Smale et al (2006) reviewed the use of numerical models to predict the air flow in refrigerated environments. D'agaro et al. (2006) specifically exemplified two-dimensional (2D) and three-dimensional (3D) CFD to vertical display cabinets. The main emphasis as derived from the latter was that 3D effects of the airflow could be not be assumed to be negligible in cabinets under 2 meters long. Also, vertical cabinets have been found to have a reduced 20% efficiency. Ambient room velocity also proved to be an important aspect in RDCs performance. It should be noted that the experimental and the model predictions results of the full 3D simulation were not comparable to each other. This may be predominantly caused by the uncertain nature of the boundary conditions (D'Agaro et al., 2006). The vast majority of papers to date simulating RDCs have been 2D in nature.

Experimental Method

The RDC, shown in Figure 1, is 1224 mm wide, 1570 mm tall from discharge to return grill and 1040 mm deep. The model is an Austral make, utilizing a refrigerant R404A. The refrigerator rating is 2567W based on 75% runtime after defrost AS1731.12 for climate class 3.

The one-dimensional LDV system model (see Figure 1) is a Measurement Science Enterprise Inc mini-LDV-G5-240 diode laser. The LDV laser system has a fringe spacing of 9.01 nm at a wavelength of 658 nm with max power set at 60 mW. The measured probe volume is 240mm away the probe with the dimensions of 150 x 300 μm by 4 mm.

The probe was mounted on a three dimensional DANTEC traverse system capable of moving in three perpendicular directions parallel to the cabinets' height, width and length in increments of 0.01mm. The traverse system has a movement range of 0.5 meters in a defined X, Y, and Z direction. The burst signal processing program used to collect velocity data is provided with the LDV system and used the frequency of the seeded flow to determine velocity. The back of the cabinet was painted matt black in order to prevent the laser from scattering or reflecting from the back of the cabinet to the laser sensor, which can cause inaccuracies in the data.

In order to make useful comparisons at different sections of the air curtain, a non-dimensional air curtain width (NDACW) was defined. The NDACW is defined as the ratio of the width of the air curtain to the width of the discharge grill:

$$NDACW = \frac{\text{Width of aircurtain}}{\text{Width of discharge grill}} \tag{1}$$

The width of the air curtain was determined using the LDV data where the air flow reached 20% of maximum velocity for the particular height. The width of the discharge grill was fixed at 85mm.

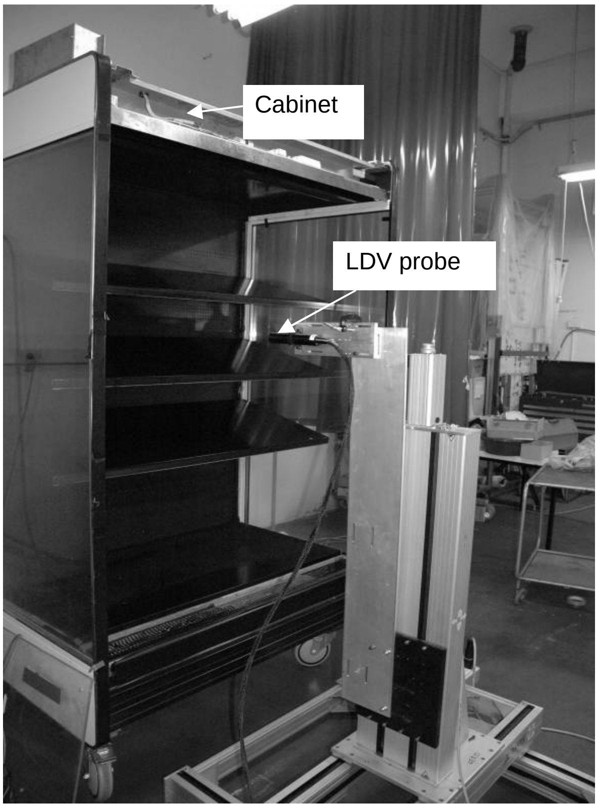

Figure 1. Refrigerated Display Cabinet with Laser Doppler Velocimetry Probe.

The RDC was turned on and the compressor allowed to warm up to reach maximum cooling. This takes anywhere from fifteen minutes to half an hour. After the compressor is sufficiently warmed up, the RDC was let to run for about ten minutes to allow the air curtain temperature to stabilize. Once this was done, the traversing system was moved every sixty seconds to give sufficient time for the laser to gather the velocity data. Temperature readings of the room were taken at different times of day for several days and it remained consistent at around 24 degrees Celsius.

The cabinet is seeded with the M-6000 model fog machine through the return grill so that the fog runs through the cooling coils before being discharged. Measurements were taken to compare against CFD and to determine the NDACW.

