VERTICAL DISPLAY CABINET

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ABSTRACT

The vertical open display cabinet is commonly used and is also a large energy consumer. 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 and the influence of the load. The function of air curtain is discussed.

Keywords: Display cabinet, air distribution, air curtain, CFD, simulation, energy balance

INTRODUCTION

The vertical open display cabinet is a common type of cabinet which has a high energy consumption. This type of cabinet makes it possible to display large amounts of food on a small surface in the store. The retailer has a primary goal to sell food. Therefore the open type of vertical cabinet is more popular than the closed even if Adams (1985), for example, reports that cabinets with permanent glass doors will reduce the energy consumption with 50 %.

Howell (1993) and Brolls (1986) discuss the influence of ambient conditions. An increase both in temperature and relative humidity will raise the energy requirement. Therefore the cooling demand reaches the largest level during the summer when the need for heat-recovery is at the lowest levels.

Based on this short introduction, the vertical display cabinet is probably one of the most important components in the supermarket system. New cabinets with improved functions will give better temperature quality in the food, save energy and favour the indoor air climate in the store.

EXPERIENCE FROM MEASUREMENTS

Axell and Fahlén (1995) and Axell and Fahlén (1998) report experimental results from tests performed according to the European standard EN 441 on indirectly cooled vertical display cabinets. Here is a brief summary of the experience from the tests:

- Cooling demand in modern vertical display cabinets can vary with a factor 4, from 8000 kWh/year and metre cabinet down to 1745.

- Energy savings due to night curtains can range from 25 % up to 40 %. The construction of the night curtain is important. There is a risk that air infiltration at the edges will cause unacceptably warm food at the edges of the cabinet during night operation.

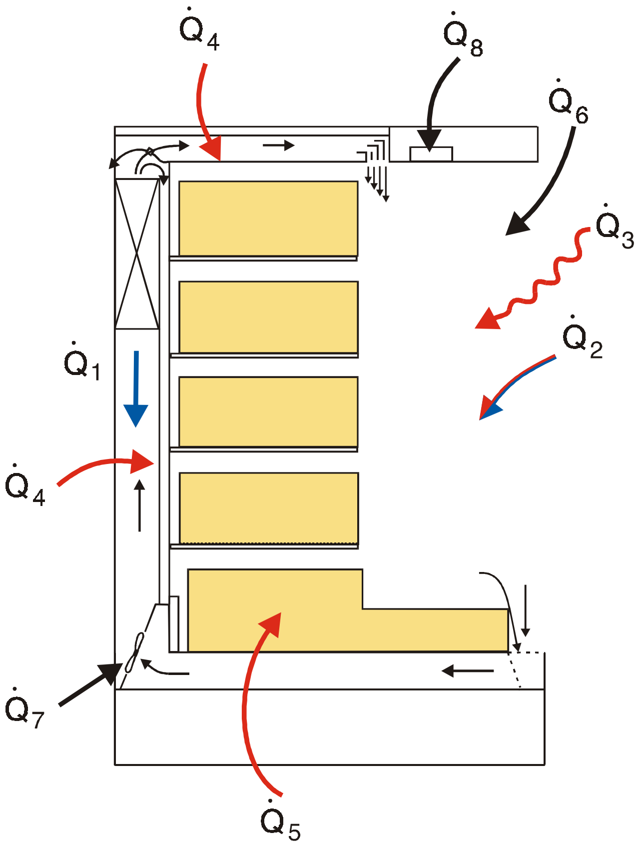
- Another interesting comparison concerns the difference in cooling requirement between a summer condition (22°C, RH = 65 %) and a winter condition (20 °C, RH = 51%). This difference ranged from 21 % up to 39 % between different cabinets. The water drained varied with 50%. This is also a measure of the degree of the infiltration.

- An increase in coil area makes it possible to run the cabinet with a higher temperature of the secondary coolant. This will also increase the COP of the refrigerating installation. As well as reduce frost growth and pressure drop. New energy efficient vertical display cabinets with a high inlet temperature of the secondary coolant makes it possible to run the cabinet with no defrost at all. This saves both energy and costs for defrost equipment.

- The airflow inside the cabinet and the function of the air curtain in particular are very important factors and largely determine the correct operation of the cabinet.

ENERGY BALANCE – COMPARISON OF ANALYTICAL MODELS AND EXPERIMENTAL RESULTS

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. In figure 1 the heat losses in a display cabinet are illustrated.



