NOVEL AEROFOILS USED FOR REDUCING ENERGY CONSUMPTION AND IMPROVING TEMPERATURE PERFORMANCE FOR MULTI-DECK REFRIGERATED DISPLAY CABINETS

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ABSTRACT

The paper presents a study of the impact of using air guides attached to the front of the shelves in an open fronted multi-deck refrigerated display cabinet (ODC). A 2D computational fluid dynamics (CFD) model of an ODC was created. The infiltration heat loads with and without the guides were predicted. A higher infiltration heat load without the guides was predicted than when the guides were fitted. The reduction in entrainment was predicted to be 34% equating to an overall reduction in heat load of 24%. Two cabinets were tested with and without the guides to the EN23953 test standard. Adding the air guides reduced the maximum temperature test pack by 0.6ºC as well as reducing the energy consumption by 15%. When the cabinet controller was adjusted so that the maximum pack temperatures were the same for the two tests, the aerofoils reduced energy consumption by 17%.

1. INTRODUCTION

Open fronted multi-deck refrigerated display cabinets (ODCs) are commonly used to store food in retail outlets. The benefit of ODCs is that they present no barrier to customers. Glass door display cabinets (GDCs) can be problematic in narrow aisles due to open hinged doors blocking the aisle. Sliding doors do not block the aisle but when a door is slid open it blocks the other side of the cabinet stopping a potential sale.

ODCs use an air curtain to provide a barrier between the cold food inside and the warm air outside. The air curtain is a jet of cold air which discharges downwards from a duct at the top front of the cabinet at approximately 1 m/s. As the ODC contains colder air than its surroundings, the air naturally wants to fall out of the cabinet due to gravity (cold air is denser than warm air). This causes the air curtain to bend in towards the cabinet at the top and cold air to spill out of the cabinet at the bottom. Cold air is also discharged through slots/holes in the rear duct, partly to cool the product on the shelves but also to pressurise the cabinet and stop the warm air bending in towards the cabinet. The air curtain entrains warm air into it which warms the curtain and eventually enters the cabinet. According to Howell and Adams (1991), up to 75% of the total cooling load of a vertical ODC is due to the infiltration of outside air through the air curtain.

The bending of the air curtain and entrainment causes heat and moisture (warm ambient air contains more moisture than the cold refrigerated air) to enter the cabinet. This means that ODCs use more energy than equivalent GDCs. Evans (2014) presented information reported by various authors, which stated that glass doors could save between 25 and 86% of the energy used by ODCs. Much of the variability in reported savings can be related to the frequency and duration of door opening. ODCs also have a larger range in temperature than GDCs. Evans, Scarcelli and Swain (2007) found an average temperature range of 5.1ºC for GDCs and 8.6ºC for ODCs. This means that it is more difficult for ODCs to maintain safe temperatures in the warmest location in the cabinet (the front product) without freezing the coldest (rear) product. Increased warm moist air entrainment can lead to defrosting problems in ODCs. The cold spillage from ODCs also causes the aisles of supermarkets to be cold and during the winter supermarkets are required to add heat into the store to counteract this.

This paper presents novel air guides (patent filed) mounted on the shelves of ODCs to reduce entrainment and thus reduce energy consumption and temperature performance of ODCs. The guides were first numerically modelled using CFD to see the effect and finally tested on two different ODCs.

2. CFD MODEL

A steady state two dimensional representation of an open-fronted multi-deck refrigerated display cabinet was modelled using Ansys CFX 14.5 CFD code. Heat transfer by convection between the ambient and the refrigerated air curtain was modelled. Buoyancy was modelled using the Bousinesq approximation. The temperatures of food products on the shelves were not modelled, nor were effects of thermal radiation or humidity. Parameters of the model are shown below.

