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NUMERICAL SIMULATION OF OPEN REFRIGERATED DISPLAY CABINETS

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ABSTRACT

Open refrigerated display cabinets are becoming more widespread since they are believed to enhance sales by providing easy access to the chilled products. Air curtains are used as a barrier between the warm ambient air and the chilled compartment of the fridge. The effectiveness of the air curtain depends on many parameters. The objective of this work is to study the effect of jet velocity, turbulence intensity and temperature on the performance of a commercial refrigerated display cabinet aiming at minimizing energy usage. A 2-D numerical model suing double precision was solved using the computational software “Fluent” that include the full buoyancy effect and radiation between surfaces. Results include temperature variations, estimation of the entrainment of air into the fridge and heat exchanged with the ambient air in the room. The numerical results indicate that jets with lower velocities at colder temperature enhance the efficiency of the open fridge. A reduction of 19.5 % in the air entrainment and 23% in the heat gain was observed in comparison with the current setting. Temperature measurements and flow visualization using smoke were conducted to validate the numerical simulation.

INTRODUCTION

In spite of the high energy usage of the open refrigerated display cabinets they are becoming more widespread in comparison to the closed display refrigerated cabinet. They are believed to enhance sales as they provide easy access to the chilled products. The high energy cost is caused by the entrainment of ambient warm air to the fridge and the spell of the cooled air to the outside of the fridge. Air curtains are used as a barrier between the warm ambient air and the chilled compartment of the fridge. The effectiveness of the air curtain depends on many parameters such as the width and length of the air jet producing the air curtain, initial jet velocity, turbulence intensity and temperature, position of the air return grill and the condition of the air on either side of the air curtain. The sealing ability of the air curtain depends on the amount of the initial momentum present in the air curtain jet and the size of the transverse forces which the air curtain is attempting to seal against. Air flow inside the fridge plays an important role in producing the force balance needed as well as achieving a uniform temperature for the products inside the fridge.

R. H. Howell, et. al. (1976) studied the factors affecting the development of plane air curtain jets and heat and moisture transfer through it. They found that the initial turbulence intensity has a big effect on the amount of heat and moisture transfer. The total heat transfer is directly proportional to the initial velocity and temperature difference across the air curtain and the latent heat transfer can have a big influence on the total heat transfer. R. H. Howell and M. Shibata (1980) investigated heat transfer through turbulent recirculated plane air curtains and found that there is for each air curtain a certain value of the deflection modulus, which minimises the rate of heat transfer. Pratik and Loth (2003) studied numerically the entrainment by a refrigerated air curtain down a wall at different Reynolds number, different inflow profiles and different Richardson numbers. They found that the entrainment rate was a function of Reynolds number with a minimum occurring at flow speed prior to transition. The entrainment was also sensitive to the initial velocity distribution with constant gradient profile giving the least entrainment. Field and Loth (2003) studied air curtain along a wall with high inlet turbulence (6%). They used particle image Velocimetry to investigate the dependence of the air curtain dynamics, growth and velocity field on the Reynolds number. Many researchers have studied the effects of many parameters on the performance of air curtains in doorways such as the work by W. B. Gosney, H.A.L. Olama, , K. Siren, K. Green, P. Chen et. al., J. Van Male, T. C. Pappas, S. A. Tassou, G. R. Longdill and L. G. Wyborn. Eric B. Lawton and Ronald H. Howell (1995) described the advantage of installing and operating of an air curtain on doorway for retail facilities with the conclusion that the air curtain paid for itself in less than two seasons.

Others looked at the performance of air curtains in a refrigerated display cabinet. Y.T. Ge and S.A. Tassou (2001) used a finite different technique to predict and optimise the performance of the air curtains. Based on their results correlations where found to enable calculations and parametric analysis for the design and refrigeration equipment sizing purpose. G. Cortella and et. al. (2001) used a finite difference technique based on the stream-function-vorticity formulation to investigate the influence of various design parameters on the performance of a vertical multi-deck cabinet.

M. Axell (2002) have studied the effect of load arrangement in the vertical display cabinet and highlighted that the energy loss increases with the increase of humidity.

They also studied the effect of multiple air curtains. H. Navaz and et. al. (2002) have used ROYA computer code as well as DPIV technique to investigate the effect of the air curtain velocity and temperature difference on air entrainment, in a particular refrigerated display case. They concluded that entrainment closely depends on the jet velocity in a linear relationship and very little dependency on temperature.

