Parametric Investigation of the Air Curtain for Open Refrigerated Display Cabinets

V. K. Titariya, A. C. Tiwari

Abstract*: Air curtains are widely used in open refrigerated display cabinets (ORDC) as well as doorways of Conditioned Space and retail premises. The main purpose of the air curtain is to control the heat and moisture transfer between the conditioned space and the surrounding ambient also to reduce the air exchange between the two environments. This article presents comprehensive results which can be used to optimise and predict the performance of air curtains in cabinets. The parameter investigation in this article has investigated how the density, velocity and temperature of the air inside and outside the curtain vary as a function of height for various ambient climatic conditions. These results are obtained from the models, developed to enable quick calculations and parametric analyses for the designing and sizing purposes of refrigeration equipments.

Index Terms: Air curtain; extract grille; open refrigerated display cabinet; transition zone.

I. INTRODUCTION

Air curtains have been used in conditioned stores and other refrigeration applications for many years. More recently their application has also increased into retail premises and other shops where ease of access is believed for higher sales. That's why open refrigerated display cabinets (ORDC) are still the most common merchandising fixtures in supermarkets.

In ORDC, air is forced through an evaporator coil which is generally situated on the base of the cabinet by fans normally these fans are located on the front side of the coil. The cooled air after that passes through the back-panel of the cabinet which is perforated and allows the air to diffuse it through the product and the remaining air then passes into the canopy of the ORDC from which it is discharged in a downward direction over the front surface of the product in the form of an air curtain. This air, together with the entrained ambient air, is drawn back into the ORDC through air grille located at the front of the base before it is forced by the fans through the evaporator coil.

The advantage of the air curtain on ORDC is that it provides an artificial barrier between the warm side of supermarket environment and cold side display area, while still allowing the warm human hands to penetrate to pick up food displayed on the shelf. The main disadvantage of the air curtain is that it increases the energy load on the cabinet, not only in the form of the sensible cooling but also by the defrost load due to freezing and condensation of the water vapour present in the humid store air.

This moisture and heat exchange between the chilled air of ORDC and the air of surrounding can be reduced by using of multiple air curtains, particularly in case of frozen food cabinets where products temperature will maintained at or below -18^{o}C. In multiple air curtains, the innermost air curtain is normally the coldest, with the second one being slightly hotter. If a third outer air curtain is employed, it is generally at ambient temperature, and used for reinforcement of the jet inertia and reduce the `cold feet effect' in the store aisles. The most common practice in the high cooling temperature cabinet is to use of single jet air curtains is to reduce the complexity and cost even it has been shown that double jet air curtains can provide energy savings over single jet air curtains[1].

The performance of the air curtains depends on a number of parameters like [2]:

1. The length and width of the air jet
2. The initial jet velocity
3. The jet initial turbulence
4. The dimensions and position of the air return grille
5. Condition of the air on either side of air curtain

All the above parameters are functions of the application and design of the air curtain.

II. REVIEW OF PREVIOUS WORK

In the last thirty years a number of models have been developed to aid the performance and design prediction of air curtains.

According to Schlichting [3], the vertical position where the air flow changes to a fully developed flow with falling air velocity depends only on the width of the supply opening for low turbulence intensities (Ti < 1 %).

Hayes [4] shows that the horizontal force due to the temperature difference between the cold atmosphere inside the display cabinets and the warm ambient air dominates, while the horizontal force resulting from the rise in pressure caused by air recirculating into the cold side can be neglected. The resulting horizontal force is therefore created by the temperature difference, which acts by causing a difference in density between the delivery position and the neutral zone, which is the vertical position at which the pressure difference is zero.

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Van [5] developed a model to investigate the moisture transfer through an air curtain and influence of the initial turbulence velocity on heat. Modeling and experimental results showed that although initial turbulence velocity would have little effect on the heat and moisture transfer through air curtains, air curtain length to width ratios above twenty, its effect on short air curtains, length to width ratios of less than ten would be considerable and could not be neglected.

