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EXPERIMENTAL STUDY OF THE COLD AISLE PHENOMENON IN SUPERMARKET DISPLAY CABINETS

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ABSTRACT

This study brings some new light on the dynamical mechanism of the so-called cold aisle phenomenon caused by the spillage of cold air from two display cabinets installed in opposed lines.
From PIV velocity measurements, large scale smoke visualisations and robotized scanning of thermocouple temperature measurements, it could be shown that the height of the cold aisle and the steepness of the vertical temperature gradient are strongly dependent on a stable double recirculation movement in which the momentum seems more influenced by the dynamics of the entrainment by the two air curtains in front of the cabinet than by the slow air motions associated with natural convection.
These results suggest that new means can be found to reduce, through dynamical actions, the customer discomfort associated with the cold aisle phenomenon.

1. INTRODUCTION

An important part of the electricity used in supermarkets is dedicated to the refrigeration of the displayed foods. In the open refrigerated vertical display cabinets generally used, the only barrier between the customers and the displayed food is a cold air curtain which provides a separation between the cold inside of the cabinet and the hot ambient air of the store. One of the main concerns comes from the incomplete insulation associated with this air curtain. Due to its higher momentum, the air curtain initiates a mixing and entrains the warmer ambient air towards the lower part of the cabinet. One part of this mixed air penetrates in the cabinet, bringing heat and moisture which increase its cooling demand. The other part is poured forward on the floor, bringing low temperature air outside. HOWELL and ADAMS [1] in their study of the store climate influence on the efficiency of a single air curtain display cabinet showed that the infiltration of ambient air constituted the major part of the cooling demand source. CHEN and YUAN [2] showed that the increase in ambient temperature directly causes a temperature rise inside the cabinet, supplied and returned air, while variations of relative humidity have only a slight effect.

When these cabinets are installed in opposed lines, an important quantity of cold air is spilled in the lower part of the aisle between the lines, then reducing the thermal comfort of shoppers. According to the ISO 7730 [3] standard, thermal discomfort can be caused by an abnormally high vertical temperature difference between the head and ankles, a consequence of which is a linearly growing percentage of people dissatisfied as a function of this temperature difference. Several researchers, as Xiang and Tassou [4] or FOSTER and QUARINI [5], have numerically studied the thermal discomfort problem, particularly in front of a display cabinet. XIANG and TASSOU[4] simulated the cold aisle phenomenon with specially adapted boundary conditions. Their results showed that a vertical temperature difference up to 9°C could be obtained in the aisle for a store ambient temperature of 23°C. They proposed various methods to reduce this thermal gradient, the most efficient of which was based on bottom extraction of the cold aisle and top supply of heated air. LINDBERG et al. [6] estimated the percentage of people dissatisfied by thermal discomfort due to the cold spillage.

Our study aims at experimentally investigate the relations between the cold air spillage, the cabinet cooling load and the customers thermal discomfort in a commercial configuration of vertical display cabinets for various store climate setting, in view of the reduction of the cold aisle. After a thermal and dynamical characterization of the air curtains in use, we provide a physical analysis of the cold aisle phenomenon. Then the influence of ambient temperature and relative humidity on thermal comfort is described.

2. EXPERIMENTAL SET UP AND MEASUREMENTS

The experimental set up was based on commercial vertical refrigerated display cabinets, manufactured in units of 1.25 m in length, 0.8 m in width and 2.2 m in height, comprising five shelves and a bottom chest distributed along a total display height of 1.6 m. These units can be put end to end for installation in supermarkets. They are equipped by two air curtains (a hot outer one, and a cold inner one). In this study, two rows of vertical display cabinets, forming a 6.5 m long section, were installed face to face, with a ground spacing of 2 m, delineating a 2 m wide aisle. Tylose test products were stored on the shelves and in the bottom chest.
The experiments were carried out in a semi-controlled environment. The ambient temperature in the test room was settled in the range [15°C, 25°C] by using an electric heating system, while the relative humidity was passively varied by taking advantage of the thermodynamic variations in the outside environment.