Heat losses

- **Defrost**, $\dot{Q}_1$, (Dependent of store RH)
- **Infiltration latent**, $\dot{Q}_2$, (Dependent of store RH)
- **Infiltration sensible**, $\dot{Q}_2$, (Dependent of store T)
- **Radiation**, $\dot{Q}_3$, (Dependent of store T)
- **Conduction, roof and rear**, $\dot{Q}_4$,(Dependent of store T)
- **Conduction, gables**, $\dot{Q}_5$, (Dependent of store T)
- **Light, external**, $\dot{Q}_6$
- **Fan, internal**, $\dot{Q}_7$
- **Light, internal**, $\dot{Q}_8$

Figure 1. *Energy balance of an open display cabinet.*

Three different model assumptions for the energy balance are compared under “steady state” conditions with no exchange of food in the cabinet.

1. Model with infiltration calculated with the defrost water as a tracer, Billiard and Gautherin (1993).
2. Model with infiltration calculated from a moisture balance over the curtain and with an assumption that the air curtain is uniform, Fahlén (2000).
3. Model with infiltration calculated from an energy balance over the curtain.

In the three models the following losses are the same. Defrost, external lighting, conduction through the gables, and internal electrical consumers (fan and lighting). In model 3 the conduction through the rear and the roof is calculated from air mass flow multiplied by enthalpy difference (temperature increase between the position after the cooling coil and the outlet condition for the air). In the two other models the same loss is calculated taken into account the surface temperature at the outside of the cabinet, the conductivity in the wall and the air temperature in the channel.

To generate inputs to the different models, experimental studies have been performed according to EN441 at different climate conditions. The cabinet has been equipped with an increased number of measuring positions; air condition (t, RH) in the shelves, the outlet and return temperature, the air condition before and after the cooling coil, the amount of condensate water, surface temperatures both on the cabinet and the walls in the climate chamber.

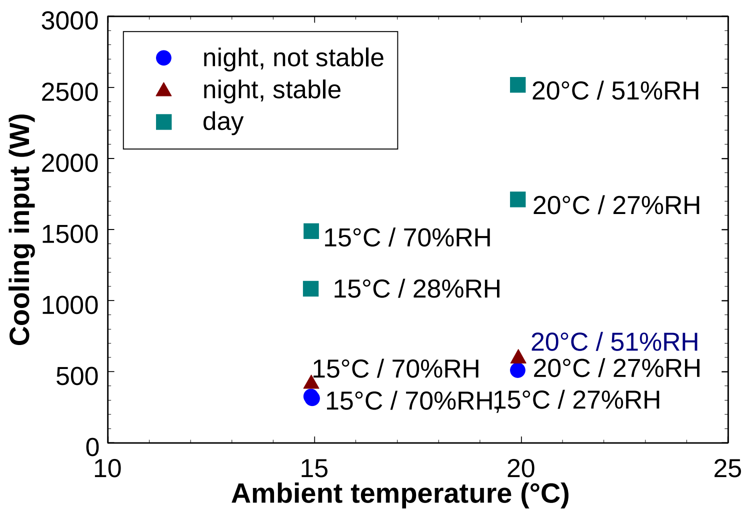


Figure 2. *Cooling input versus ambient temperature.*

Figure 2 shows the savings with a night curtain. With a good function of the night curtain the losses are caused by conduction, external ligthing and the internal eletrical consumers.

A common way to study the function of the cabinet is to measure outlet and return temperature plus ambient temperature. Figure 3 illustrates that infiltration calculated from the dry temperature before and after the cooling coil will underestimate the losses more and more with an increase in humidity.

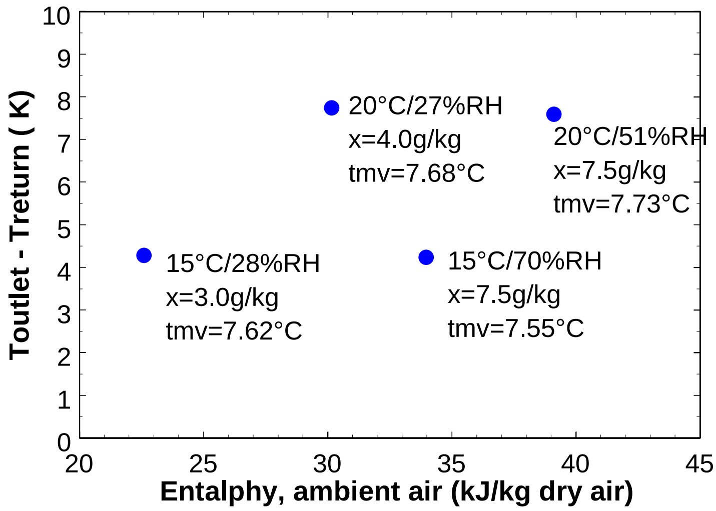


Figure 3. *Temperature difference between outlet- and return temperature versus ambient enthalpy.*

The best agreement with measured cooling capacity is achieved with model 3, see figure 4. The losses are overestimated with 7 %. In model 3 the infiltration from the ambience is in the order of 53 % and 16 % of the air to the return grille is coming from the cold air inside the cabinet.