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The objective of this work is to numerically study the effect of the air-curtain's velocity, turbulence intensity and temperature on the air flow inside a commercial refrigerated display cabinet (model called XLP) (different from that of H. Navaz et. Al.), the amount of air entrained into the fridge and the heat exchanged with the ambient air in the room. The main goal is to find an optimum combination of these parameters to minimize energy usage.

Description of the XLP- Model

The commercial refrigerated display cabinet under investigation in this study is called the XLP. The XLP is designed in such a way to conserve energy and have high efficiency. Air is forced through the evaporator coil and then split into two parts. One part (at low temperature) goes through a duct at the back panel of the cabinet, which is perforated and allows air to diffuse through the product. The other part (at slightly less cold temperature) goes through another duct to feed the air curtain. The fridge has four shelves; the return grill at underneath the bottom shelf. Figure (1) shows the fridge and the included part of the room that was chosen to be modeled.

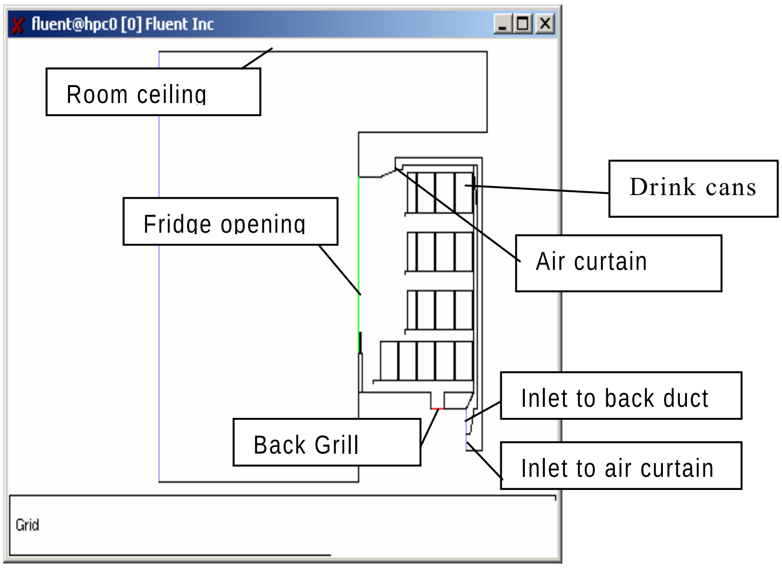


Figure (1), Modelled geometry

MATHEMATICAL MODEL

In order to predict air velocity and temperature in the open refrigerated display cabinets, the momentum, continuity and energy equations have to be solved simultaneously. These equations for steady, two-dimensional and turbulent flow; including the effect of buoyancy are given below in equations 1-4:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$\frac{\partial(\rho vu)}{\partial x} + v\frac{\partial(\rho vv)}{\partial y} = \rho g\beta(T - T_\infty) - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

$$\frac{\partial(\rho uT)}{\partial x} + \frac{\partial(\rho vT)}{\partial y} = \frac{k}{c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

In these equations, u, v, p, and T are the average velocities in the x and y directions, the average pressure and temperature, respectively, whileρ, μ, β, k, c and g are density, viscosity, coefficient of thermal expansion, thermal conductivity, specific heat and acceleration of gravity, respectively. The above governing equations are non-linear partial differential equations for which a closed form solution is not possible. The computational fluid dynamics software Fluent was used to solve the above equations and determine the air temperatures and velocities for a variety of design scenarios in order to get the optimum combination of these parameters to enhance the fridge efficiency. Fluent software uses a control volume based finite difference technique. The governing equations are discretized on a curvilinear grid to enable computations in a complex domain. Interpolation is accomplished via a first-order Power-Law scheme or optionally via a higher order upwind scheme. First order interpolation was used in this work. The equations are solved using a semi-implicit algorithm with an iterative line-by-line matrix solver.

The realisable k-Epsilon turbulence model (Fluent Incorporated, 1997) is chosen, since it effectively handles flows with complex secondary flow features. As stated in the fluent manual "The term ``realizable" means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows". Effect of variation of the air properties due to temperature was included in the analysis to allow for buoyancy effects. The incompressible ideal gas was chosen for the variation of density, kinetic theory was chosen for the other thermal properties. Radiation was also considered in the analysis; the Surface to Surface model was used (i.e. ignoring the effect of the medium between the surfaces). This process started by estimating view factor between the surfaces involved. Then throughout the solution every 10 iterations radiosity of the surfaces were updated through another iterative process to include the heat transfer due to radiation and find the surface's temperatures.