A flow visualization system was used to display the low speed air motions in the aisle. A led floodlight generated a 2m*2.5m light sheet in the middle transverse plane of the aisle, which had been previously seeded with a smoke generator. A CDD camera was used to record image sequences of the air movements in the aisle at a frequency of 8 pictures/second.

The PIV technique was used to characterize the two-dimensional velocity field across the air curtains. This technique enables the access to the velocity vectors map in a localized frame delimited by a camera sight in a plane laser light sheet. A 50 mJ/pulse, dual-head pulsed Nd-YAG laser, with a 5 ns pulse duration, was utilized to partially illuminate the air curtain. The laser was passed through a 6 mm cylindrical lens to form a 1 mm thick laser sheet which was then reflected by a mirror in a plane perpendicular to the cabinet front. The air curtain was seeded with a smoke generator. Two cameras, fixed side-by-side on a vertically mobile mounting plate, captured a set of 1024 consecutive image pairs at each measurement station to give access to valid measurements of the velocity. The image pairs were processed with a classic PIV correlation based software (LA Vision – Davis software).

Inside the cabinets, parameters such as the air temperature at the supply and return grilles, and the temperature inside the products stored on the shelves, were measured by T type thermocouples.

The temperature field in the aisle was mapped with a rake of 40 T type thermocouples. The rake was moved and precisely located in the vertical and longitudinal directions by a two axes robot.

An illustration of the experimental set up and the measurement points inside the cabinet can be found in figures 1 and 2.

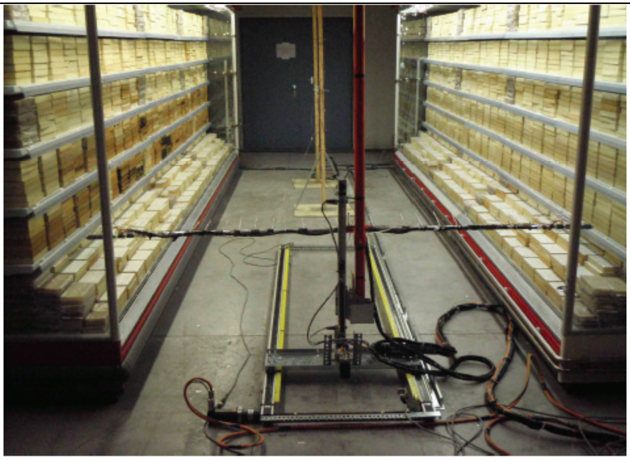

Figure 1: Experimental set up: the display cabinets and the mobile measurement system.

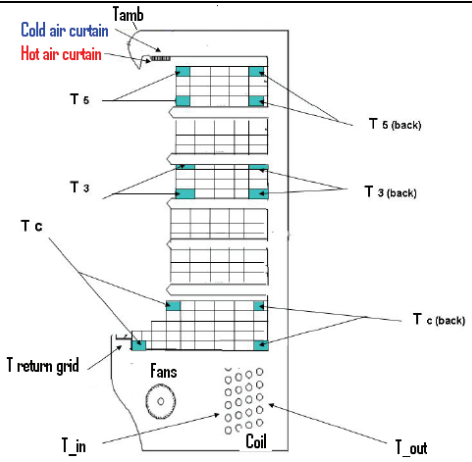

Figure 2: Measurement points in the display cabinets .

3. RESULTS

3.1 Characterization of the air curtains

Figure 3 shows transverse profiles of mean vertical velocity and temperature obtained at various streamwise positions *y* in the air curtains. In each of these vignettes, the transverse profiles are plotted as a function of the cross-stream distance from the cabinet front *x*. They illustrate the entrainment of ambient air in the air curtain.

