Air Curtains Integrity When Misusing the Refrigerated Display Cabinets

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Abstract: Tilted air curtains are used as barriers between two environments of different temperature, humidity and quality and are the core elements in Refrigerated display cabinets. Energy consumption and performance became the concern of end users of cabinets as the Entrainment of one environment Fluid (air) into the curtain by shear layer mixing contributes to both the sensible and the latent heat load on the other environment and the impingement of the air curtain formed. Obstructions of any type on the path of the air curtain endanger its integrity. Protrusion present in the direction of the flow impacts the performance of the air curtain and defeats its purpose of existence.

Computational Fluid Dynamics (CFD) software method is used to evaluate the impact of such intentional and non intentional obstructions, on the performance of the air curtain formed by the tilted jet plane and is also validated by comparing the CFD calculations results with experimental results.

Qualitative design combination of various geometrical parameters and various levels of obstruction in the direction of the flow(s) are proposed in order to guarantee the existence of the air curtain.

Keywords: Display Cabinet; Simulation; Velocity; Turbulence, Infiltration Rate, Air Curtain.

1 Introduction

Air curtains can be used as dynamic barriers to control and ensure invisible separation between the two different environmental conditions areas. Quality control and conditions of the environments including temperature, contaminants, pressure and humidity can be maintained independently upon the provision of the specific parameters that will allow the maintenance of the integrity of the air plane jets.

The performance of this dynamic barrier will be under continuous threat of fluctuating due to the easy existence of perturbation that could result from the intrusions of personnel or hands resulting in breaking the integrity of the barrier and requirement of further periods of time to rebuild the jet coupled with consequences of such broken integrity.

The complexity of maintaining the quality and condition of one environment from changes due to influence of another adjacent environment necessitates identification of the combination of several factors. Such maintenance is managed upon the consideration of the dynamic nature, the balance between the jet momentum flux and the pressure difference between the two environments, surface stresses, infiltration, entrainment, turbulence generation, internal interactions, physical obstruction by objects and people and nature of work space.

A typical application of the tilted air curtain is being used in refrigerated display cabinets that exist practically in any commercial outlet, supermarket or mall. With the continuous increase of energy cost, the generation of suitable refrigerated environment became a concern for owners in specific when such environment is not protected well against the infiltration of the second environment which is usually at different temperature and humidity conditions. If infiltration rate accounts for 70% -80% of a typical case cooling load and if the refrigeration accounts for 50% of typical store electric load, then efforts should be undertaken to minimize the infiltration rate aiming at reducing the energy cost.

Having identified the need for the maintaining the tilted air curtain in a display cabinet, the objective of this present work is to develop a model-based design methodology for the establishment of tilted air jet plane, and to point out the impacts of obstructions in the direction of the plane with recommending the benefit of changing the tilt angles from positive to new negative values.

Air jet planes can be vertical, horizontal or tilted and were introduced for the first time in year 1916. Function and tightness studies were performed in the last 40 years and mainly concentrated on the vertical and horizontal types. Under several titles, air jet planes were immensely considered in research work in both domains: experimental and computational. Some were successful in addressing those parameters that have significant impact on the performance of the jet. Identification of those parameters and quantification allowed the determination of certain rates like infiltration and or entrainment expressions and to a certain extent.

Many have contributed in developing a number of mathematical models to aid in the design and performance prediction of the air jets. Explicit method was employed to solve the differential equations describing the flow and to prove that the performance of the air jet can be simulated effectively using the finite difference technique; Hetsroni and Hayes [1].

Finite element method as well as other several patents were taken out on open protection devices with few investigations have been reported; M. Havet et al. [2], who made the study on an air curtain used as a dynamic barrier to separate two environments indicated that the curtain is strongly sensitive to perturbations such as draughts. Studies taking into consideration all major parameters affecting the air curtain flow field by the utilization of modern analytical, computational and experimental techniques, were done by Homayun Navaz et al. [3], and by Brandon S. Field, Eric Loth [4], on the entrainment of ambient air on vertical air curtain upon varying the Reynolds numbers 4200-8000 and the Richardson Number 013-0.58 which again showed that the entrainment of the ambient air was governed by variety of eddy engulfing structures. Also, a numerical simulation was utilized on the two dimensional solution of a vertical down ward-blowing plane jet, J.J Costa et al.[5], and on the flow and heat transfer characteristics of vertical air curtain in a vertical display cabinet with a two –fluid turbulence model; Ke-Zhi Yuet al.[6] .

