

INFLUENCE OF AIR DISTRIBUTION AND LOAD ARRANGEMENT IN DISPLAY CABINETS

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ABSTRACT

The vertical open display cabinet is a common type of cabinet which has a high energy consumption. This paper discusses energy models and air distribution in the cabinet. Energy balance considerations and experimental results show that infiltration is the predominant heat load factor. Computational Fluid Dynamics (CFD) is used in order to study the air distribution. Different models are presented and discussed and the influence of the load inside the cabinet is investigated. The research also deals with the difficulties of measuring low air velocities (< 0.1 m/s).

1. INTRODUCTION

Refrigeration is responsible for a significant amount of the energy consumption in the commercial sector. Vertical display cabinets are commonly used and have a large energy requirement and therefore work has already been done in Sweden to promote development of energy efficient products. Axell^(2,3) relates a procurement competition in which the winner managed to halve the annual energy input compared with key values for contemporary cabinets. Even at this level there is still room for improvement regarding both energy input and variations in temperature of the merchandise. Anema⁽¹⁾, Bobbo⁽⁵⁾ and Nordtvedt⁽⁹⁾ have pin-pointed that the open display cabinet is a weak link in the chill chain. Firstly the designer has to consider the requirement to keep an adequate temperature control inside the cabinet with a low energy consumption. Secondly the retailer wants a flexible product which allows him to display his products in an attractive way for the customer. To fulfill all requirements in the same product is a real challenge for the cabinet designer. The current research project aims at providing improved knowledge regarding the energy flows in vertical display cabinets in general and the air flows in particular.

2. ENERGY BALANCE

The vertical open display cabinet has an air curtain instead of a door to prevent heat and mass transfer between the cabinet interior and the ambience. A typical cabinet has a cooling coil, a fan to distribute the cool air inside the cabinet, lighting to display the food and could also be equipped with frame heating. A common way to distribute the cool air is from the rear of the cabinet through perforated plates and from the top of the cabinet by means of an air curtain. The cabinet could be equipped with more than one curtain and then the outer curtain usually delivers air at a higher temperature than the inner curtain.

Experiments and heat balance investigations show the importance of the interaction between the interior condition in the cabinet and the ambient condition in the store. Billiard⁽⁴⁾ presents a heat balance model of an open display cabinet. The model does not take into account the exchange of food products. Input to the model is data measured during one week. The reported deviation between measured cooling capacity and the calculated heat loss is 7 %. The different contributions to the heat gains are presented in figure 1. The portion of gains which depends on the ambient condition is close to 67 %. He also discusses the importance of a good strategy for defrosting. The temperature rise in the food during a defrost could be several degrees Celsius and it may take hours

to return to the correct temperature in the food. It could even be a problem to keep the food inside the temperature limits. Hence the defrost strategy is very important for the temperature quality inside the cabinet and it affects the energy savings. Experimental results from SP, The Swedish National Testing and Research Institute, provide the same experience and Axell^(2,3) reports energy savings due to night covers between 25 % and 40 %.

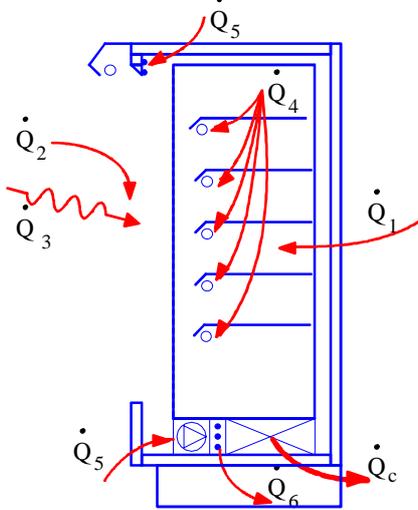


Figure 1. Energy balance of an open display cabinet.