- Ambient temperature outside of the cabinet = 25°C
- Temperature of air curtain and rear panel flow = -1°C
- Mass flow rate of air curtain = 1 kg/s per metre length
- Flow rate through rear panel = 1 kg/s per metre length
- Number of shelves = 5 + well
- Depth of shelves and well = 500 mm
- Distance between shelves = 300 mm
- Height of product on shelf = 150 mm
- Height of shelf = 40 mm
- Depth of discharge and return grille = 100 mm
- Aerofoil (air guide) type = NACA4314 (non-symmetric)
- Aerofoil length = 40 mm
- Distance from aerofoil to shelf = 100 mm
- Inside of discharge grille in line with edge of shelf
- Outside of discharge grille in line with edge of aerofoil

3. CFD PREDICTIONS

A multi-deck cabinet with air guides and an identical cabinet without air-guides were modelled so that a direct comparison of the effect of air guides could be made. The shape of the air guides was an aerofoil of type NACA4314. The numerical mesh and all other modelling parameters were kept as similar as possible, so that only differences due to the air guides would be apparent.

Figure 1 shows velocity vectors for the unmodified and air-guide cabinet. Although the unmodified cabinet appears to show air guides, these are not actually there and are a consequence of making the meshes similar (such that differences in results could not be attributed to different meshes). Velocity vectors were very similar for the two scenarios.

Figure 2 shows temperature contours for the unmodified and air-guide cabinet. The diagram shows that there is more mixing between the cold (cabinet) and warm (ambient) environments without the air guides. This can be seen by the air curtain getting wider in the unmodified scenario and the cold spillage onto the floor increasing.

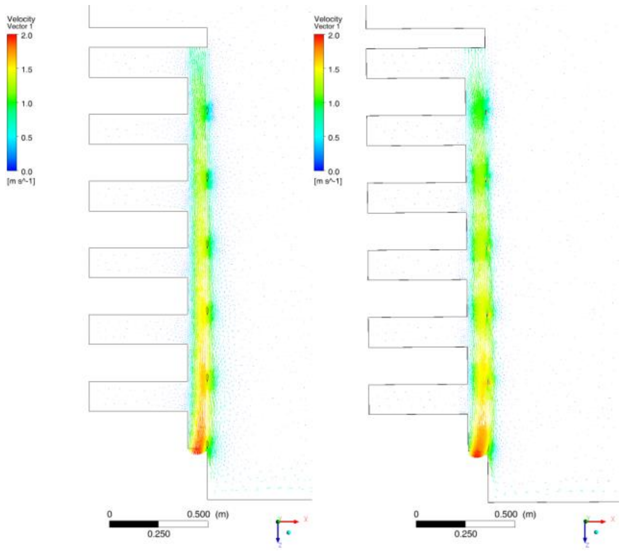

Figure 1. Velocity vectors for the unmodified (left) and air-guide cabinet (right).

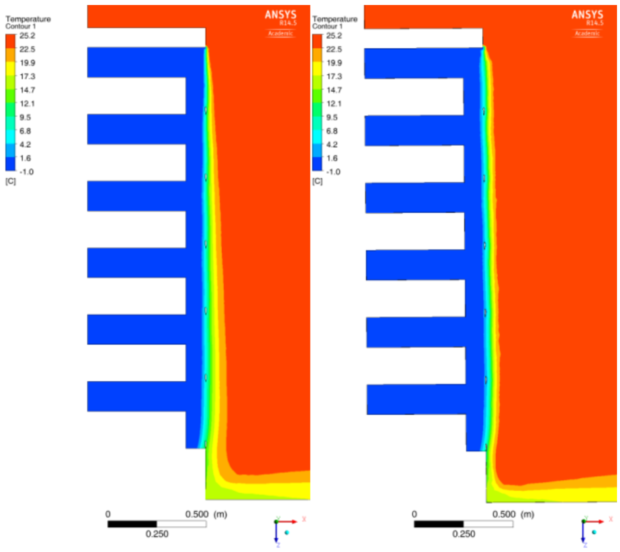

Figure 2. Temperature contours for the unmodified (left) and air-guide cabinet (right)

Figure 3 shows streamlines (coloured for turbulent kinetic energy) for the unmodified and air-guide cabinet. The diagram shows that turbulent kinetic energy increases much more as the air curtain progresses from discharge to return in the un-modified cabinet.