However, many experimental works were done on the air jet with little on tilted angle in comparison with the horizontal and vertical air barriers. Works indicated that a breaking point for air curtains occurs if the deflection modulus is below the minimum value for the particular air curtain configuration and the initial turbulence intensity has a moderate effect on the rate of heat transfer through the curtain; Howel reports [7], [8]. Another experiment showed that the mass entrainment rate, dominated by eddy engulfment of ambient air, was directly proportional to the air speed of a down ward vertical blowing isothermal wall jet at moderate Reynolds Numbers (1500-8500) with significant inflow turbulence; Brandon S. Field , Eric Loth [9].

Experiments on vertical air curtains were more popular. The implication of changing several parameters like ambient air temperature, indoor relative humidity, ambient air flow, Air supply velocity, air flow from back panel and night covers on the performance of the refrigerated display cabinet was identified; Y. Chen, X. Yuan [10]. Also, H. Navaz et al. [11], carried an investigation on the Jet entrainment in air curtain of open refrigerated display cases where certain parameters like turbulent intensity, shape of the mean velocity profile at the discharge air grille, and the Reynolds Number were identified, quantified and the amount of entrained air was computed and showed that the shape of the vertical velocity profile and the turbulence intensity present at the supply air grille controlled the entrainment rate and at different stages. Plane air jets were experimentally studied as well by Karin Loubier, Michel Pavageau[12], using PIV with an emphasis put on the flow structure in the impingement region of jet systems.

Experimental results were not always in conformity with previous works as it was the case with the findings of I. Gray, P. Luscombe et al. [13] when describing that need of having only 70% of total air delivery in circulation needs through air curtain and the balance through side discharge.

The correlation of the numerical solutions with the experimental works results were limited and in specific when using the Computational Fluid Dynamics (CFD) technique. An apparent conflict was demonstrated upon lowering the Reynolds Number aiming at minimizing the air entrainment in a vertical air curtain with the risk of loosing the integrity of the air curtain structure. CFD predictions on infiltration were shown to vary with time limiting the possibility of utilizing the analytical models; A.M. Foster, et al. [14].

CFD modeling which was used to aid the design of retail display cabinets provided a rapid means to understand air flows, optimum jet velocity and their effect on surrounding temperatures; A. M.. Foster et al [15].

From the above review, it was concluded that attention was not paid to seeing how these air curtains were performing when ending at the location of its use and in which manner are operated and on a daily basis, thus opening areas for attracting further investigation on how to manufacture cabinets with minimum implications on the air curtain when they become in use.

Fig. 1, Fig. 2 and Fig.3 picture the misuse of the method of loading the display cabinets.

Fig.1 Boxes obstructing the return grille of a refrigerated display cabinet.

Fig.2 Produce obstructing the return grille of a refrigerated display cabinet.

Fig.3 Upper shelf of a display cabinet extended causing the loss of the air curtain.

2 Methodology

To overcome the difficulty in getting the unreliable results in data collected from an experimental set up, this research describes the several experimental and numerical tools that are used in analyzing and assessing the performance of the tilted air jet plane of a refrigerated cabinet.

However, the benefit of the use of Computer Fluid Dynamics (CFD) software [16], is clear in terms of both time and money saving, and such experiments can be performed for a final check of the correctness of results.

2.1 Experimental set – up Model

Experimental studies were carried out on a refrigerated display cabinet with internal dimension of

D x W x H = 0.6 m x 1.8 m x 1.9 m. This cabinet was located in the laboratory facilities at the Beirut Arab University Laboratory in a room of 10 m x 10 m x 4 m with its back side to one of the walls.

A modular simple display case composed of supply air grille and return air grille positioned at variable angles and the air in the room is allowed to mix with the supply incoming air from the jet along the length of the Discharge air grille and along its height. The domain is bounded by two surfaces on the width of the Discharge Air grille and the Return Air Grille.

The main aim of experiments was to detect the implication of locating obstructions and extended shelves on the integrity of the curtain illustrated by its infiltration rate. The experimental results not only provide necessary boundary conditions for later calculation, but also supply data that will be later compared with the results of simulation to assess the accuracy and viability of the established CFD model.