Heat gains

- Defrost
- Heat transfer by infiltration
- Radiant heat transfer
- Heat transfer through cabinet walls
- Fan
- Lighting
- Frame heating

Howell⁽⁸⁾ has studied how the ambient relative humidity affects the energy consumption. In this model, the exchange of food in the cabinet is included. Individual contributions to the heat losses are divided in two categories:

Dependent of the store relative humidity

- Defrost
- Latent heat transfer by infiltration
- Frame heat (or anti-sweat)

Independent of the store relative humidity

- Radiant heat transfer
- Heat transfer through cabinet walls
- Sensible heat transfer by infiltration
- Energy change in the cabinet due to restocking of food
- Internal consumers of electricity in the cabinet (fan, lighting)

Brolls⁽⁶⁾ discusses factors which depend on the store condition and affect retail display cabinets. The effects of controlling the ambient condition on energy extraction for an open display cabinet are demonstrated in figure 2.

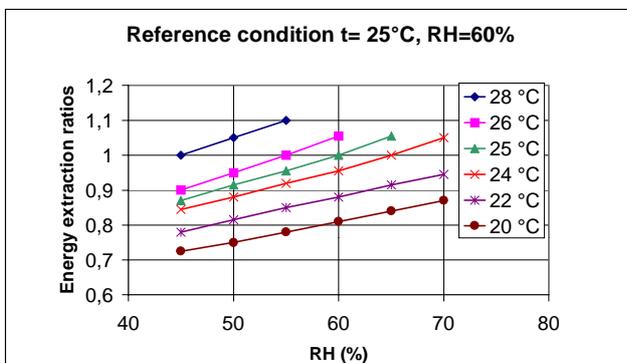


Figure 2. Heat extractions versus relative humidity.

Dependent on the store condition:

- store ambient (t, RH)
- merchandising of the cabinet
- siting of the cabinet
- refrigeration system control

Experience from the aforementioned procurement competition showed that the ambient condition greatly affected the cooling requirement. The difference between a summer condition (22 °C, RH = 65 %) and winter (20 °C, RH = 51%) for the different cabinets ranged between 21 % and 39 %. The water drained during a test cycle (24 h) varied with 50 %. This is a measure of the degree of infiltration in the cabinet. The difference in brine temperature and the function of the air curtain are important factors. The air flow inside the cabinet, and the air curtain in particular, are very important and largely determine the correct operation of the cabinet. Therefore more detailed studies have been performed of the air flow inside the cabinet in a combination of experimental and theoretical studies

3. CFD-MODEL OF A VERTICAL DISPLAY CABINET

For the theoretical analysis, Computational Fluid Dynamics (CFD) has proven to be an effective tool to study the flow pattern inside and in the surroundings of the cabinet. Experimental studies of display cabinets are tedious because of the time it takes to reach thermal equilibrium.

A common way to distribute the cool air in a vertical display cabinet is through perforated plates in the rear of the cabinet and in the front as an air curtain. This paper deals with air distribution from the rear. Air is blown through the space between the shelves and cools the load. The horizontal air flow will also function as a stabilizer for the air curtain. The air velocities in the shelves are much lower than the velocities in the air curtain. Typical values are in the order of 0.05 m/s - 0.4 m/s and the velocities in the curtain may be 3-5 times higher. The choice of low velocities inside the shelves is to protect the load from drying caused by forced convection and to minimize the risk that the air flow will disturb instead of stabilize the air curtain. An even temperature profile is necessary if all the packages are to be kept inside the temperature limits and with a target to decrease the cooling capacity a reduction in temperature spread must be achieved. For this reason it is also important to avoid uneven frosting of the coil.

Simulations have been performed with the CFD-code SOFIE using the k-ε turbulence-model. Welch⁽¹⁰⁾ provides more detailed information regarding SOFIE. Two different cases have been studied: the first case is a two-dimensional model including the whole cabinet and an area of 600 mm in front of the cabinet and the other is a three-dimensional model for one shelf. The calculations have been performed assuming isothermal and steady-state conditions.