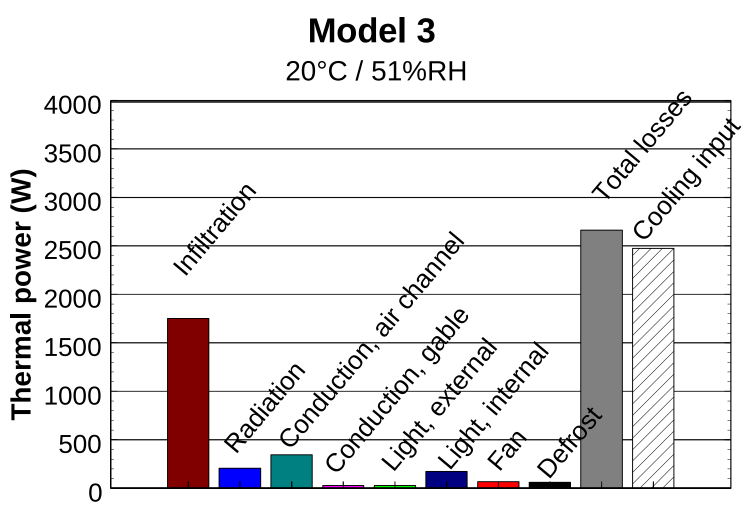


Figure 4. *Model with infiltration calculated from a energy balance over the curtain.*

Model 2 is planned to be used as a simple method for field measurements (temperature or humidity). The method assumes a symmetric air curtain which is not applicable on this cabinet. The "field model" 2 can easily be modified to produce improved results and be generalized for other cabinets. The difference between measured cooling capacity and total heat losses can be used to perform a new calculation and with a few iterations it is possible to reach a better agreement with model 2.

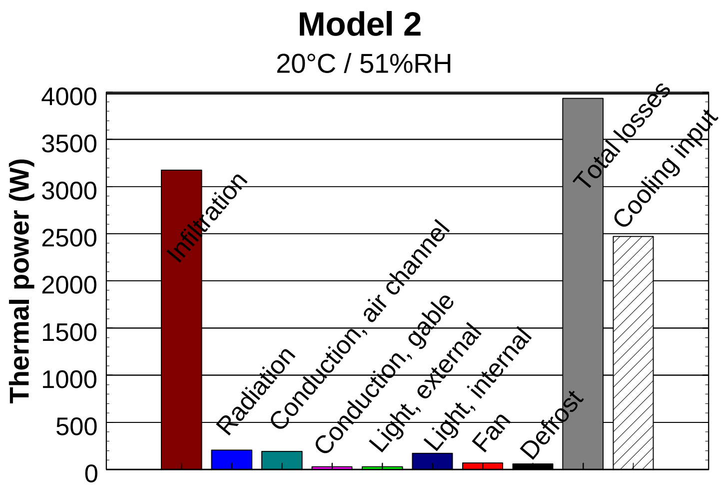


Figure 5. *Model 2 with infiltration calculated from a moisture balance over the curtain and with an assumption that the air curtain is uniform.*

Billiard and Gautherin (1993) reported a deviation between measured cooling capacity and the calculated heat loss of 7 %. This calculation is performed on a vertical freezer placed. The uncertainty with a method where the melting water is used as a tracer for the infiltration will increase with a decrease of the moisture content in the ambient air and with a higher temperature of the secondary coolant.

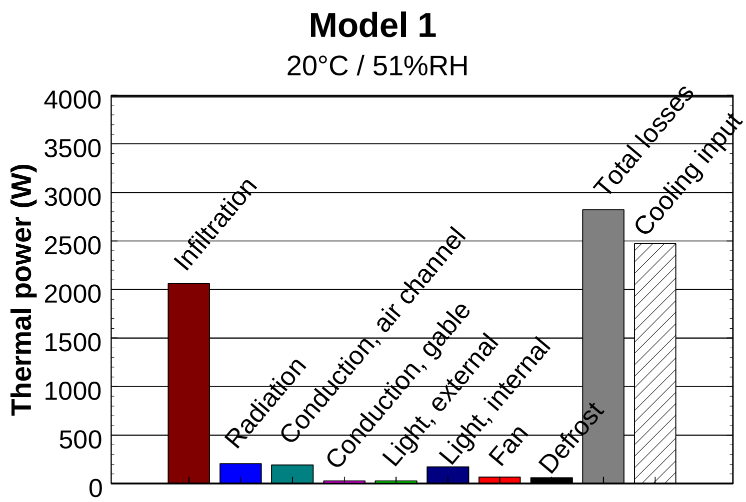


Figure 6. *Model 1 with infiltration calculated with the defrost water as a tracer.*

CFD – AIR DISTRIBUTION MODELS AND MEASUREMENTS

Both experimental results and the energy balance show that the infiltration is the most important contribution to the losses in a display cabinet. Computational Fluid Dynamics (CFD) has proven to be an effective tool to study the air distribution.