The model developed by Van [5] was used by Howell [6] to investigate moisture and heat transfers across air curtains employed on ORDC. Tests carried out on two different size of air curtain at different room and cabinet conditions showed differences between measured and computed heat transfers of between 0.7% and 26.5% [6].

Nearly 50 years ago,[Jennings, 1965 #723], suggested a solution for high temperature range cabinets in the form of two parallel air curtains intended for the protection of frozen foods. However, a single air curtain can still be more effective than an air curtain consisting of several parallel streams.

Adams [7] reports that, for optimum performance, an air curtain should be designed so that mixing is minimum on the warm outside and maximum on the cold inside. To achieve this supply opening is to be designed so that the air velocity is lower on the outside.

Cortella, Manzan et al. [8] have performed CFD calculations on a open refrigerated display cabinet having a single air curtain. They report that a velocity of 0.6 m/s was optimum for the particular ORDC concerned, and that a common velocity range for air curtains in ORDC is between 0.5 and 0.8 m/s. Morillon [9] reports that the trend is towards lower velocities of air curtain.

III. SIMULATION AND EXPERIMENTS ON AIR CURTAINS

The purpose of this experiment is to describe the parameters that affect the stability of an air curtain. The air curtain is the single component that has by far the most effect on the energy efficiency of a cabinet. In order to develop efficient air curtains, there is a need of methods for characterising the stability of the air curtains.

A. Methods for Experimental Studies of Air Curtains

The performance of the air curtain in a display cabinet has been investigated by a combination of experimental work and CFD calculations, with the aim of developing a methodology for investigating air curtains under non-isothermal conditions. Experience from the investigations of air flow over the shelves in the interior of the cabinet, it is difficult to measure low air velocities with acceptable accuracy when using hot-wire anemometers. The review of the literature also showed that several of the authors had used temperature measurements to calibrate their CFD models, and so the following two methods have been used in order to validate the calculated response.

- Temperature measurement using thermocouples mounted on a rake.
- Temperature measurement of a sheet of paper in the air curtain, as measured by an IR camera.

IV. THE EFFECT OF BACKPLATE AIR SUPPLY ON A VERTICAL AIR CURTAIN

Air curtains tend to deflect inwards towards the cold interior of the cabinet as a result of the density difference across them. In a display cabinet to which air is also supplied through the back plate, the momentum of air supplied through the back needs to be considered. This air counteracts the tendency of the air curtain to bend inwards towards the cold air in the cabinet. The air coming through the backplate, and opposing this motion, should therefore be included in a local force balance down towards the air extraction position. The air flow and vertical velocity distribution of the air coming through the backplate are affected by variations in the amount of items on the shelves and by the design of the backplate. The air coming through the backplate is intended primarily to cool the items on the shelves, although it also has a stabilising effect on the air curtain.

If the velocity of the air coming through the backplate is changed, there will be a corresponding change in the vertical position air curtain where the flow of the air curtain departs from the initial centre line. At the bottom of the cabinet, the air curtain tends to deflect outwards from the cabinet. It can be seen that air should not be supplied through the backplate at the bottom of the cabinet, as the resulting horizontal flow from the backplate tends to influence the air curtain deflection more outwards from the cabinet.

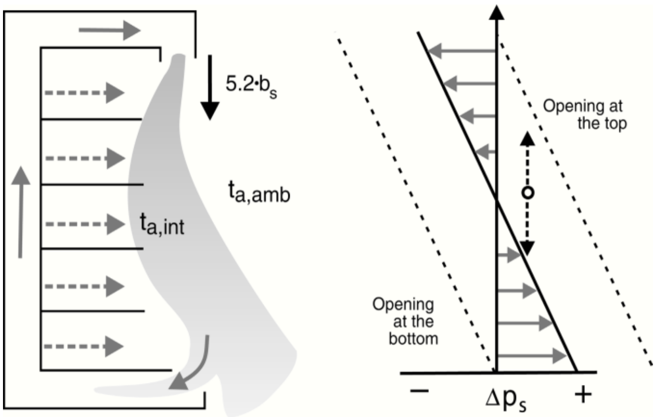

Figure 1: Schematic diagram of the air curtain in a display cabinet and of the forces acting on it.