In the full-scale model, the boundary condition to the surroundings is a constant pressure. Shelves and load inside the cabinet are modelled as inactive blockings. Measurements and calculations have been performed for three different cases: 1) a cabinet without load, 2) a cabinet loaded according to EN 441, 3⁽⁷⁾, 3) a cabinet with a partial load (no load in shelves 2 and 4).

The number of cells is in the order of 100 000, which means that simulations take quite a long time. To investigate if it is possible to decrease the computing time with a coarser grid, small three-dimensional models were developed for one shelf. The idea has been to see if it is possible to replace the real hole pattern in the plate with a simpler one. The cabinet has circular holes evenly distributed in the plate. Three different types of holes were used in the calculation:

1. Square holes (with the same hydraulic diameter as the circular holes).
2. Thin slot (with the same opening area as a whole row of circular holes).
3. Wide slot (the width of the slot is the same as the diameter of the circular holes).

The influence of the load was investigated with a height of the load according to EN 441. The load has been varied in depth (x-direction of the shelf) as follows: an empty shelf, 100 % load, 95 %, 75 % and 50 %, starting from the front of the shelf.

4. EXPERIMENTS

The total flow capacity of the cabinet was measured together with the outlet flow from the air curtain. The rest of the flow was assumed to be distributed through the rear and this flow was the inlet condition to the small CFD-model. To the full-scale model, however, the total flow capacity was the inlet condition.

To validate the calculations, velocity profiles were measured in the shelf for all of the different cases. Symmetry was assumed and velocity profiles were measured in one half of the cabinet in all shelves as follows: 5 positions in height (in each shelf), 2 positions in depth and 5 positions sideways. Velocities have been measured with different types of thermal anemometers. The temporal mean values have been calculated for each position. Mean values for the two-dimensional model have been calculated for each position based on four lateral positions (the values closest to the side wall are excluded).