A common way to distribute the cool air in a vertical display cabinet is through perforated plates in the rear and as an air curtain in the front of the cabinet. Air is blown through the shelves to cool the load. The horizontal air flow will also function as a stabilizer for the air curtain. An even temperature profile is necessary if all the packages shall be kept inside the temperature limits and with a target to decrease the cooling capacity a reduction in temperature spread must be achieved.

Axell, Fahlén et al. (1999) reports results from simulation performed with the CFD-code SOFIE using a k-ε model. A full-scale model of the cabinet was used to study the influence of the load in the shelves. The velocity profiles from the rear were compared with measured results. The most even velocity profile and the highest velocities were achieved with full-load in the cabinet.

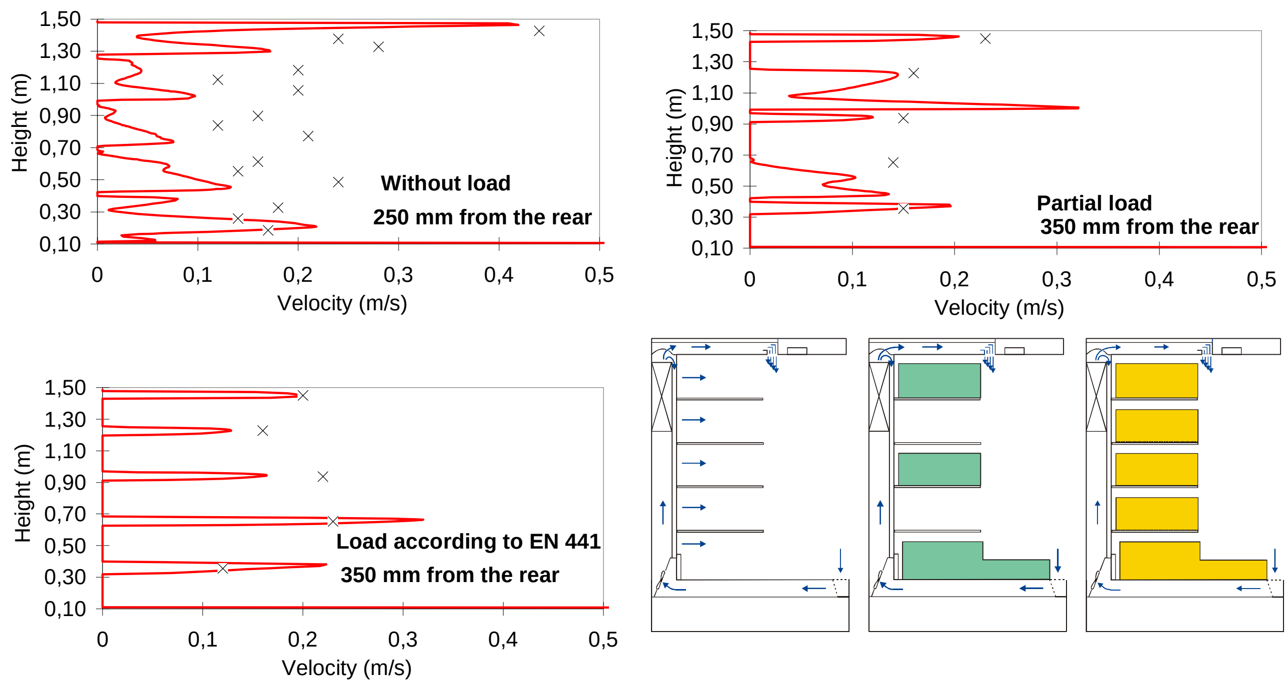


Figure 7. *Comparison between calculated and measured velocities. Line = calculated value X = measured value*

A model for one shelf indicated that the velocity profile at different depths in the shelf was strongly influenced by the size, shape and distribution of the openings in the rear. Also in this model the influence of the load was investigated. The conclusion is that the cabinet is very sensitive for the arrangement of the load. In reality the arrangement of the load and variation in the load during day/week in the store will probably affect the temperature quality of the food. Camporese (1991) has studied the effects of load arrangement on thermal performance of open display cabinets. The results show that the different load arrangements will influence the temperature quality of the food both with and without night curtain.