The vertical momentum of the air curtain falls in proportion to the horizontal forces acting on it, thus increasing the tendency of the air curtain to depart from its initial centre line.

A. Conditions

The force acting on the air curtain is that, which is caused by the difference in density of the two spaces, the cold air in the cabinet and the ambient air, therefore it is important to design the model so that the pressure difference can be investigated which is indirectly caused by the temperature difference. The model used here does not include any cooling air flow through the backplate. The distance of the air curtain to delivery line from the front of the shelf is 200 mm in the model.

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The purpose of moving the air curtain further away from the shelves is to investigate the ability of the air curtain to maintain its centre line right from the supply position to the extract grille.

The following assumptions have been taken for the model:

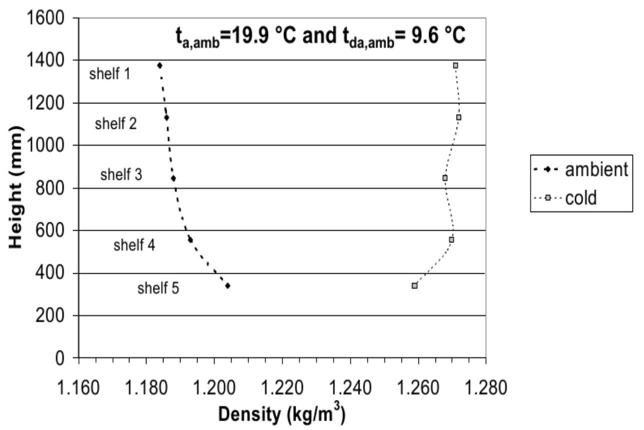
- All the surfaces of cabinet are at a constant temperature.
- Other surfaces in the cabinet are to be at 0 °C.
- The air is dry.
- The delivery temperature of the air curtain is 0 °C.
- The velocity profile of the air curtain supply is chosen as even.
- The turbulence intensity is 0.1 % at the supply position.
- The turbulence model is of the k-ε type.
- The ambient temperature is 25 °C.
- The width of the air curtain supply opening and extract opening is b_s.
- The inlet and return of the air curtain are centered above each other.
- The delivery angle, α_s, is assumed to be 0°.

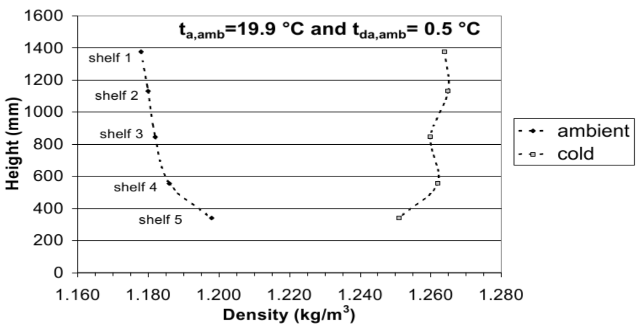
The velocity profile in the model was chosen as even so that the velocity was the same throughout the cross-section of the air curtain at the delivery position.

According to Schlichting [10], the length of the transition zone is a function of only the width of the air curtain, and so its stability will be maintained with a height/width ratio, $H/b_s \leq 5.2$, for low turbulence intensities of < 0.1 %. This would mean that a height/width ratio of less than 5.2 would mean that the air curtain velocity would be maintained from the delivery position down to the extract grill of the cabinet.

V. RESULTS

The following graphs describe the results from the parameter investigation.