Flow visualization also was performed on the cabinet to determine the location of the air curtain. The laser sheet had a power rating of 500mv and the laser frequency was 532nm. The sheet was placed in the midplane of the cabinet with a camera perpendicular to the sheet. The flow was then seeded from the return grill and photos were taken with a Nikon E90 camera. The result was the midplane being illuminated by the laser sheet, giving an overview of how the flow behaved.

The laser sheet was mounted on a movable pedestal and positioned at the optimal distance so that the laser was illuminating the entire height of the cabinet in the midplane of the RDC. The camera was placed perpendicular to the laser sheet behind the glass side of the RDC. The camera was set to the highest light sensitivity of 1200 in the ISO option for brightness and a 0.2-0.4 second shutter time for clarity and definition of the flow regime.

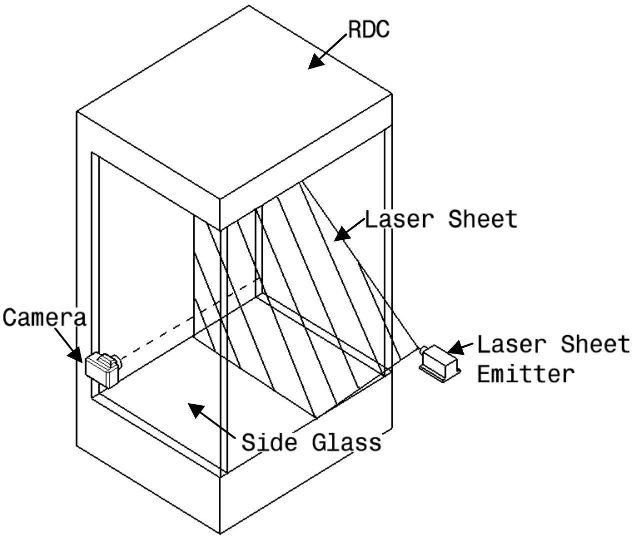

Figure. 2 – Isometric view of laser sheet setup

All the lights were extinguished in the outside environment so as to allow for the illumination of the flow to be clearer. The cabinet was warmed up for ten minutes so the air curtain could stabilize. A fog machine was used to seed the flow at the return grill of the RDC and was blown until the laser sheet illuminated the flow. Photos were then taken using a Nikon E90 camera until insufficient number of fog particles illuminated the flow. The fog machine was used to reseed the flow. Several hundred photos were taken to ensure that the air curtain behavior would be captured. The same procedure was completed on the RDC with the shelves removed.

It should be noted that the experimental values in Table 2 were carried out with walls erected inside the RDC at the sides of the 30cm midsection. A similar methodology has been used to analyse the air curtain with more scrutiny and with less concern of the surrounding area effecting it (Field and Loth, 2006).Walls were placed on the straight shelf scenario only for ease of instalment so only straight shelf, walled experimental values are available. This was to make a direct comparison to the 30cm slice in the numerical model.

Numerical Model

For the numerical simulation, the commercial code ANSYS CFX 12.1 was used. Governing equations of mass, momentum and energy were solved. Buoyancy was included to account for the difference in the density within the airflow. Turbulence was handled via the two-equation k-ε model. Steady state results were deemed to be obtained and convergence was assume to be reached when the mass residual fell below the prescribed criterion 10^{-5}.

A structured grid was constructed for the cabinet and the surrounding room region. Figure 2 shows the cross-sectional mesh of the computational domain. The mesh consisted of 3 million hexahedral elements and a 30 cm slice of the midsection of the cabinet has been solved along the lateral direction reducing the computational burden (see Figure 3 and 4). Fine resolution was required for series of holes at the back panel that ran across the entire cabinet. The holes were about 4 mm in diameter and were arranged in rows of 75. There are 32 rows in all located in, what were deemed as, key areas of the refrigerated display cabinet.