5. RESULTS

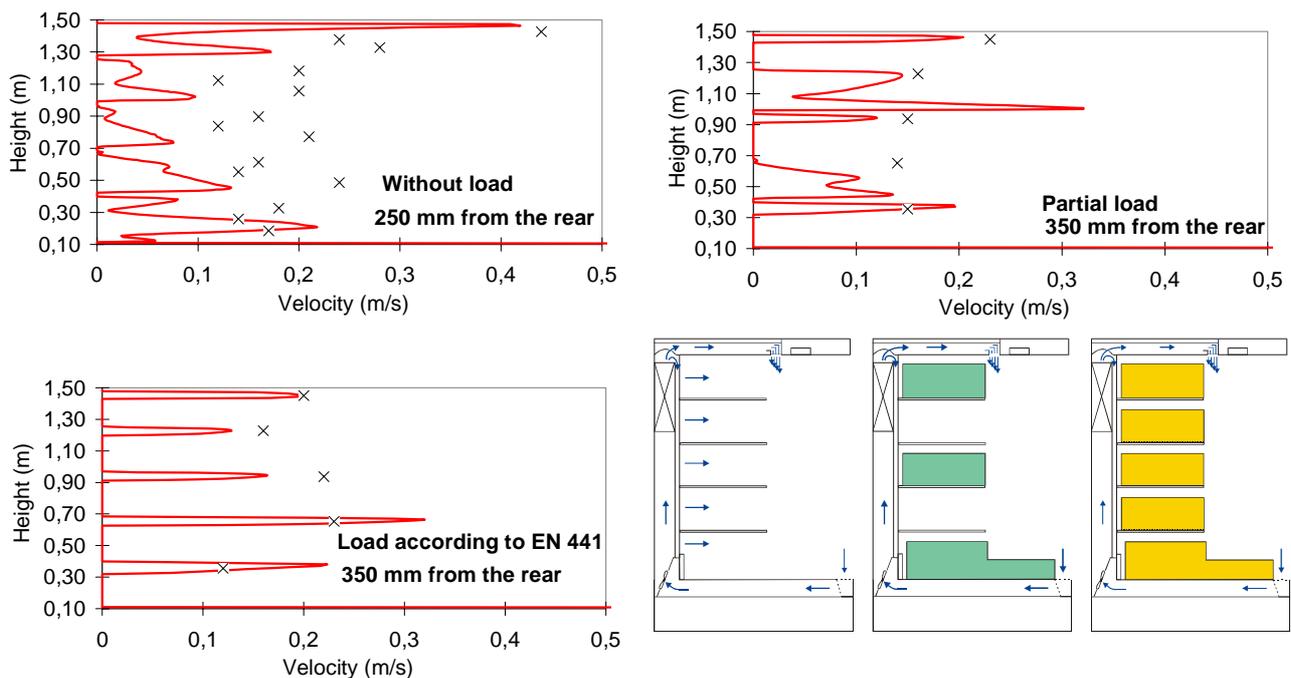


Figure 3. Comparison between calculated and measured velocities. Line = calculated value
X = measured value

The full-scale two-dimensional model shows a good qualitative agreement with measured values. Without load in the cabinet, the horizontal variation in the measured mean velocity inside a shelf was relatively small. On the other hand, the variation between the different shelves was large ($\pm 50\%$; 0.1 to > 0.3 m/s). There were also substantial vertical velocity variations. With a load inside the cabinet, both the relationship between the velocities in the different shelves and the magnitudes were changed, see figures 3 and 4.

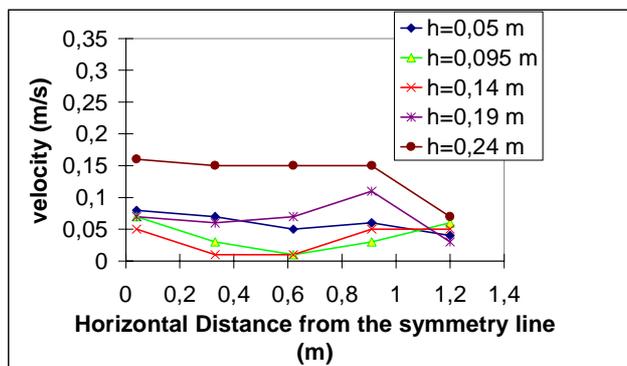


Figure 4. Without load: mean horizontal velocities in shelf no. 2, `h` refer to height .

In the three-dimensional model, the real hole pattern (rows of circular holes) was replaced by another type of opening in order to achieve a coarse grid and decrease the computing time. The different model assumptions were compared and the velocity profile in different positions depth-wise were studied, see figure 5. You have to move to the front of the shelf before the different profiles have the same shape and magnitude, and the flow has forgotten the inlet condition in the rear.

Calculated and measured values showed a qualitative agreement for the model assumption with square-shaped holes, see figure 5. However, even in the case with loaded shelves, the differences between the three models were relative large and only at the front of the shelf did the velocity profiles show a comparable shape and magnitude. The quantitative agreement between calculated and measured values is best in the cases with loaded shelves. With packages in the shelves, the velocities reach their highest values. The unloaded cases result in large deviations, probably due to measuring difficulties at the resulting low air velocities (< 0.1 m/s).