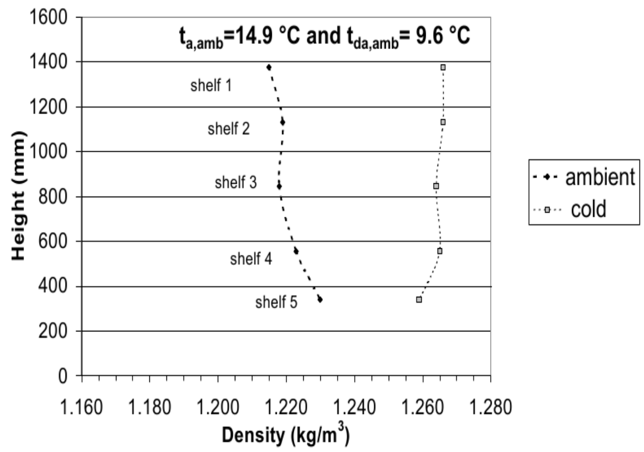


Figure 2: Air density as a function of height on the cold and warm sides of the air curtain.

Figure 2 shows corresponding density differences between the two sides, as a function of height. The figure shows that the density difference is decreasing with falling dry bulb temperature and is relatively independent of variation in ambient vapour ratio.

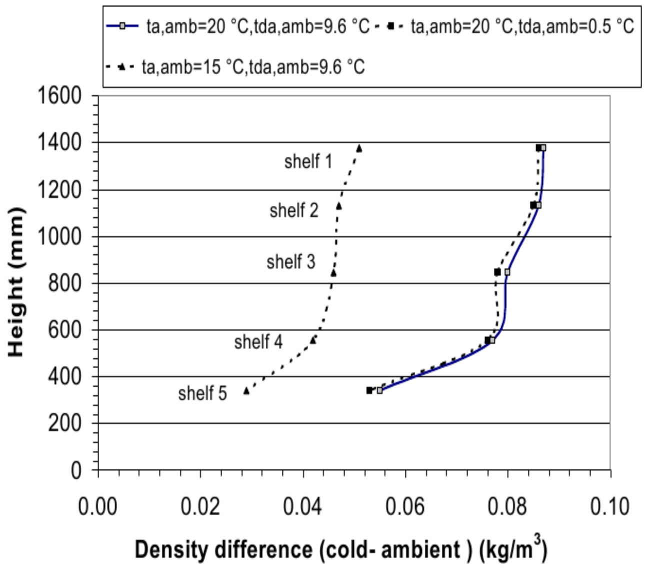


Figure 3: The density difference of the air between the cold and warm sides of the air curtain ($\rho_{a,int.} - \rho_{a,amb}$) as a function of height.

It can therefore be seen that it is most relevant to investigate the deflection modulus at the maximum design ambient temperature. Increased moisture transport through the air curtain results in greater latent heat input and possibly also an increased build-up of frost on the air coil.