2.2 Data obtained

Due to the irregularities of flow, a more or less significant amount of ambient air is always entrained, reducing the temperature control capabilities and increasing the energy consumption. In a display cabinet, air is extracted through a linear grille at the base of the opening and fans then force it through the cooling coil situated underneath the bottom of the load volume. The cooled air is forced to a supply plenum located behind the compartment. A fraction of the air is sometimes fed into the unit through perforated plate at the back of the cabinet, while the remaining quantity of the cold air is blown through the DAG forming the tilted jet plane.

Fig. 4 shows a schematic diagram of the display cabinet is shown describing the infiltration and entrainment portions.

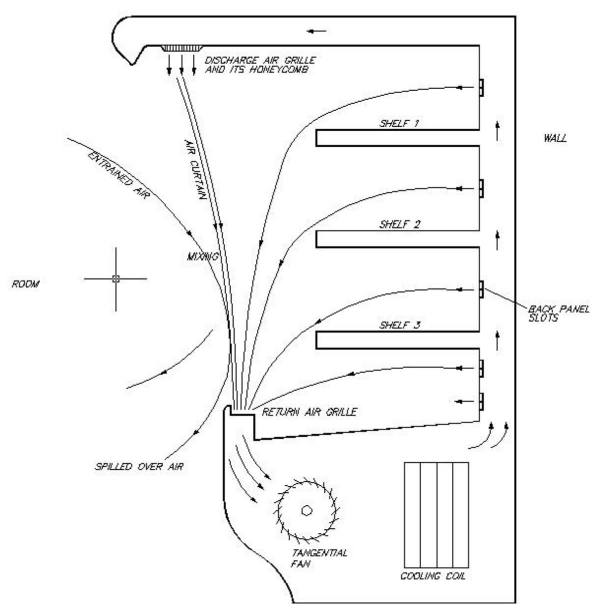

Fig. 4. Schematic refrigerated display cabinet

The various geometrical angle parameters are shown in Fig. 5.

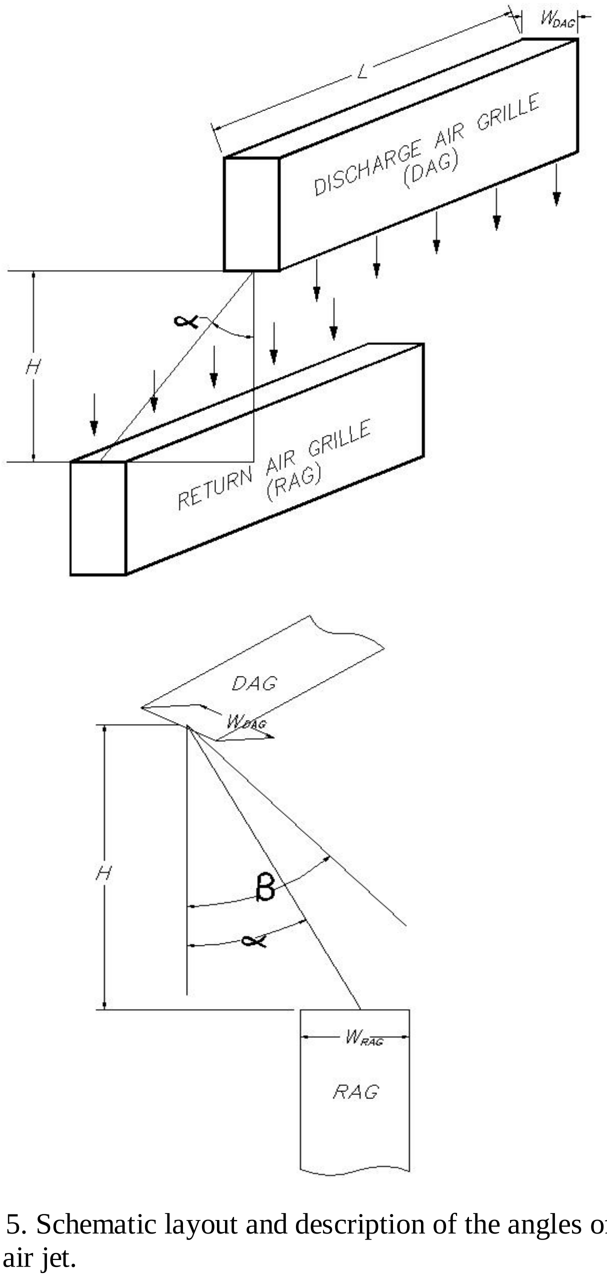

Fig 5. Schematic layout and description of the angles of the air jet.