To solve any flow problem using Fluent, one needs to divide the domain into control volumes, which constitute the grid. The domain in this problem was chosen to include the fridge and a large section of the room up to 1.5 m far from the fridge and was extended up to the roof, fig(1). The size of the control volume depends on the expected behaviour of the flow. Small control volumes were chosen wherever great variations of the variables are expected so that velocity and temperature of the flow in these regions could be accurately predicted. Larger control volumes were chosen outside these regions to reduce the memory needed. The perforated back panel between the back duct and the cabinet is assumed to be a porus jump with a constant loss coefficient. The fridge was modelled being loaded with cans of drink that was assumed to be solid blocks with thin aluminium walls and has inside a solid with the water properties.

As mentioned before, there are two inlets from where cooled air enters the fridge; one inlet feeds the air curtain and the other feeds the back duct. At both inlets velocity, temperature and level of turbulence were specified. The outlet to the return grill was assumed to be a pressure outlet (the value of the pressure was obtained by a successive solution of the problem until all mass flow of air was circulated back within accuracy of the order 10^{-5}). This value varied for each case. Type of material and thickness of the fridge parts were incorporated. An insulated wall and ceiling for the room was assumed, i.e. no heat flux, floor was taken to be at T = 20 °C, a convection boundary condition was assumed at the back of the fridge (h_c=10 W/m^{2}K, T_∞=30 °C). At the open end of the room a pressure inlet was assumed with atmospheric pressure and T = 24 °C. A lamp was incorporated in the model and produced heat flux.

RESULTS AND DISCUSSIONS

A steady, two-dimensional model of the fridge loaded with cans of drink was investigated to study the effect of the air curtain velocity, temperature and level of turbulence intensity at inlet on the air entrained to the fridge and the heat gain from the ambient room air through the fridge opening. The main set up of the fridge has air velocity at the inlet to the air curtain as 0.416 m/s, at a temperature of -0.559 °C and the back duct has air at a velocity of 0.393 m/s at a temperature -1.454 °C. Two other velocities were examined; they are 0.216, 0.616 and two temperatures; -1.0 °C and -1.454°C. All cases were modelled for two values of turbulence intensity; 2% and 10%. A double precision were used in all cases. The first step was to solve for the current setup and validate the numerical results with some measured temperatures at some points inside the fridge. Then vary the parameters as given above and compare the results for the different cases to conclude the optimum combination of the parameters.

Validation of the Results

Temperatures at different positions on the four shelves were measured for the current set up and a comparison with the temperatures obtained from the numerical solution is given in figures (2&3).

The temperature were measured using T-type thermocouple at intervals of 10 seconds via a data acquisition system (Yokogawa, model DC100) with accuracy of +/- 0.5 °C. Data acquisition software MSR32 by Kohlenberg was used. Results show that a similar trend exists however, the variation of the temperature measured is at a much less slope than the numerical predictions. The reason for that seems to be the presence of the cans of drink that blocked the interaction to some degree between the cold air coming through the perforated back wall and the warm air entrained from the room. It needs to be mentioned also that the porous media which the air go through to the fridge cabinet

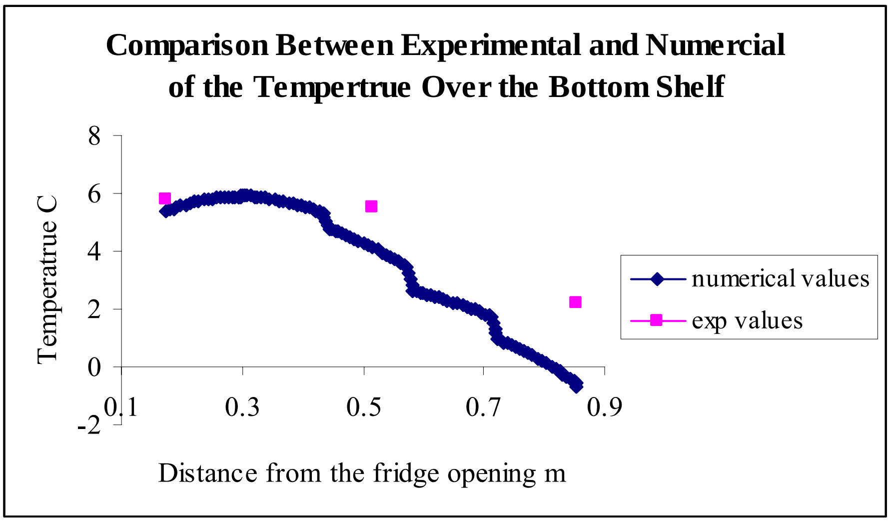


Figure (2) Comparison between experimental and numerical o temperatures on the bottom shelf