CFD simulation has been performed on the curtain. In figure 8. measured temperature profiles with thermocouples and with IR-camera are compared with the results from the simulation. There is a qualitative agreement but the model is still under development.

Temperature profile in the air curtain measured with thermocouples (left picture) Result from CFD simulation (right picture).

Temperatureprofile in the upper part of the air curtain. Measurement are performed with IR-camera luftridå med värmekamera. Note that the picture is a mirror of the other

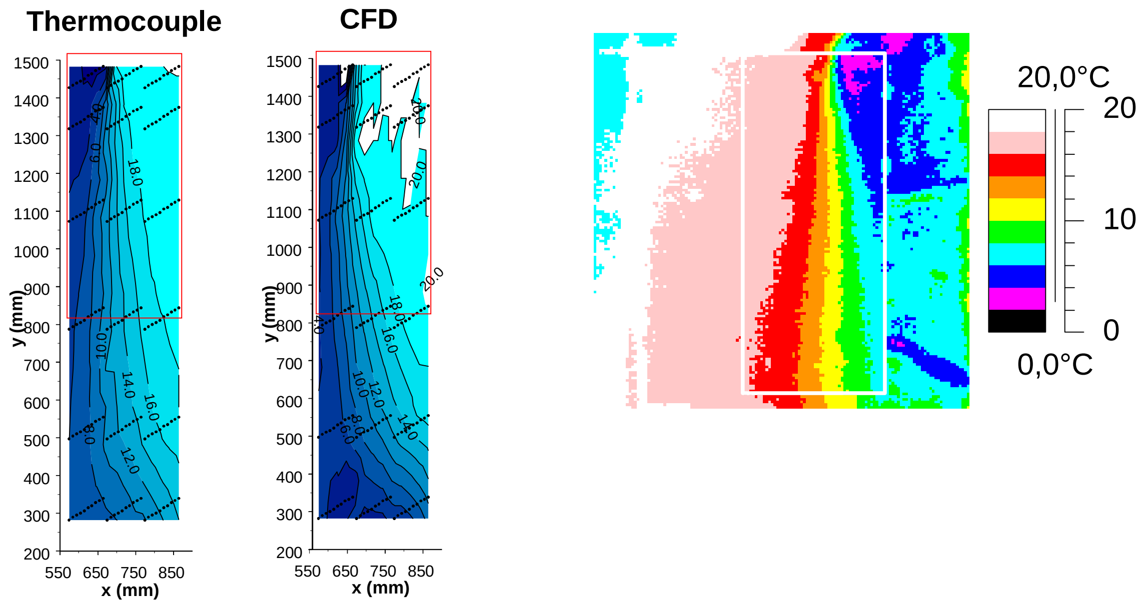


***Figure 8**. Measurement and CFD simulation. Outlet velocity 0.7 m/s.*

Cortella.G (1998)has performed simulation and reports that the cabinet (with a single curtain) is much influenced by the air velocity: with a too low air velocity the correct storage temperature cannot be guaranteed, while with a too high velocity the flow becomes turbulent and the heat and mass transfer with the ambient increases. Test have been performed with the air curtain velocity in the range from 0.3 to 0.8 m/s at the supply diffuser.

The velocity 0.6 m/s produces the most effective flow pattern of the air curtain. This finding is in accordance with the standard choice for vertical cabinets, in which typical values of the air velocity range from 0.5 m/s to 0.8 m/s. At 0.3 m/s the air flowing from the back interfer with the air curtain. Therefore, the expected “barrier effect” to the infiltration of warm air from the ambient is compromised.

AIR CURTAIN - A THEORETICAL STUDY

The flow regime in an air curtain can be divided in three regions:

1. Transition zone ($u = u_o$; $x < 5.2bo$; Schlichting (1955); $u = u(x, y, b_o, u_o)$
2. Established zone ($u < u_o$; $x < 5.2bo$; Schlichting (1955); $u = u(x, y, b_o, u_o)$)
3. Recompression zone (Fully developed velocity profile)

The sealing ability of an air curtain depends on the amount of initial momentum, $u_o b_o \rho_o$, present in the air jet and the size of the transverse forces which the air curtain is attempting to seal against. Hayes (1969), defines a dimensionless ratio, the deflection modulus, D_m.