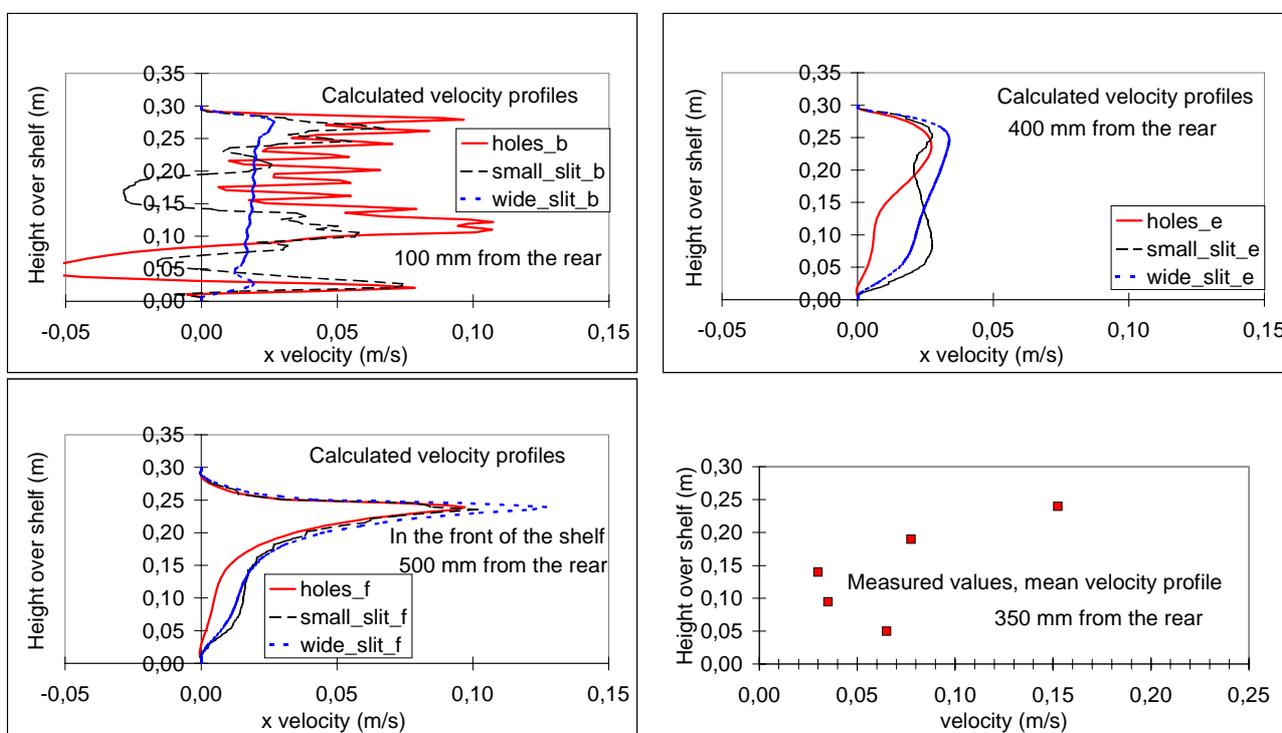


Figure 5. Calculated and measured velocity profiles in shelf no. 2, `x` refer to depth from the rear to the front of shelf.

With a load of 50 % depth-wise (from the front of shelf), the influence of the different hole patterns is very small compared with the case with a load of 95 %, see figure 6. In the first case the empty space near the rear act as an equalizing box.

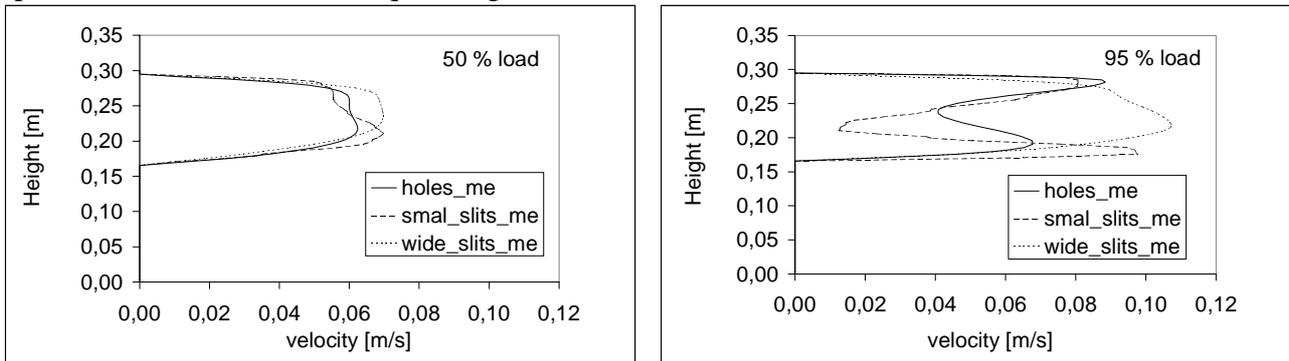


Figure 6. Calculated velocity profiles. Different load profiles (depth-wise) from the front of the shelf toward the rear.