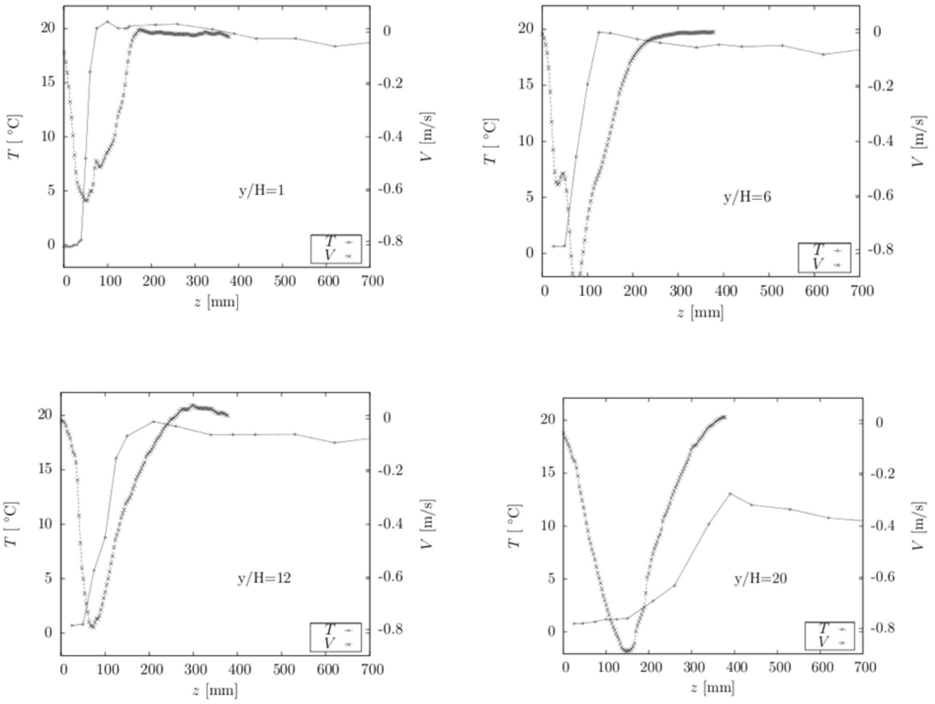

Figure 3: Transverse profile of velocity and temperature in the air curtain at various streamwise positions y; H is the discharge grid half-width, associated with the cold curtain origin (70 mm).

The double curtain appears to progressively merge in a single wide curtain, the temperature of which shows the evolution towards a complete mixing between the cold and the warm curtains. Near the bottom of the cabinet (y/H=20, around 60 cm from the floor), the mixed air, relatively cold, is in direct contact with the air of the aisle, this one being much cooler than in the upper part of the aisle.

3.2 The cold aisle characterization

The temporal sequences of the flow visualization in the aisle indicated the presence of two large scale counter-rotating eddies in the aisle, as shown in the snapshot example provided in figure 4.

Figure 4: Visualization of the air movement in the aisle.

The spilled cold air (the part of the mixed curtain not recycled into the cabinet loop) impacts the floor and goes towards the centre of the aisle where it bumps into the air similarly issuing from the opposite cabinet, what induces an ascendant movement in the centre of the aisle. This updraft is both backed off downwards by the natural convection and deviated horizontally on both sides by the viscous entrainment of the curtains of the cabinets. This gives rise to a double recirculation which keeps a relatively stable height in the so called cold air.

A map of the aisle temperature field for a vertical plane is shown in figure 5. It displays a low temperature (T_{cold}) zone close to the floor followed by a gradual increase with the height up to a maximum value (T_{hot}) which stays constant up to 2 m above the floor. We can notice that this stratification is not homogeneous in the cross stream direction x, the height of the cold recirculation being maximum in the central plane of the aisle (x=0). The mean temperature vertical profile for z=0, an example of which is given in figure 6, exhibited a particular shape allowing to define characteristic values of the cold aisle. For a given longitudinal location x, the characteristic height h_{min} and h_{max} of the colder and hotter part of the aisle could be defined as the vertical position hmin and h_{max} where, in the central ocation z=0, the dimensionless temperature $(T-T_{cold})/(T_{hot}-T_{cold})$ is equal respectively to 0.1 and 0.9. The temperature at these locations, which we defined as the characteristic temperature of the colder and hotter parts of the aisle, are then denoted T_{min} and T_{max}.