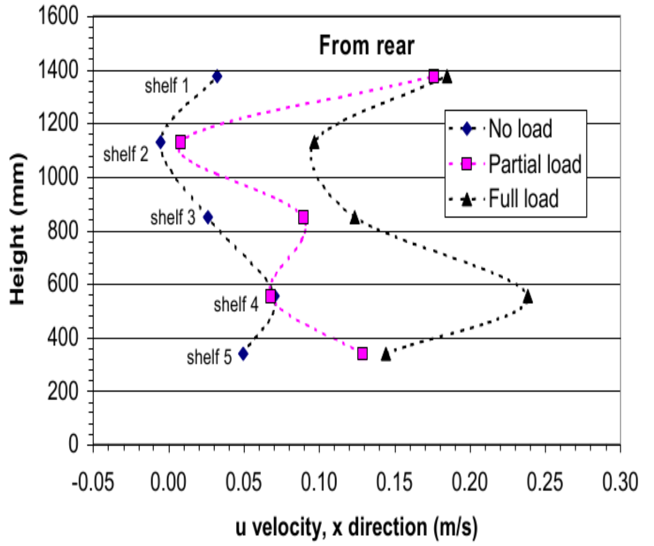
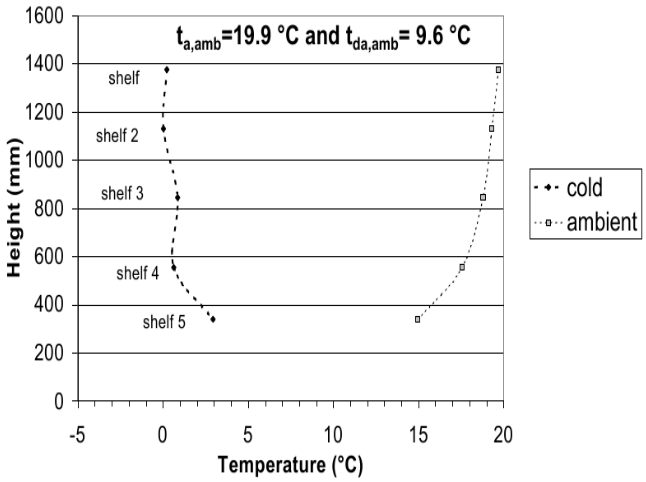
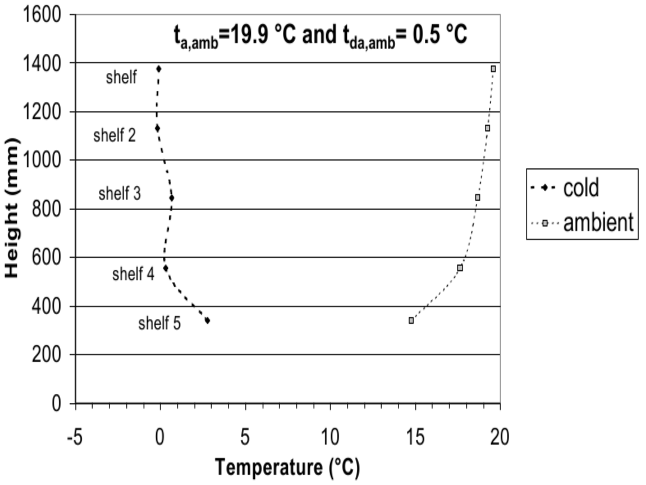


Figure 4: Air velocity as a function of height.

Figure shows that the mean velocity in the x-direction varies from one shelf to another, with the highest velocities occurring over those shelves carrying a full load of goods. Comparing the vertical air velocity in the air curtain with the horizontal velocity over the shelves shows that the two are of the same order at shelf level no. 4, which means that the resulting velocity component in the air curtain is diagonally outwards from the cabinet. At the bottom shelf level (no. 5) the horizontal velocity through the backplate is higher than the vertical velocity in the air curtain, which means that the direction of air flow in the curtain is relatively more horizontally outwards from the cabinet.





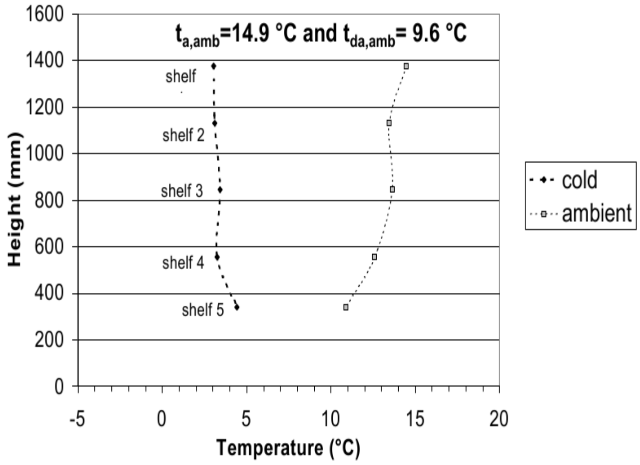


Figure 5: Air temperature as a function of height on the cold and warm sides of the air curtain.