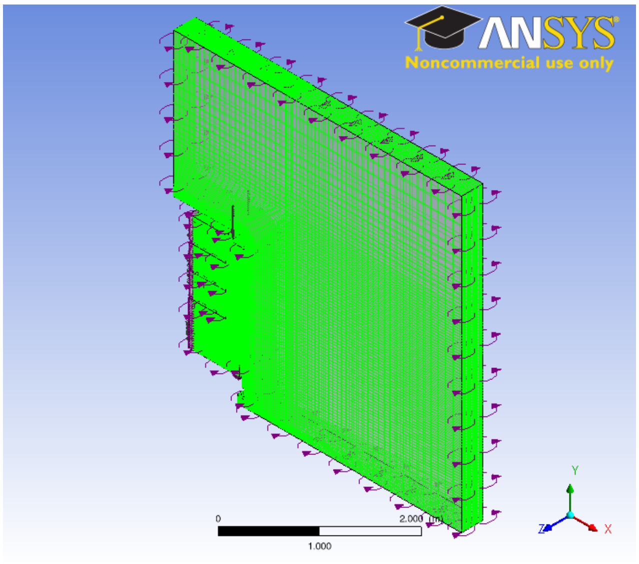

Figure 3. Isometric view of the straight shelf computational mesh

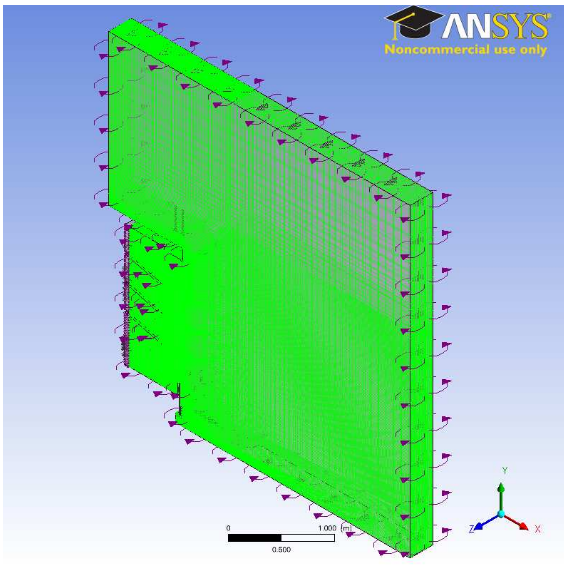

Figure 4. Isometric view of slanted shelf computational mesh.

Boundary Conditions

The inlet of the air curtain was set at 1m/s as well as the suction of the return grill. The temperatures of the inlet of the cabinet were set at 3.71 degrees Celsius. The back panel velocities and temperatures ranged from 1-5 degrees Celsius depending on the row of the holes and were it was located. All boundary condition data mentioned above was gathered through experimental means. The LDV was used for the entrance velocity data and thermocouples were used to measure temperatures.

Specification of the boundary condition on the sides of the midsection region along the lateral direction remained unclear. Several boundary conditions were tested such as periodic, symmetry and opening all of which have proved to exert a strong influence of the airflow structure within the RDC. Further quantification on the appropriate boundary condition is currently being investigated.

Table 2 simulation values were gathered with the side boundary conditions set as walls in order to compare with the experimental walled RDC.

Results

Figure 5 shows the flow visualization of the smoke traces in the vicinity of the shelves recorded during the experiment which depicted the prevalence of the air curtain separating the internal cooler airflow within the ORDC from the external warmer air. In Figure 6, preliminary computed airflow appeared to reveal similar qualitative behaviour of an air curtain, which descended from the discharge grill and some of the air curtain escaped into the aisle while the some returned through the discharge grill.

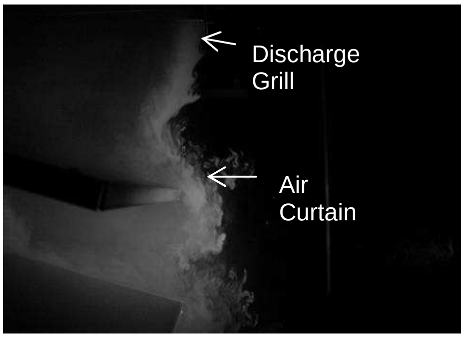

Figure 5. Flow visualization.

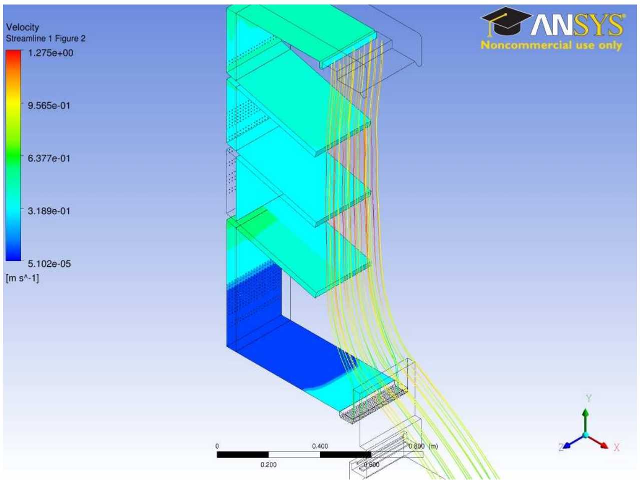

Figure 6. Numerical simulation in isometric view.