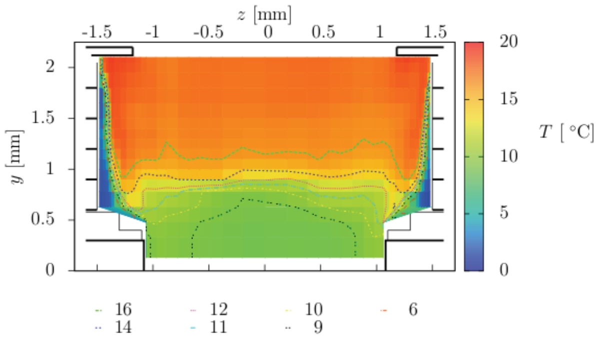

Figure 5: Typical temperature map for a vertical plane in the middle of he aisle.

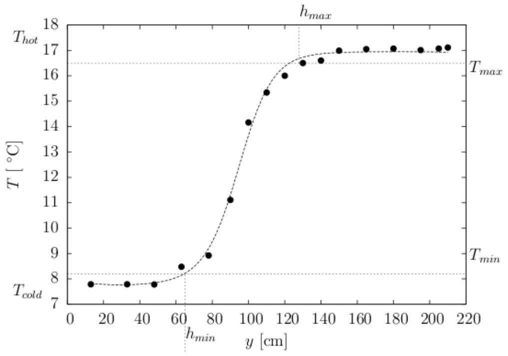

Figure 6: Mean temperature profile for z=0 Determination of the characteristic heights and temperature of the cold aisle

As shown in figures 7 and 8, the characteristic temperatures T_{min} and T_{max} are linear growing functions of the ambient temperature, while the height h_{min} and h_{max} are rather constant in our test range, with some scatter due to humidity variations and measurement uncertainties. The relative stability of h_{min} and h_{max} whatever the ambient temperature suggests that the height of the colder part of the aisle is not related to thermal effects in direct relation with natural convection. It seems that this stagnation corresponds to the height of the large counter-current structures observed in the flow visualizations while the temperature difference between the ambiance and the air curtain only imposes the level of the global thermal gradient (T_{max}-T_{min}) in the aisle.

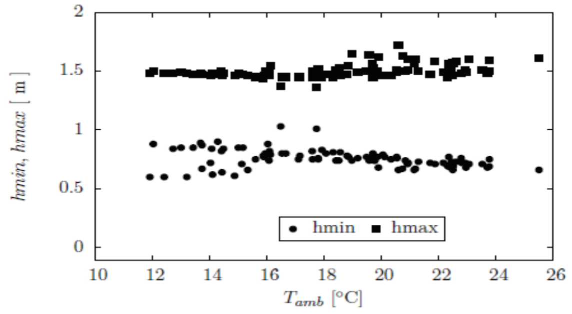

Figure 7: Characteristic height of the cold aisle.

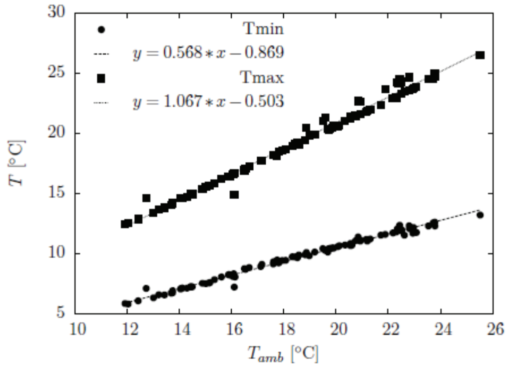

Figure 8: Characteristic temperatures of he cold aisle.

Thus we can assume that the lower temperature of the cold aisle results from a dynamically determined mixing of the cold spilled air and the hotter air from the ambiance. In this mixing process, we chose the variable: a=(T_{amb}-T_{min})/(T_{amb}-T_{ac1}) (wehre T_{AC1} is the temperature of the cold air curtain) to characterize the proportion of cold air spilled to the aisle. This variable, based on a simple temperature balance, gives a rough approximation of the heat mixing NAVAZ et al. [7].

This entrainment is constant for ambient temperature values ranging from 12°C to 19°C, and weakly increasing for higher values (cf figure 9).