Figure 5 shows that the temperature declines in the vertical downward direction outside the display cabinet, and that the temperature in the cabinet raises at the lowermost shelf. The results show that the dry bulb temperature of the air in the cabinet varies from 0.2 °C in shelf no.1 to 3.0 °C in shelf no. 5 at the bottom of the cabinet when the ambient dry bulb temperature is 19.9 °C and the dewpoint temperature is 0.5 °C. This means that the cooling power requirement is greatest on the lowermost shelves.

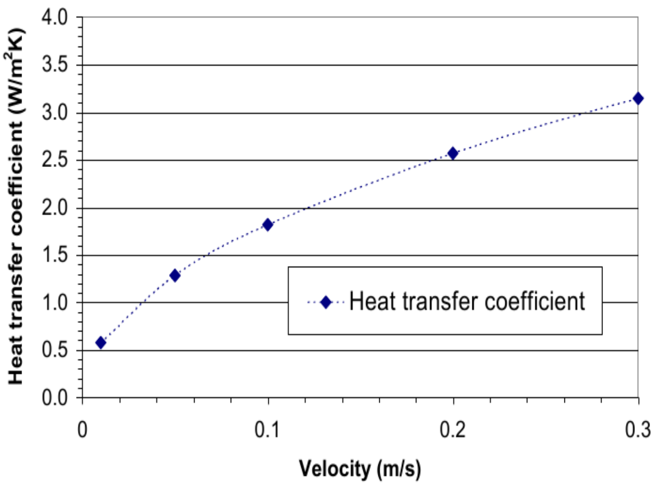


Figure 6: Convective coefficient of heat transfer as a function of air velocity through the backplate. (Assuming force laminar flow along a plane surface)

Convective heat transfer from the foods is related to the air velocity, and can vary by a factor of 1.5-2 on the lower shelves, where the cooling requirement is greatest, depending on how the cabinet has been loaded. From the point of view of stability of the air curtain, the horizontal velocity component (u) should be small so that the air flow in the air curtain is not deflected out over the front of the cabinet. Heat transport from the vertical surfaces of the items at the front of the shelves can occur only by convective heat exchange with the air curtain.

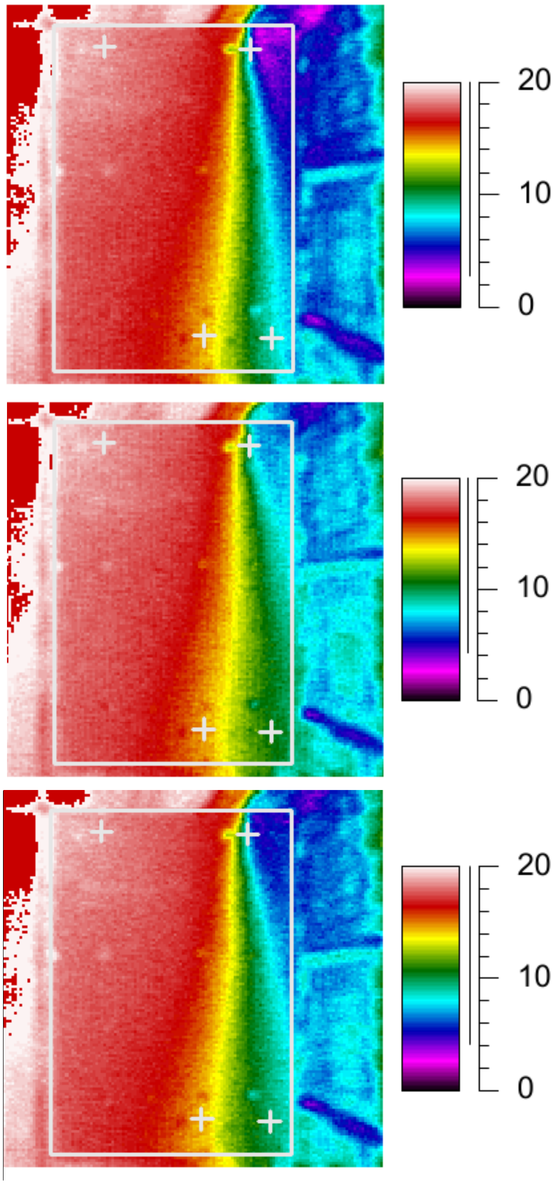


Figure 7: A series of measurements made using the IR camera, revealing the motion of the air curtain as its supply temperature varies.