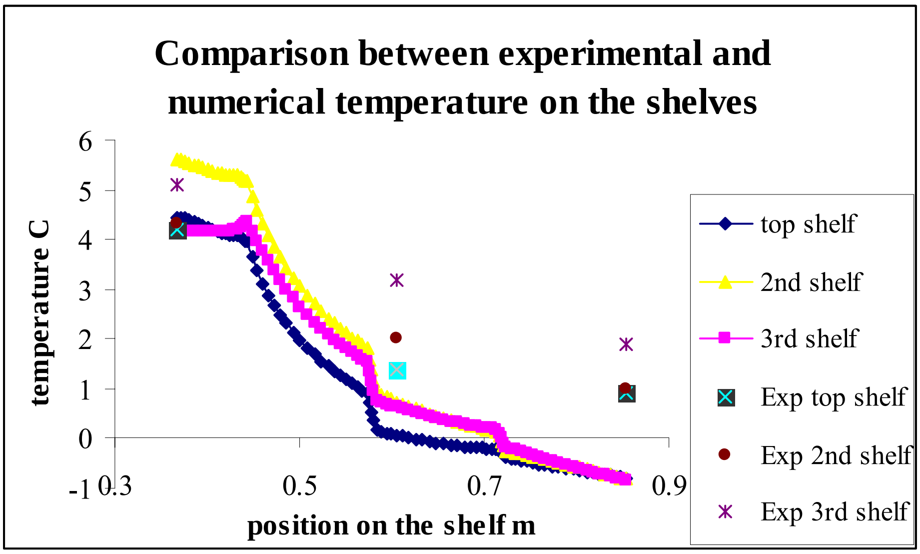


Figure (3) Comparison between experimental and numerical o temperatures on the shelves was assumed to have constant resistance to the flow which is not an accurate representation of reality.

Temperature and Flow prediction

For the original setup, the temperature distribution and streamlines for the airflow inside the cabinet, and in the part of the room that was included in the model, are given in figures (4&5). The results confirm the spell of the cool air at the feet level close to the fridge and the entrainment of the warm air into the fridge at the top where the air jet issues from the air curtain. Smoke flow visualization was conducted and it confirmed the flow behavior obtained from the numerical model; including the re-circulation zone in the middle part of the lower edge of the fridge. However the flow visualisation showed more complicated flow behaviour at the ends due to 3-D effects that was not included in the numerical model.