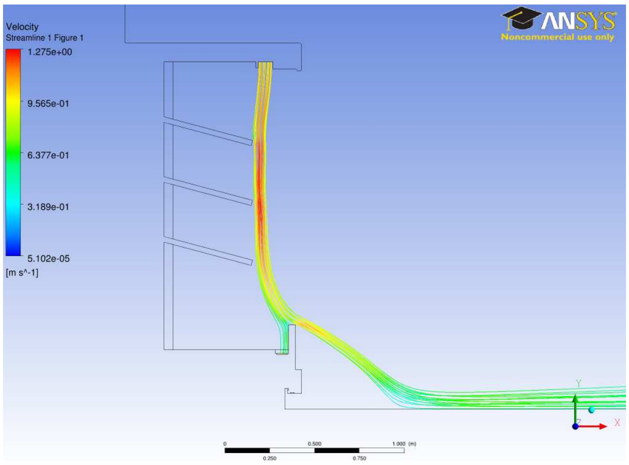

Figure 7- Streamlines of numerical simulation

Figure 6 and 7 shows the 3D streamlines and the temperature contours on the cabinet shelves. Qualitatively, the streamlines look similar in behaviour to the flow visualization. There is a slight increase in velocity after passing of the first shelf. This could be due to the interference the first shelf has on the flow of the air curtain. This interference can be seen in the flow visualization in Figure 5. After passing the shelf, the air curtain recovers some of its original velocity but not to the extent predicted in the simulation. The negative buoyancy effect of the air curtain causing it to moving into the back of the cabinet, as seen in the flow visualization, is not captured in the simulation.

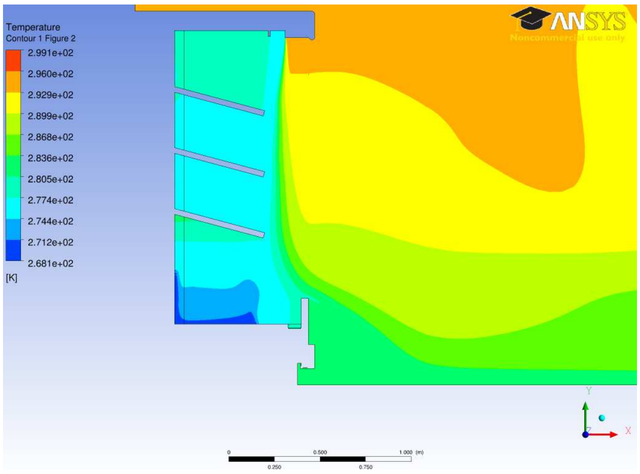

Figure 8. Temperature contours of numerical simulation

The temperature contours in Figure 8 reveal the effect that the air curtain has on the cabinet. You can also see the warm air being let into the cabinet at the bottom. This is what causes entrainment into the cabinet, causing more stress on the compressor to cool the incoming air.

Location	**NDACW**
Middle slanted shelf experiments	1.65
Bottom slanted shelf experiments	2.35
Middle slanted shelf CFD	1.53
Bottom slanted shelf CFD	1.41

Table 1 – NDACW of bottom and middle slanted shelves

Location	**NDACW**
Middle straight shelf experiments	1.76
Bottom straight shelf experiments	2.47
Middle straight shelf CFD	1.53
Bottom straight shelf CFD	2.24

Table 2 – NDACW of bottom and middle straight shelves with walls

As can be seen from table 1, the NDACW also seems to break down at the lower limits of the air curtain. This can be easily attributed to the nature of the air curtain as it heats up and starts to display very turbulent behaviour. The experimental results from table 1 and table 2 are similar when looking at the values of the NDACW. The CFD of each case, however, are different.

The straight shelf simulation and experimentation values in Table 2 seem to agree far more than in the slanted shelf scenario. The agreement can seem to increase with the walls in place and imply that 3D effects are significant.

Conclusion

The experimental data proved invaluable in seeing the issues with a full 3D CFD run of a conventional RDC. This emphasizes the need for experimental data in order to look at the differences between the real world and CFD simulations. Though the experiments do show correlation to real life results, the magnitude in which the simulation overestimates the velocity cannot be ignored. The fact the 3D simulations only showed correlation when the walls were set in place on the physical RDC brings to light the importance of the 3D effects on the air curtain.

There are many considerations that need to be taken when resolving a full three dimensional cabinet. The side boundary conditions of this midsection are unclear and lead to results that were inconsistent with the real data. More investigations should be carried out involving 3D CFD. The 3D models of RDCs thus far are not satisfactory in resolving the complexities that are inherent in RDCs. Using more powerful computers and processing systems would help in making more complex geometries and meshes that simulate RDCs more accurately. The validation of more complex 3D RDC models should be carried out.

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