An investigation has been made to compare different types of measuring equipment (thermal anemometers) and also to see if it is possible to measure all positions at different heights in the shelf (the same x and z positions) at the same time, `x` refer to the depth of the shelf and `z` refer to the distance along the shelf. The deviation between the two different types of sensor is not so large but it seems that the sensors should not be installed too close to each other (5 at the same time), see figure 7. Both types use a heated measuring element. Disturbance between the sensors can be created both by natural convection and by the size and shape of the sensor.

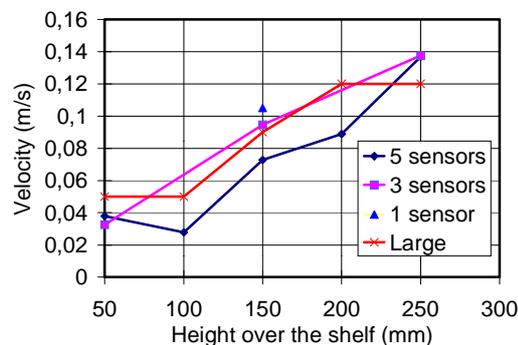


Figure 7. Comparison of a small (5, 3 and 1 sensors at the same time) and a large thermal anemometer (1 sensor).

A comparison of the calculated resulting velocity component with the value in the x-direction show values of the same order, which indicates that the sensors are not influenced by velocity components in other directions. Measurements have also been made to investigate if the sensors are sensitive for installation in different directions (parallel and perpendicular to the flow). Results seemed to be unaffected by directional effects.

6. DISCUSSION

A review of different energy models and experimental results show that infiltration is the most important contribution to the heat loss for open vertical display cabinets. Results show that the difference in cooling capacity during day and night conditions are substantial. A comparison of the drained water and the estimated latent heat of the air shows a good agreement. Vertical cabinets are

sensitive for the ambient condition in the surroundings. One way to improve the performance is by installation of a dehumidification equipment in the store but the best way must be a better control of the air curtain.

A good qualitative agreement was reached with the different CFD-models. The velocity profiles inside the cabinet were strongly affected by the load. The best agreement was reached in cases with full load in the shelves (highest air velocities). These cases also showed the best function by creating an even distribution of the air.

The size, shape and distribution of the opening area in the rear will affect the velocity profiles in the shelves. If the main focus is on the function of the air curtain it would be reasonable to use the simplest assumption. All of the models showed good agreement at the front of the shelf. For more detailed studies of the air distribution in the shelves, the inlet condition from the rear will be important. The cabinet is very sensitive for the arrangement of the load. This is important to know both in work with simulations and in experimental work. In reality the arrangement of the load and variation of the load during the day/week in the store will probably affect the temperature quality of the food. Therefore a challenge for the future is to develop an improved air distribution system.

A combination of simulations (CFD) and experimental work provides an opportunity to save time. Work with small sub-models seems to be an effective way to study different phenomena. The experience can later be included in a full-scale model.

7. REFERENCES

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DES MEUBLES DE VENTE EFFICACES ˆDÉNERGIE

RÉSUMÉ: Le meuble frigorifique de vente vertical ouvert est un type de meuble frigorifique fréquent qui a une consommation d'énergie élevée. Dans cet article, les transferts d'énergie et la distribution de l'air sont discutés. Les bilans sur l'énergie et les résultats expérimentaux montrent que l'infiltration d'air contribue de façon prédominante à la perte de chaleur.

La simulation numérique des écoulements (CFD) est utilisée dans le but d'étudier la distribution de l'air. Différents modèles sont présentés et discutés. L'influence de la charge à l'intérieur du meuble est examinée. L'étude porte également sur l'importance et les difficultés liées aux mesures de faibles vitesses d'air.