Figure 4 shows streamlines (coloured for velocity) and temperature contours for the unmodified and air-guide cabinet zoomed in to the 3rd shelf from the top. It can be seen from the diagram that the warm air entrains further towards the unmodified cabinet and that velocities are higher close to the shelf for the unmodified cabinet.

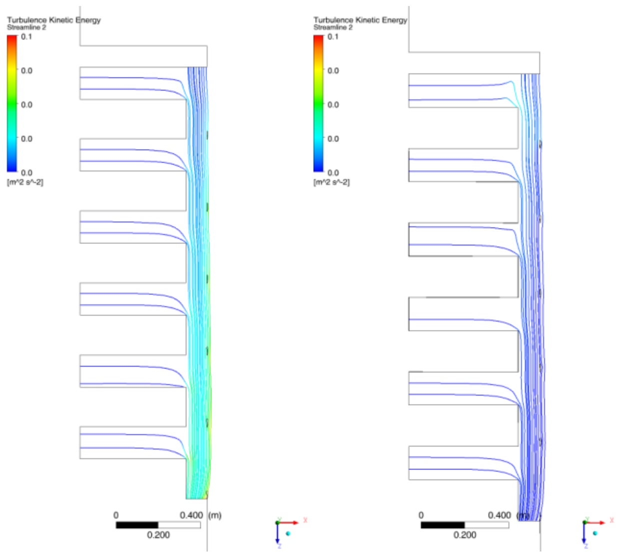

Figure 3. Streamlines for the unmodified (left) and air-guide cabinet (right). The streamlines have been coloured to represent the turbulent kinetic energy.

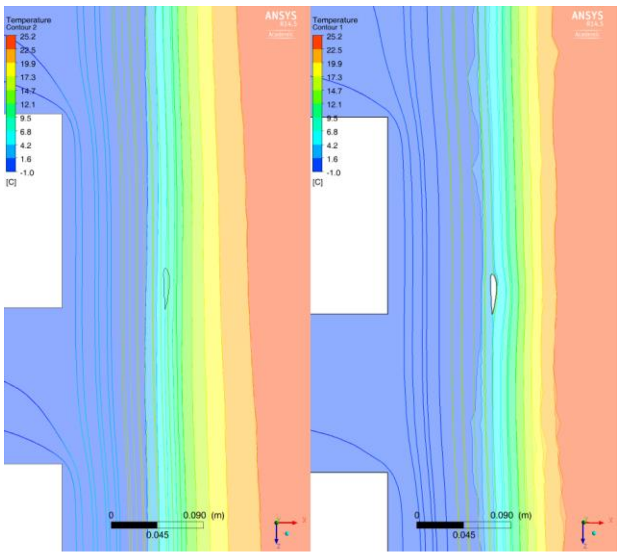

Figure 4. Streamlines (coloured for velocity) and temperature contours for the unmodified (left) and air-guide cabinet (right) at the third shelf down.

The temperature and enthalpy increases from the discharge to the return are shown in Table 1. The temperature and enthalpy increases (per metre length of cabinet) come from entrainment between the warm ambient and cold air curtain. In the case with air guides the entrainment is only 66% of the case without aerofoils, showing a reduction of entrainment of 34%. Table 1 also shows the domain imbalance, a numerical error which reduces as the model becomes more accurate. For the results to be valid it should be lower than the differences you are trying to detect, which in this case it is. Table 1 also shows the number of iterations made in each model.

Table 1. Temperature and enthalpy increases from discharge to return, domain imbalance, number of iterations and tetrahedral elements.

Scenario	**Temp increase (K)**	**Enthalpy increase (W/m)**	**Domain inbalance (W/m)**	**Number of iterations**
No aerofoils	3.3	650	2.0	1170
Aerofoils	2.2	430	0.2	1180

4. CONFIDENCE IN NUMERICAL RESULTS

The model was initially solved to an RMS residual of $1x10^{-4}$. This was reduced to $1x10^{-5}$ in the final calculations. $1x10^{-5}$ is good convergence, and usually sufficient for most engineering applications. There was no appreciable difference in the results (similar benefit from aerofoils) between the two solutions, showing that further reduction in RMS residual was not necessary.