The data acquisition systems included temperature acquisition system equipped with special grade T Thermocouples, accurate +/- 0.1 º C, a relative humidity reader accurate to +/- 3%, flow meters. The set up of thermocouples in the experiment were varied to allow steady readings. The sampling interval is 2 seconds. The data visualization provided by the software had helped in determining the steady state of the built up curtain. The known directions are prerequisite to effective measurements with the flow meters in the direction of the flow at the inlet.

2.3 Experimental Results

The variations in the geometrical set up are carried by:

1. Model the fluid flow inside the plenum and all back panel ductwork

2. Make sure the velocity profile that is obtained from this model is similar to the experimental data that is taken outside the DAG.

3. Make changes to the DAG geometry and by running the simulation through all the ductworks, obtain the vertical velocity profile at the DAG exit plane.

4. Identify those velocity profiles that resemble a parabola and possess only one peak

5. Identify the velocity profile that is the closest to a skewed parabola shifted towards the inside of the display case.

6. Use the most promising velocity profiles obtained in steps 4 and 5 as a boundary conditions for the flow outside the display case to measure the entrainment rate

7. Vary the turbulence intensity at the DAG for these velocity profiles to ensure the consistency of results at all turbulence

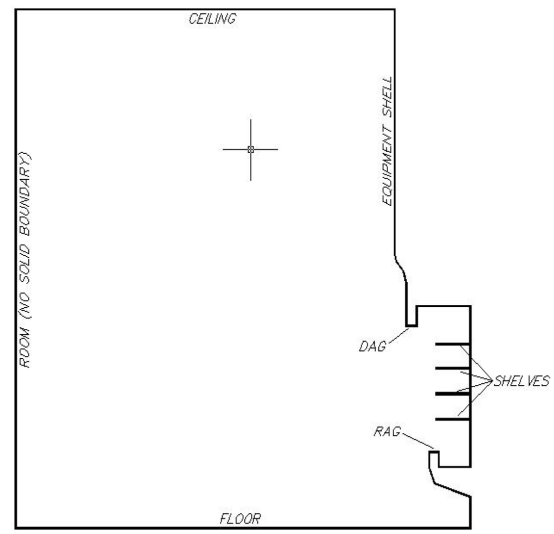

Fig.6 Preparation of Mesh and definition of boundaries.

Results obtained were compared to the particular case study results done by H. Navaz, M. Amin, D. Dabiri, and R. Faramarzi on a specially built air curtain using CO_2 as one environment in University laboratory, [17]. In spite of the difference in the equipment used in the experiments done in their lab, there was deviation not exceeding 7% and while comparing the meshing done by this study with data provided.

3 Numerical Solution

A numerical model is presented to assist in the design of the tilted air jet plane, it allows the calculation of the Infiltration rate which is described as:

$$\frac{[\,DAG]-[RAG]}{[DAG]-[ENVIRON.2]} \qquad (1)$$

where [quantities] are in CO_2 concentrations.

This rate is caused by entrainment, inclination of the jet or the momentum to transverse forces and very much by the stack effect which is created by differences in air densities on the two environment sides and resulting in a linear variation in pressure along the jet.

This is carried by calibrating the two-dimensional CFD code .

The availability of the software has remarkably increased the capability of the computation of the air flow pattern and in particular using the finite element method and the sequential procedure which are employed to discretise and solve the governing differential equations, based on the stream function–vorticity formulation.

Simulation was carried by varying the various parameters including the velocity profiles and keeping the interest in maintaining an unbroken air curtain.

The mixing of the conditioned jet with the still ambient air is dependent on variables such as the length of the mixing region, initial velocity, temperature, and moisture content distributions and initial turbulence intensity. For vertical display cabinet air curtains, the length to width ratio will, in most cases, be large and the effect of initial turbulence intensity quite small. For this reason, the developed model assumes a well-designed curtain with a low turbulence intensity of 1%.