D_m = *Momentum in the air curtain / Transverse forces*

$$D_m = \frac{\rho_o \cdot b_o \cdot u_o^2}{g \cdot H^2 \cdot (\rho_c - \rho_w)}$$

The tranverse forces are a function of the total pressure difference. The total pressure difference depends on Δps, stack effect caused of differences in air densities on the two sides of the curtain and Δpa= self generated pressure difference across the air curtain that occurs because of the momentum which is added to the cool side of the curtain. Hayes and Stoecker have shown that $\Delta pa << \Delta ps$ for recirculated curtains so that only the stack effect need to be considered.

$$\Delta p = \Delta p_a - \frac{g}{g_c} \cdot (\rho_c - \rho_w)(x - x_o)$$

The stack effect is generated by the difference from the top to the neutral zone, where , xo is defined as the location where the pressure difference due to the stack effect is zero

If this momentum is not maintained then the curtain will not seal the opening and an exchange of air between the inside and outside will occur due to natural causes. The air curtain will break and bend towards the cold side. If the momentum is maintained much higher than the minimum value for continuous sealing, excessive mixing between the air curtain jet and the outside air will occur, resulting in unnecessarily high rate of heat transfer. Therefore the optimum design velocity of an air curtain requires knowledge of the minimum deflection modulus for each type of air curtain. Hayes and Stoecker recommend as practice to double the momentum of the jet for the optimum, that means an increase of the initial velocity, u_o by a factor $2^{0.5} = 1.4$. (Howell 1980) reports that the best way to determine the minimum deflection modulus is by experiment.

The function of the air curtain depends on following parameters:

- Initial width, b_o
- Height, H
- Outlet velocity, u_o
- Turbulence intensity
- Inlet angle, α_o

For a constant ambient condition the stabilization of the air curtain can be expressed by the deflection modulus which is a function of b_o, H and u_o. The heat transfer can be expressed as $Nu /(Re\ Pr)$ and is a function of b_o, H and u_o.

Howell (1980)reports following from an experimental analysis of turbulent recirculated air curtains, (*0.8 m/s <* u_o *< 5.2 m/s)* :

- A breaking point for air curtains does occur if the deflection modulus is below the minimum value for the particular air curtain configuration.
- Initial turbulence intensity has a moderate effect on the rate of heat transfer through an air curtain.
- The total heat transfer through a recirculated air curtain is directly proportional to the initial jet velocity and the temperature difference across the air curtain.
- Transverse and longitudinal temperature differences can be used as correlating parameters for recirculated air curtains.
- The heat transfer parameter *Nu / (Re Pr)* correlates well with the deflection modulus *Dm*.
- There is a value of Dm which exists for each air curtain configuration which minimizes the rate of heat transfer across the air curtain.

Hayes gives design data for the case of a non recirculatory air curtain at the doorway of a sealed room or building. For a given height, *H*, and temperature difference following parameters are important:

- Discharge angle, α_o
- Slot width, b_o
- Outlet velocity, u_o

Thick curtains result in slightly less heat transfer than thin ones. The reduction in heat transfer due to a thick curtain is in the order of 10 %. A higher velocity than the stability point must be chosen in order to re-establish the curtain quickly after it is disrupted by traffic, for example customers. An increase in velocity also increases the rate of heat transfer.

The variation of *Nu/(RePr)* with the parameter H / b_o appears to have the greatest influence on the heat transfer. The discharge angle and the deflection modulus have very little influence on *Nu/(RePr)* at high values of the deflection modulus. However, at low values, where the air curtain will be operated for minimum heat transfer rates, the discharge angle and the deflection modulus have considerable influence. The value of *Nu/(RePr)* increases quite rapidly as the minimum value of the deflection modulus is approached, i.e. the point where the air curtain breaks. At first glance it might appear that the heat transfer coefficient approaches a constant value at higher values of the deflection modulus. However, in this region the heat transfer coefficient is directly proportional to the outlet velocity.

Dupre (1995) discusses the main differences between the commercially used air curtain technologies, the air intake and outlet temperatures, and the technical solution of the double-air-curtain display cabinet providing recycled air at a temperature above 0 °C. He makes a classification of air curtains.

It is important to note that only the inner curtain passes the cooling coil. A comparison of double curtain with recirculation and without at the same ambient condition show that the energy savings with recirculation are 20 %. To compare the different types of air curtains the temperature difference between the inlet and outlet temperature in the air curtain is measured. For an ideal wall the temperature difference is 0°C.The measured temperature differences for the different air curtains are:

Air curtain	Temperature difference (inlet-return) °C
Single air curtain	8
Double air curtain	6
Double air curtain with recirculation	4
Tripple air curtain with recir	2

Adams (1992) reports that the air curtain shall be optimized so the mixing is maximized on the cold side and minimized on the warm side. This means that the velocity shall decrease outward to the warm side and the temperature profile shall increase outward to the warm side. He also discusses the possibility with more than one curtain mentioned above.