The mesh was refined, particularly in the region of the air curtain and there was no appreciable difference in the results (similar benefit from aerofoils) between the two solutions, showing that further refinement of the mesh was not necessary.

The k-ε turbulence model was used initially. For general purpose simulations, the k-ε model offers a good compromise in terms of accuracy and robustness. In general, turbulence models based on the ε-equation predict the onset of separation too late and under-predict the amount of separation later on. This is problematic, as this behaviour gives an overly optimistic performance characteristic for an aerofoil.

As the amount of the entrainment in the two solutions was found to be very dependent on the level of turbulence, another turbulence model was used for the final solution. The k-ω based Shear-Stress-Transport (SST) model was designed to give highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy-viscosity. This results in a major improvement in terms of flow separation predictions. Results using the two models did not vary appreciably and therefore it was felt that the results given were accurate.

5. MEASUREMENT METHOD

Tests were carried out on two different ODCs (Table 2) both with integrated R404A refrigeration systems. The tests were carried out in a test room conforming to the EN23953:2005 standard. During the tests, the room conditions were maintained within climate class 3 (25°C and 60% RH).

Table 2. Details of the cabinets.

Model	Cabinet A	Cabinet B
Shelf width (mm)	2500	1250
Shelf depth (mm)	444	387
Well depth (mm)	490	467
Number of shelves	5	4
Total Display Area (TDA) (m^2)	3.82	1.63

The cabinets were loaded with standard ‘m’ packs (packs and loading as specified in the EN23953:2005 test standard). Twelve measurement positions were sited on three of the shelves and in the well. The temperature measurement packs on the shelves and well were placed at the edges and centre of the cabinet at the rear and front of the shelves at the bottom and top of the stack of packs. Each measurement pack had a calibrated ‘t’ type thermocouple (copper-constantan) inserted into the geometric centre of the pack.

A power meter (Northern Design, MultiCube) was connected with the stabilised mains electrical supply (230 V) to monitor and record electrical power. This power consumption is known as the direct electrical consumption (DEC).

During all tests, temperatures of the 'm' packs, air temperatures downstream and upstream of the evaporator, relative humidity and power were recorded every minute using a data logging system (Orchestrator software and Datascan measurement modules, Measurement Systems Ltd.).

Three tests were carried out for Cabinet A:

1. A baseline test with the cabinet in its original configuration at the default (delivered) controller settings.
2. A test at the same controller settings as in test 1 but with the novel air guides fitted. Details of the guides and their fitting are described below.
3. A test with the air guides fitted but the cabinet controller adjusted so that the maximum ‘m’ pack temperature was the same as in test 1.

Two tests were carried out for Cabinet B:

1. A baseline test. The aim was for the cabinet to achieve the M2 classification (all ‘m’ packs must be equal to or greater than -1 and equal to or less than 7°C throughout the test). To achieve this, the cabinet was operated with a set point that caused the cabinet to run continuously except during the controller forced off cycles and defrosts.
2. A test with the air guides fitted but the cabinet set point adjusted to provide approximately the same maximum test pack temperature as in 1.

In all tests the temperature performance and energy consumption (according to the EN23953:2005 test standard) was recorded over a 24-hour period. During tests the cabinet lights were switched on for 12 hours during the test period in accordance with the requirements for the UK ECA (2010) scheme.

6. AIR GUIDES

The metal air guides were aerofoil shaped (Figure 5) of maximum dimensions 45 x 6 mm. The air guides were located at a distance of 85±3 mm between the outer edge of the ticket strip and the inner edge of the aerofoil (minimum gap) and were approximately vertical. The air guides were slotted into brackets which were bolted to the ends of the shelves (Figure 6).