The turbulent mixing process in air curtains can be described using the Navier–Stokes equations of motion for a Newtonian fluid.

Continuity equation

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad (2)$$

Momentum equation

$$U\frac{\partial U}{\partial x} + V\frac{\partial V}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\left(AT\ \frac{\partial U}{\partial y}\right) \qquad (3)$$

Energy equation

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\left(Aq\ \frac{\partial T}{\partial y}\right) \qquad (4)$$

Diffusion equation

$$U\frac{\partial c}{\partial x} + V\frac{\partial c}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\left(\rho D\ \frac{\partial c}{\partial y}\right) \qquad (5)$$

To obtain a final solution for the velocity, the above finite difference equations were solved simultaneously and iteratively until the boundary conditions are satisfied within a specified degree of convergence illustrated by 2 e -5 .

4 Results

Various values of the air velocity were assumed for the air curtains assuming other parameters constant, aiming at identifying the operating conditions yielding the lowest external air entrainment. A particular configuration was selected and tested for validation, revealing the validity of the simulation. In fact, when reproducing the experimental tests with a correct choice of the simplified model, an excellent agreement (about 6%) was found between the simulated and measured infiltration at an air velocity and as reported in. Though this agreement may be viewed as favorable, but there are uncertainty factors in both the numerical and the experimental outcomes.

4.1 Flow Rate Variations

For several values of the flow rate ranging from 0.02 to 0.13 m/s, the velocity profiles were obtained and the infiltration rates were calculated and assuming no obstruction or shelf extension.

As the flow rate is varied, the infiltration rate of the system is calculated as a non – dimensional parameter C = (C_DAG - C_RAG) / (C_DAG - C_Room) where CO_2 concentration is a mass weighted average.

Velocity profiles are shown in Fig. 7 upon varying the flow rates:

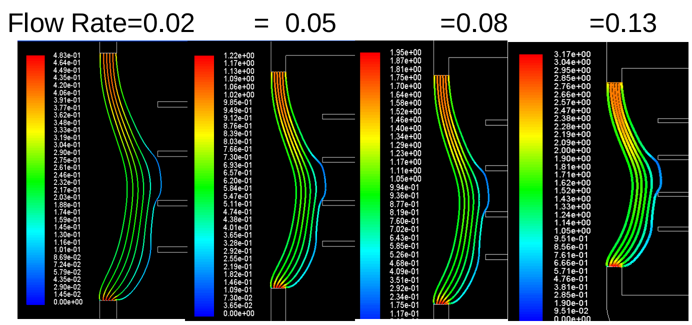

Fig.7 Velocity profiles at different flow rates

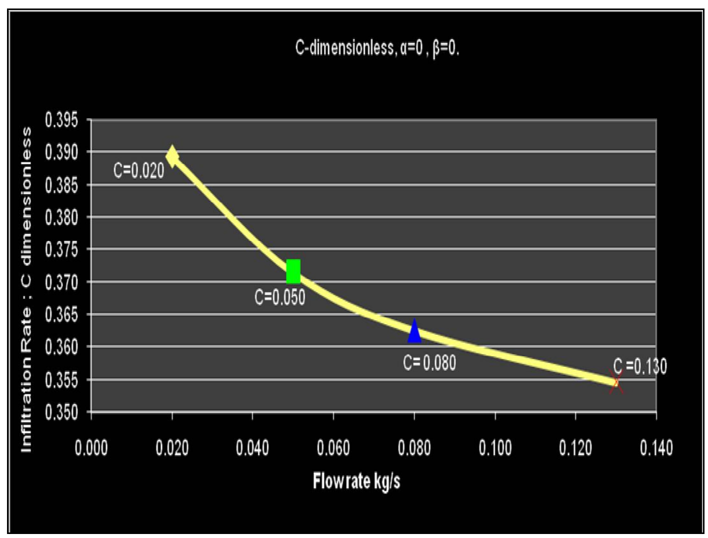

Fig. 8 (C) Dimensionless Infiltration versus Flow Rate

The dimensionless C factor representing the infiltration Rate, shown in Fig. 8 is decreasing upon the increase of the flow rate, indicating the impact of increasing the Reynolds number and width of DAG.