CONCLUSIONS

The infiltration is the dominant contribution (50-70%) of the losses in a vertical open display cabinet. The most simple solution is to equip the cabinet with doors. Adams has showed that the energy savings are in the order of 50 %. The traffic in the store with customers taken food will disturb and decrease the energy savings both for the closed and the open cabinet. But the retailer in the store will still prefer the open solution. However Nordtvedt and Nordvang (1995) have proven that the temperature quality in the food is not kept inside the temperature limit in open cabinets.

To reach the goal to keep the food inside the temperature limits, reduce the energy consumption and decrease the discomfort caused by cold air spillage the function of air curtain must be improved.

The air curtain and the infiltration is influenced by the load arrangement, traffic in the air curtain caused by customers, the ambient condition, variation in air flow and disturbance in the surrounding. These factors can be divided in two groups :

Can not be influenced	**Can be influenced**
Variation in load during the day/week in the store	“Over load” and food at the return grille for example
Disturbance caused by traffic in the air curtain (customers)	Ambient condition
	Variation in air flow
	Disturbance in the surrounding

Overload and food at wrong places in the cabinet can be handled with “load limits” and information. Both a decrease in the ambient dry temperature and relative humidity will decrease the energy consumption and facilitate the temperature quality. The climate depends both on the cold spillage from the cabinet itself and the HVAC system.

Variation in the air flow through the cabinet can be eliminated with a good strategy for defrosting and maintenance (cleaning of the cabinet regularly). It is possible to run the cabinet without defrost with a higher inlet temperature of the secondary coolant if infiltration is reduced and a larger air coil surface / more efficient air coils are installed.

Hayes among others reports that the air curtain is sensitive for wind. Bobbo, Cortella et al. (1995) for example has performed both experimental studies and simulations in open display freezer cabinets with a side wind of 0.15 m/s and 0.28 m/s. At the higher velocity the cabinet failed to achieve the correct operation and the temperature in the load increased. The installations in the surrounding of the cabinets are therefore important.

Both variation in load and customer traffic caused by the cycle in the store must be accepted and the construction must handle it. The results from CFD simulation showed that the air velocity from the rear is strongly affected by variations in the load. In the theoretical study on air curtains the deflection modulus was defined. A optimum inlet velocity can be reached for a certain H/b_o relation for a air curtain. A safty factor must be used to assure that the curtain stabilizes after a disturbance. With a wider curtain the heat transfer will be decreased and according to Hayes the gain can be in the order of 10%.

The deflection modulus is the relation between the momentum in the curtain and the horizontal force. In the theoretical study only horizontal forces caused by temperature difference between the cold interior area and the warm ambient were mentioned.

The air curtain will deflect and bend inward the cold cabinet. The position of the deflection depends on the outlet momentum and the temperature difference. In the transition zone the outlet momentum is constant and the first part of the curtain can be compared with a “wall”. In the established zone the momentum will decrease and somewhere the curtain will deflect. The counteracting force caused by the momentum from air flow from the rear must be taken into account. The velocity from the rear is influenced by variations in the load. If the air distribution from the rear is changed also the “ balance point for the curtain is changed”. The supply from the rear shall 1) cool the food and 2) stabilize the curtain. The need for cooling and the need for momentum from the rear will probably not coincide. With experience from experiments, the supply of cool air should be at the largest levels in the bottom shelf to keep the temperature quality in the food. Figure 9 illustrates the principle behaviour of the air curtain the shape of the curtain indicate that the momentum from the rear should be zero in the bottom of the cabinet. Therefore new construction for the air supplied for the cooling of the load is necessary. With air supplied in a way so the influence of the load arrangement can be neglected. The optimal design would be if the cooling supply could be separated from the function of the air curtain.

An IR camera is useful for visualization of the temperature distribution in the air curtain.

Cabinets installed in a store today can vary with approximately a factor 4 in energy consumption. The cabinets are mostly connected to a central system and the cabinet with the lowest inlet temperature will put the limit for the evaporation temperature. New energy efficient vertical display cabinets with high inlet temperature of the secondary coolant makes it possible to run the cabinet with no defrost at all. This saves both energy and costs for defrost equipment.

Figure 10 shows that the cooling capacity is directly proportional to the enthalpy difference between the inner and outer atmosphere. Therefore it is probably possible to calculate the cooling capacity for different climate condition in the ambient from experimental results performed at two different climate conditions. The cooling capacity is influenced by the store ambient condition and the mean temperature in the food.