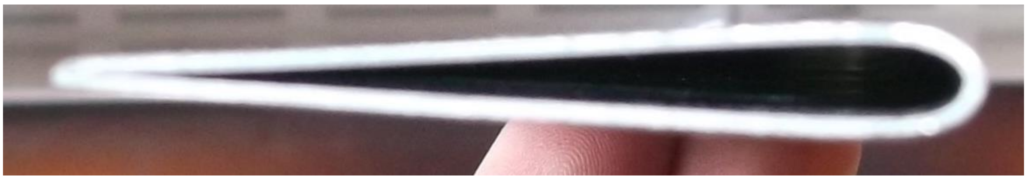

Figure 5 (left). Close up of profile air guide.

Figure 6 (right). Air guide and its attachment to the shelf.

7. MEASUREMENT RESULTS

When the air guides were fitted to Cabinet A, the ticket strips were removed. This was partly because the air guides in practise would replace ticket strips, but also because fitting of the brackets which held on the air guides required removal of the ticket strips.

Initial results of the test with aerofoil showed temperatures rising and energy increasing. Therefore ticket strips were put back on the shelves (this required cutting of the ticket strips such that they did not interfere with the air guide brackets. All results shown with air guides are with ticket strips in place.

For Cabinet B the aerofoil mounting was changed such that the tickets strips did not need to be removed.

When the aerofoils were fitted to Cabinet A the maximum temperature reduced by 0.6ºC and the energy consumption reduced by 15% (Table 2). When the set point temperature was raised to give the same maximum temperature, the energy consumption was 17% lower than with no aerofoils.

Table 3. Results for Cabinet A with and without aerofoils.

	No aerofoils	Aerofoils	Aerofoils at same maximum temperature
Overall maximum temperature (°C)	7.7	7.1	7.7
Overall minimum temperature (°C)	0.3	0.6	1.4
Overall mean (all packs) (°C)	3.8	3.8	4.4
Overall mean of visible packs (°C)	4.0	4.0	4.7
Energy consumed (TEC) (kWh/24h)	19.32	16.35	16.10
TDA (Total Display Area) (m^2)	1.63	1.63	1.63
TEC/TDA (kWh/24h/m^2)	**11.82**	**10.00**	**9.85**

When the aerofoils were fitted to Cabinet B and the temperature raised to give a similar maximum temperature, the energy consumption reduced by 17% (Table 3). The minimum pack temperature was also raised by 1ºC.

Table 4. Results for Cabinet B with and without aerofoils.

	No aerofoils	Aerofoils
Overall maximum temperature (°C)	7.4	7.5
Overall minimum temperature (°C)	-0.3	0.7
Overall mean (all packs) (°C)	3.4	3.9
Overall mean of visible packs (°C)	4.9	5.2
Energy consumed (TEC) (kWh/24h)	43.43	35.88
TDA (Total Display Area) (m^2)	3.82	3.82
TEC/TDA (kWh/24h/m^2)	**11.36**	**9.38**
ECA threshold for M2 cabinets (kWh/24h/m^2)	11.60	11.60

8. DISCUSSION

The numerical model of the air guides showed a reduction in infiltration of 34% compared to not having air guides. As the infiltration of a chilled multi-deck display cabinet is approximately 70% of the total load, this would equate to a reduction in heat load of approximately 24%.

Adding the novel air guides to cabinet A reduced the maximum temperature 'm' pack by 0.6°C and the energy by 15%. When the cabinet controller was adjusted so that the maximum 'm' pack temperatures were the same, the aerofoils reduced energy by 17%. Adding aerofoils to Cabinet A also resulted in a 17% reduction in energy for a comparable maximum 'm' pack temperature.

The measured results are in the same order although slightly worse than the predicted results.

9. CONCLUSIONS

The aerofoils have been predicted and measured to have a positive effect on reducing the energy consumption of an ODC. They also have the benefit in reducing maximum pack temperature and therefore either allowing a lower temperature to be reached, increasing storage life of the product or raising the set point and further increasing energy savings.

Changing the position of the aerofoils, their angle to the airflow, their shape and size may all have a positive or negative effect on the results; this is the subject of further studies.

10. REFERENCES

1. Howell R, Adams P. 1991, Effects of indoor space conditions on refrigerated display case performance. ASHRAE Research Project 596-RP. Department of Mechanical Engineering. University of South Florida, Tampa.
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