When comparing the results upon having different geometrical values affecting the flow rates, i.e DAG size from a width of 0.04064 m to 0.041708469 m, it resulted in 2.6% error . The infiltration rate decreases with the increase of the velocity if assuming linearity at the rate of 2.6%.

4.1 Discharge (α) positive angle Variations

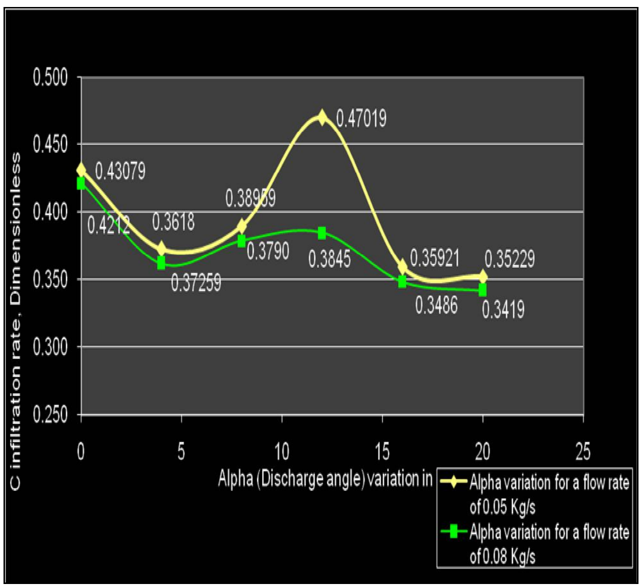

Fig.9 Plot of C Dimensionless Infiltration rate versus positive (α) angle Variations.

The variation of the positive angle (α), in Fig.10 shows that the optimum infiltration rates and for two different flow rates (0.05 & 0.08 Kg/s) are achieved at an angle = 12.5 Deg.

4.2 Obstructions of Protruding shelves

Allowing the upper shelf to protrude to the center of the discharge air grille DAG, had helped in creating independent turbulence flows in each shelf compartment aiding in the formation and maintaining the integrity of the curtain as seen in Fig 10.

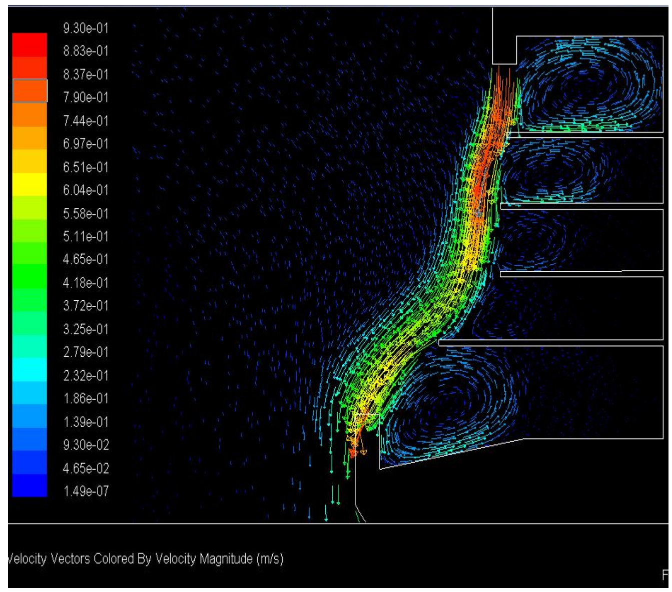

Fig.10 Velocity Vectors profile with extended upper shelf

4.3 Box & Cases obstruction 16 & 20 cm near RAG

When locating boxes or obstructions near the return grille (RAG) and extending nearly 20 cm & 16 cm, infiltration rates proved to be functional of the height of boxes as shown in Fig. 11.