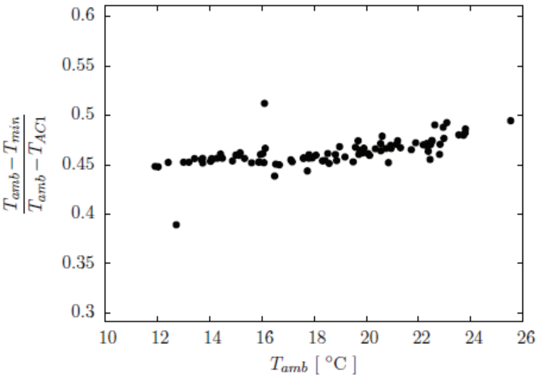

Figure 9: Proportion of cold air spilled to the aisle as a function of the ambient air temperature.

The small variations in this curve (about 6% of the mean values) can be mainly due to the variations in ambient humidity. As a consequence, the formation of the cold aisle and its holding on at a stable level and height appears dominated by the dynamics of the mixing and entrainment in the air curtains, associated with a stable recirculation in the lower part of the aisle.

3.3 Thermal comfort

The mean temperature was measured at the reference heights 0.1 m and 1.7 m above the floor, corresponding respectively to the ankle and head according to the ISO 7730 [3] standard. As shown in figure 10, the vertical temperature difference between these locations is a linear growing function of the ambient temperature. With a minimum of 6°C and a maximum of 13 °C for ambient temperatures of 12°C and 25.5°C respectively. According to ISO 7730 [3] standards, this corresponds to a percentage of dissatisfied persons up to 100%. Furthermore the hotter the store temperature, the higher the thermal discomfort of the shoppers. This too underlines the stable dynamic origin of the cold aisle problem, associated with a stable mixing process in the cold lower layer.

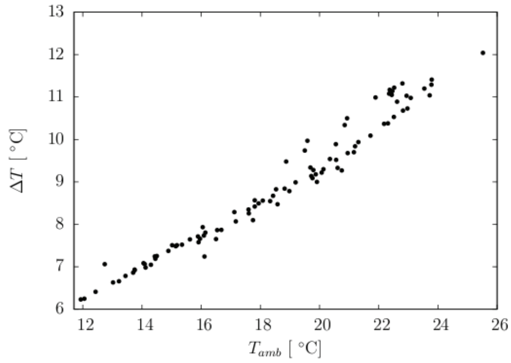

Figure 10: Temperature difference between the ankle and the head for a person placed in the centre of the aisle.

4. CONCLUSION

This research study provides a new physical description of the cold aisle phenomenon based on experimental methods. It appears that the mechanisms leading to the settlement of a stable cold aisle are essentially associated to the dynamics of the mixing between the air curtain and the ambient air, and the related recirculation of the resulting mixed air.

This physical description provides new insights that can be helpful in the search of means to reduce the cold aisle phenomenon.

In coherence with this dynamical analysis, the vertical thermal gradient in the aisle, and the local discomfort associated, can directly be linked to the temperature difference between the air curtain and the ambient air.

5. REFERENCES

[1] Howell R.H. and Adams P.A. Ef*fects of indoor space conditions on refrigerated display case performance*. ASHRAE, Department of Mechanical engineering, University of South Florida, Tampa, Florida., 596, 1991. 8

[2] Chen Y.G. and Yuan Y.X.. *Experimental study of ther performance of single-band air curtain for a multi-deck refrigerated display cabinet*. Journal of Food Engineering., 69 :261–267, 2005. 8

[3] EN ISO 7726, 2002. Ergonomics of the thermal environment.

[4] Xiang W. and Tassou S. *Investigation of methods to improve retail food store environment using cfd. Computational fluid dynamics in food processing*. Da- Wen Sun, Series Editor., 87 :143–166,

[5] Foster A.M. and Quarani G.L. Using advanced modelling techniques to reduce the cold spillage from retail cabinets into supermarket stores. IIF-IIR-Commission D2=3, Cambridge, UK, pp. 217–225, 1998

[6] Lindberg U., Axell M., Fahlen P. and Fransson, N. *Appropriate indoor climate for environmentally sustainable supermarkets – Measurements and questionnaires*. Proceedings of Clima 2007 WellBeing Indoors

[7] Navaz H.K., Henderson B.S., Faramarzi R., Pourmovahed, A. And Taugwaler, F. *Jet entrainment rate in air curtain of open refrigerated display cases*. International Journal of Refrigeration., 28 :267–275, 2005. 8, 11, 33