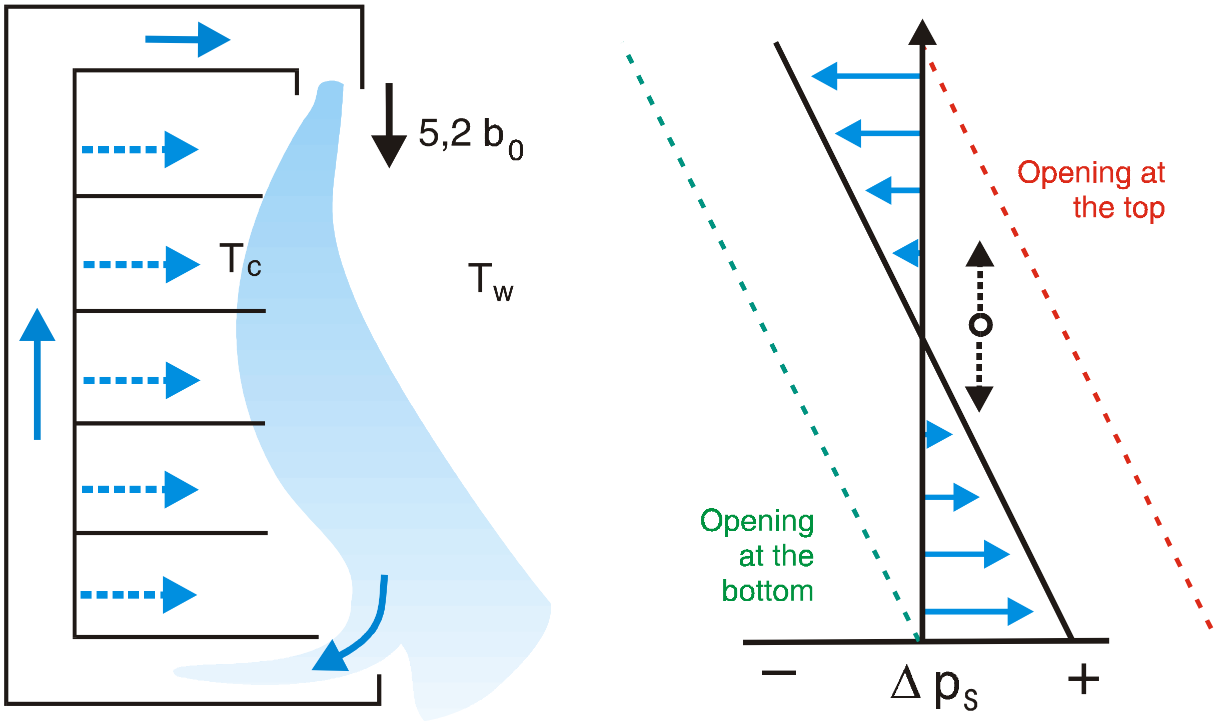


Figure 9. *The principle function of an air curtain. The figure illustrate the deflection when Tc < Tw*

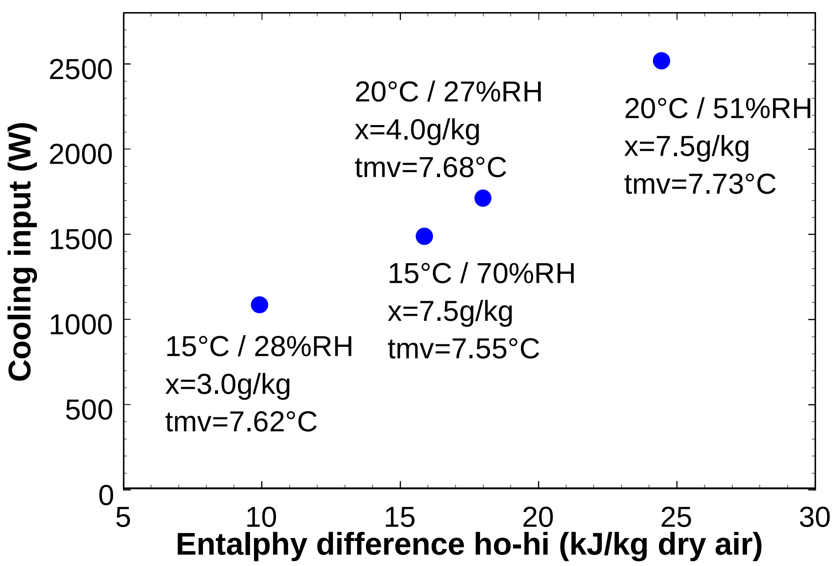


Figure 10. *Cooling input versus entalphy difference between inner and outer atmosphere.*

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