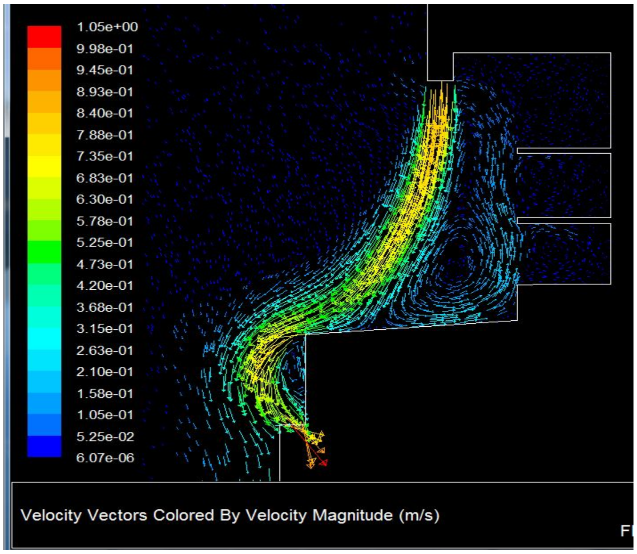

Fig. 11 Velocity vectors profile with 20 cm vertical obstruction near RAG

When locating a vertical obstruction just before the return grille, the formation of air curtain becomes apparent as shown in Fig. 12.

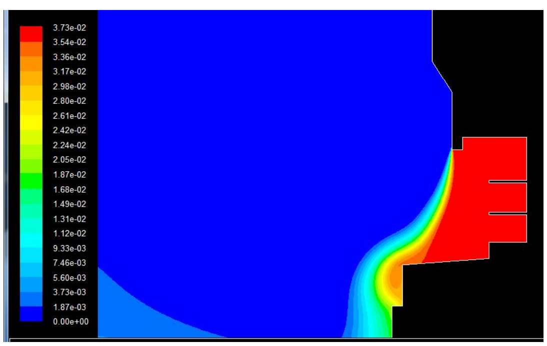

Fig. 12 Curtain development with 20 cm vertical obstruction near RAG with positive (α)

4.3 Discharge (α) negative angle variations

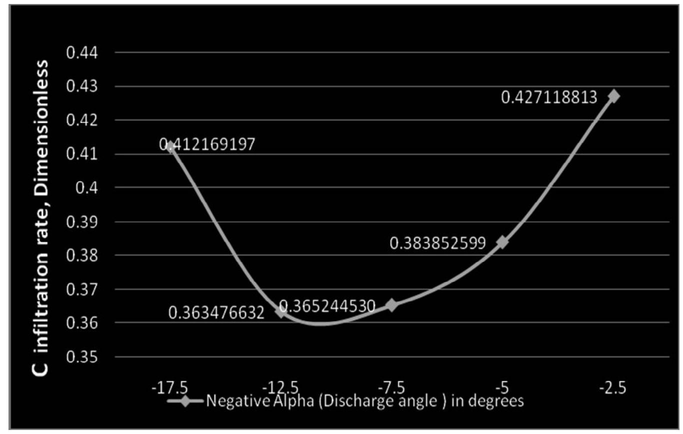

Fig. 13 Plot of C Dimensionless Infiltration rate versus negative (α) angle Variations.

The minimum infiltration rate is found at discharge angle of -11˚ < (α) < -10.5˚ With infiltration rate C of 0.360 and for a flow rate of 0.05 Kg/s.

Fig. 14 and Fig. 15 illustrates the formation of the air curtain for negative discharge angles

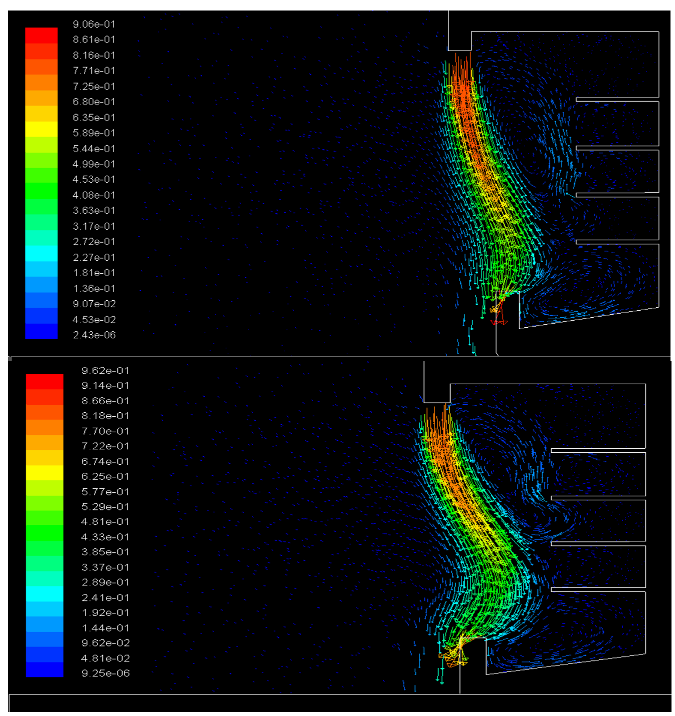

Fig.14 and Fig 15 Velocity contour (α) angle = -10 Velocity contour (α) angle = -2.5

This infiltration rate at negative discharge angle is less than the rate of the optimum positive angle (C= 0.047019).