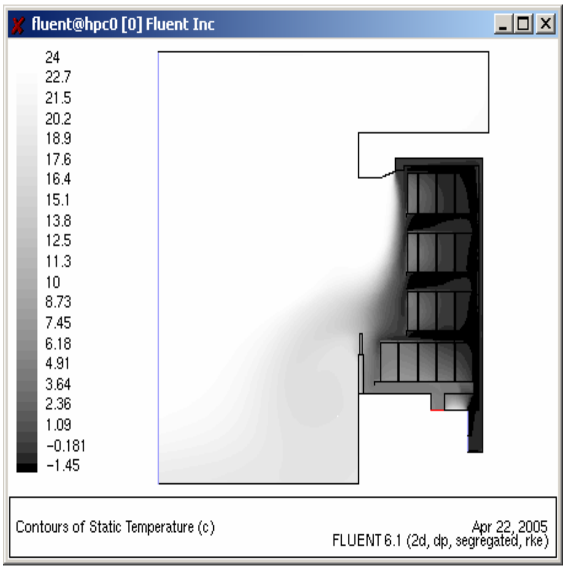


Figure (4) Temperature distribution

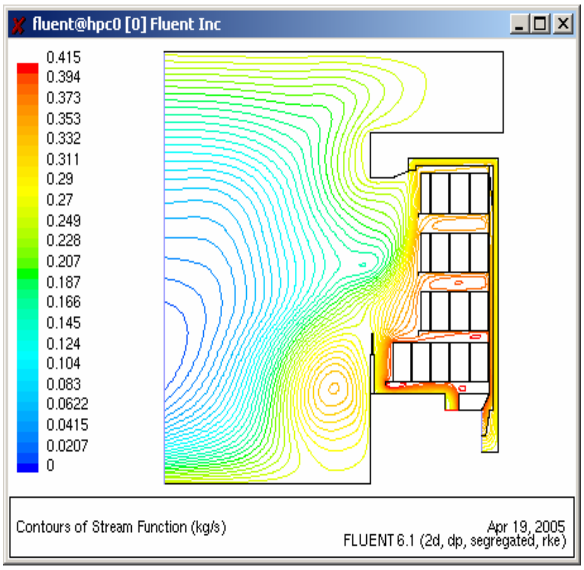


Figure (5) Flow streamlines

Air Entrainment and Heat Gain to the Fridge

Values of the velocities and temperatures at the fridge opening were read from the Fluent software for all the cases analysed. The Excel software was used to manipulate these data to estimate the entrainment and heat gain. The entrainment, defined as the volume flow rate entering the fridge opening, was obtained by the summation of the x- velocity component in each cell multiplied by the area perpendicular to it at the fridge opening. The heat gain to the fridge from the ambient air was estimated by applying the energy equation on the fridge; ignoring any heat gain through the fridge walls. The value of the energy of the air entering the fridge was estimated by summing up the cell's average velocity in the x direction times the cell's average temperature times the area perpendicular to the x-velocity times the specific heat of air and its density over the fridge opening. Table (1) summarises these results.

Figures (6, 7, 8 & 9) show the effect of air curtain's velocity, and temperature on the heat gain and the air entrainment. These results show that as velocity increases heat gain and air entrainment increases regardless of temperature or level of turbulence, which supports H. Navaz and et. al. (2002), findings. The effect of temperature and turbulence intensity is variable and does not show consistency. In many cases it was noticed that the effect of temperature on air entrainment is reversed at higher velocities from that at lower velocities. It has to be noticed that the level of turbulence is specified at the inlet of the passage that leads to the air curtain, and hence the level of turbulence at the exit of the air curtain changes and does not stay uniform as assumed at entry. Comparing all the cases studied the optimum case was for the velocity of 0.216 m/s, temperature -1.0 °C and turbulence level of 10%. This case gave the lowest heat gain of 243.655 W, which is 23% reduction compared to the current setting and the lowest entrainment of 0.001375 m^3/s, which is lower by 19.5 % of the current setting. These results if 3-D were modelled would have been lower due to the complex flow behaviour at both sides of the fridge, as was confirmed by the flow visualization. Unfortunately flow visualization did not produce figure of quality suitable for this publication.

Table (1) Estimated heat gain and the air entrainment at the different cases

Temperature °C	Velocity m/s	10% turbulence		2% turbulence	
		Heat Gain W	Entrainment m^3/s	Heat Gain W	Entrainment m^3/s
– 0.559	0.216	252.845	0.001402	255.028	0.001484
	0.416	316.344	0.001709	318.831	0.001787
	0.616	470.647	0.00221	460.734	0.002154
–1.0	0.216	243.655	0.001375	261.075	0.001423
	0.416	304.835	0.001735	316.993	0.001786
	0.616	483.23	0.002322	448.253	0.002245
–1.454	0.216	288.672	0.001477	247.872	0.001496
	0.416	308.545	0.001753	315.727	0.00177
	0.616	470.488	0.002161	503.921	0.002255

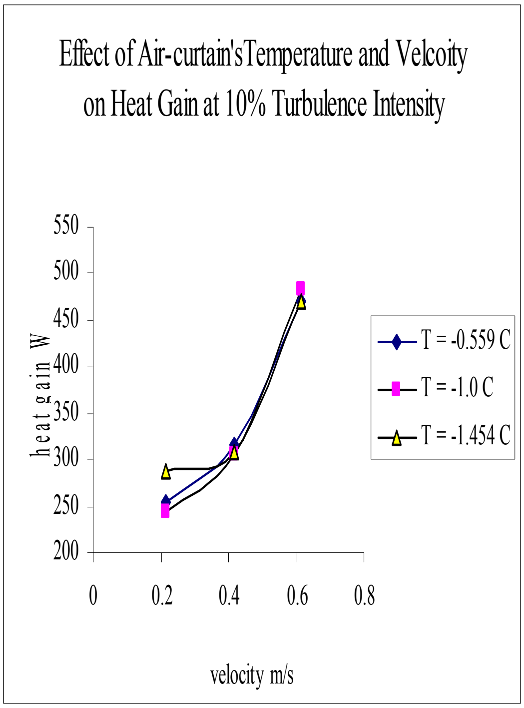


Figure (6) Effect of air-curtain’s temperature and velocity on heat gain at 10% turbulence