The picture sequence in the figure shows the changes in the air curtain when its supply temperature varies. It can be seen from the second photograph that the air curtain deflects towards the inside of the cabinet when the supply temperature is higher, but that it then straightens up when the supply temperature is reduced, as shown in the third photograph.

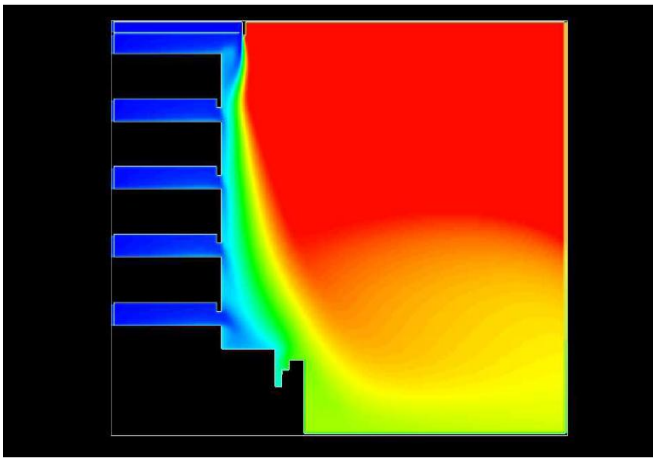


Figure 8: Temperature distribution in the entire display cabinet and the ambient in front of the cabinet.

The picture, showing how the horizontal velocity component from the back of the cabinet dominates shelf levels 4 and 5. Note that the cold air which, ideally, should be flowing vertically down the vertical surfaces of the packages at the front of the shelves, is increasingly deflected outwards away from the shelves as it approaches the bottom of the cabinet. By shelf no. 5, the direction of air flow is about 45° outwards from the shelf.

VI. CONCLUSION

The above results and reasoning show that the air flow from the back of the cabinet is affected by the load on the shelves. The mean horizontal velocity over the shelves varies, depending on the amount of goods blocking the air flow. These variations are so wide that both the cooling of items on the shelves and the stability of the air curtain vary, depending on the load in the cabinet.

The conclusion is that heat can be removed from packages on the shelves either by radiation to cold surrounding surfaces or by convective heat transfer to cold air flowing past the packages. In a display cabinet having an air supply through the back, the coldest air is supplied at the back of the shelves, where the cooling requirement is least. If the packages are to be cooled by air flowing past them, the air should be distributed in some other way so that the air velocity is less sensitive to load variations, and with the air flow being controlled so that it is the vertical velocity component that dominates at the front edges of the shelves. If this is the case, then there is less risk of interfering with the air flow in the air curtain.

. The results from the CFD calculations show that the velocity of the air curtain at the bottom is so low that the climate chamber air flow can affect the measured results. Nevertheless, the conclusion is that the CFD model provides sufficiently good agreement to allow modified models to be used for a parameter investigation of the air curtain.

An air curtain in a display cabinet should provide good protection and remove heat from the foodstuff packages at the front of the cabinet. If the velocity is low, the curtain tends to deflect inwards towards the cold interior of the cabinet. If the cabinet is fully loaded, this need not be a problem, as the items on the shelves provide a physical barrier to further inward deflection. However, in practice, it is not realistic to assume that a display cabinet will always be fully loaded, and so two criteria have been defined which a display cabinet air curtain must fulfill. The air curtain must operate properly, providing full protection, even though the cabinet may not be fully loaded, and it must also provide cooling for the items at the front of the shelves. The stability/function of the air curtain should be independent of the way in which the items on the shelves are cooled.

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