It is concluded that a negative discharge angle is allowing less infiltration rate.

When locating a vertical physical obstruction near the return air grille and with a negative discharge tilt angle, the infiltration rate is minimized as shown in Fig. 16.

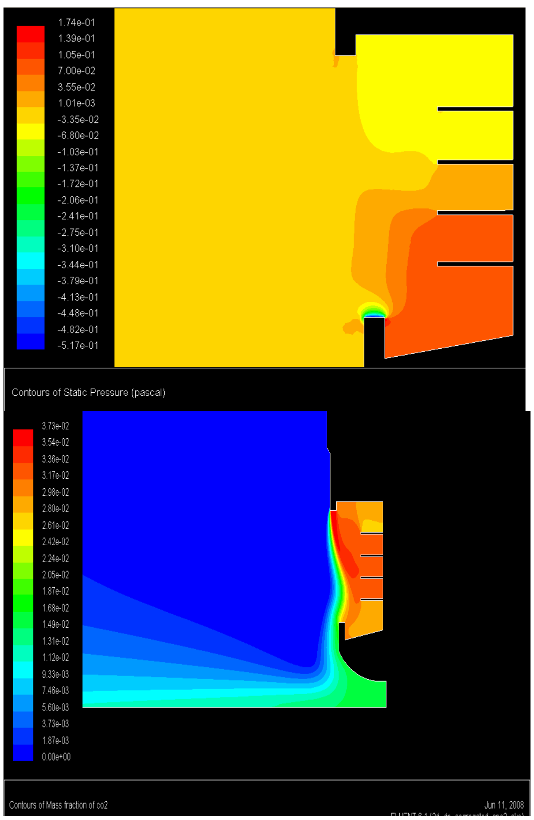

Fig. 16 Curtain development with 16 cm vertical obstruction near RAG with negative (α)

In many applications of the refrigerated display cabinets, where inclined jets are utilized, filling of cases, or on the worst scenario, locating many boxes on the return grille (RAG) may hamper the formation of the air curtain. This is driven by the intent of maximizing utilization of the limited volume of the display cabinet.

5 CONCLUSIONS

The application of the CFD technique based on an experimental set up and as validated is proved to be a successful tool in identifying the geometrical and flow parameters that affect the infiltration rate. It allowed the identification of the impact of protruding shelves or locating obstruction on the optimum performance.

In the absence of any obstruction, the increase of the flow rate will improve on the efficiency of the tilted air curtain.

The lower the discharge angle (α), better results on the infiltration rate are anticipated, and in fact, the optimum discharge angle (α) is in the vicinity of – 10 degrees. This would call for increasing the depth of upper shelves, and in contrary to the available designs of display cabinets, to be more than the lower shelves.

On the other hand, when extending a physical obstruction like a shelf, but not to go beyond the projection of the discharge grille will help in creating internal turbulences allowing a better formation of the air curtain. This could be seen as a substitute for the back panel openings.

Vertical obstruction near the RAG proved to be a problem in maintain the air stream of the inclined curtain, but with negative values of the discharge angle, locating boxes will be aiding the performance of the inclined air curtain.

Finally, external perturbations resulting from pressure changes, whether derived from physical motions or other partial flows normal to the tilted jet plane, and on both sides of the tilted air curtain affects the optimum selection of such parameters. The CFD technique will be capable of identifying the implications of the change in the basket of these parameters. To achieve the objectives of minimizing energy consumption of display cabinets, and in implementing the construction of negative tilted angle, upper shelf shall not extend below the center line of the discharge air grille, lower shelf shall not allow locating boxes extending above the return air grille and coupled with continuous owners orientation over the presence of the air curtain and the need for preserving its integrity.

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