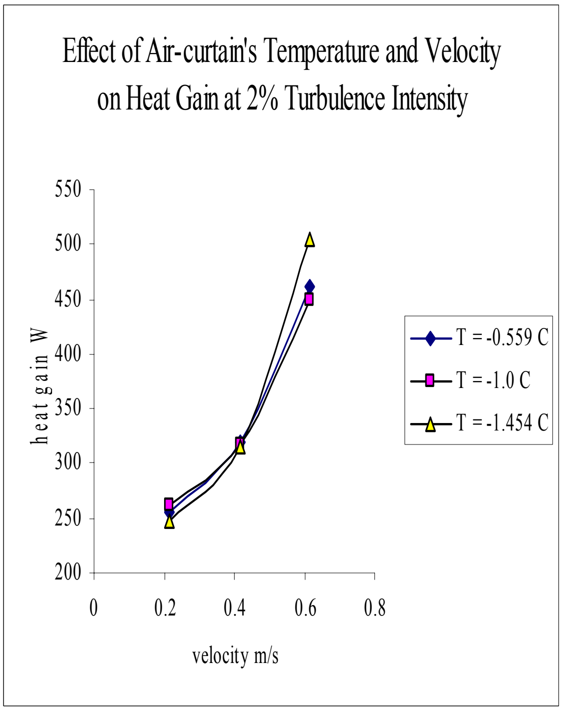
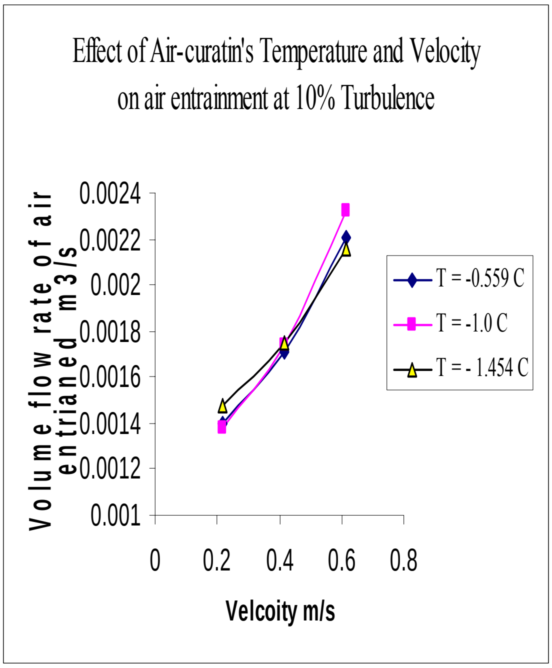


Figure (7) Effect of air-curtain’s temperature and velocity on heat gain at 2% turbulence



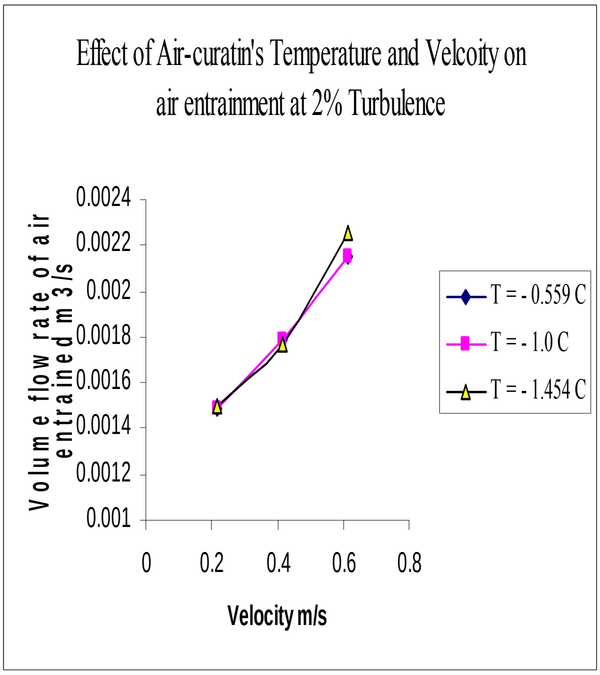


Figure (8) Effect of air-curtain’s temperature& velocity on air entrainment at 10% turbulence

Figure (9) Effect of air-curtain’s temperature& velocity on air entrainment at 2% turbulence

CONCLUSION

Air curtain velocity has an obvious and consistent effect on the air entrainment and the heat gain into the open display fridge. However, temperature and turbulence effect vary.
Numerical modelling is a powerful tool to investigate effect of different parameters in the design in order to decide on the optimum combination of these parameters studied.

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