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USE OF HEAT PIPES TO IMPROVE TEMPERATURE PERFORMANCE OF A CHILLED REFRIGERATED DISPLAY CABINET

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ABSTRACT

A heat pipe was used to provide cooling to the front of the shelf of a glass door refrigerated display cabinet. The heat pipe reduced the core temperature of the test pack above it by 0.2 K. A thermal imaging camera was used to ascertain boundary conditions for a CFD model which then predicted a reduction in the core temperature of the test pack above the heat pipe by 0.5 K The reason for the limited benefit of the heat pipe measured and predicted was that the temperature of the shelf below the front pack was only slightly higher than the heat pipe cooling it. Using the thermal imaging camera and the CFD model, the predictions were extended to an open fronted cabinet. The heat pipe was predicted to reduce the core temperature of the test pack above it by 1.7 K Heat pipes were shown to be of more benefit in open fronted than glass door cabinets.

1. INTRODUCTION

Nunes et al (2009) showed a wide variation in temperatures measured inside refrigerated retail display cabinets, ranging from −1.2 °C to 19.2 °C. Poor temperature management was found to be the major cause of produce waste (55%).

Evans, Scarcelli and Swain (2007) reported that 97% of maximum temperature packs were located at the front of an open fronted chilled multi-deck cabinet and 94% at the front of a chilled glass door cabinet. This is because the food at the front of a cabinet is exposed to thermal radiation and air infiltration, whereas food at the rear is shaded from radiation and infiltration.

Reducing the temperature range of these cabinets whilst maintaining the maximum temperature allows the set point temperature to be increased. This improves energy consumption and reduces the chances of the cabinet evaporator icing and of product freezing. A mechanism to transfer more heat from the front packs to cooler regions, e.g. the rear duct of the cabinet, would allow for improved temperature control.

A heat pipe is a heat transfer device that uses phase change (latent heat) to provide high heat transfer. The heat pipe contains a saturated fluid. At the end which is warmest, the liquid in the pipe will evaporate, absorbing heat from its surroundings. The vapour then travels along the heat pipe to the other end, which is coldest, where it will condense into a liquid, releasing latent heat. The liquid can either return to the warm end via gravity or capillary action and the cycle repeats. Due to the very high heat transfer coefficient for boiling and condensation, the heat pipe is a very good thermal conductor. The effective thermal conductivity varies with heat pipe length and other characteristics between 10 to 10,000 times that of copper.

Maidment et al (2005) developed a finite difference model to study the application of a heat pipe on a refrigerated retail display cabinet. The results indicated that the heat pipes could provide improved heat transfer, which could contribute to lowering core food temperatures by approximately 2.5 to 3.5 K.

Lu et al (2010) fitted a shelf with heat pipes with an inclined condenser in one end and showed a reduction in food core temperatures of approximately 3.0 to 5.5 K.

Currently the application of heat pipes has only been to open fronted refrigerated display cabinets. Evans (2014) has shown that open fronted chilled cabinets are in many cases being replaced by cabinets with glass doors, due to environmental concerns regarding energy efficiency. The aim of this work was to use heat pipes to reduce the temperature gradient between the front and rear of a refrigerated display cabinet with glass doors.

3. EXPERIMENTAL METHOD

A heat pipe of 18 mm outside diameter copper tube with an unknown refrigerant and wick and length of 500 mm was used to provide cooling to the front of the shelf of an Epta glass door cabinet. The heat pipe had fins (40 x 40 mm) on one of the ends.

The cabinet had 4 shelves and a base. The heat pipe was attached to the underside of shelf 3 (third shelf from the top). The non-finned end was attached by two aluminium pipe supports which were in turn screwed into an aluminium plate (200 x 50 x 12.5 mm) which was fixed to the underside of the shelf (Figure 2). Silicone based heat transfer compound was used between all connections to allow good thermal contact. The axis of the heat pipe was positioned 125 mm from the end of the shelf.

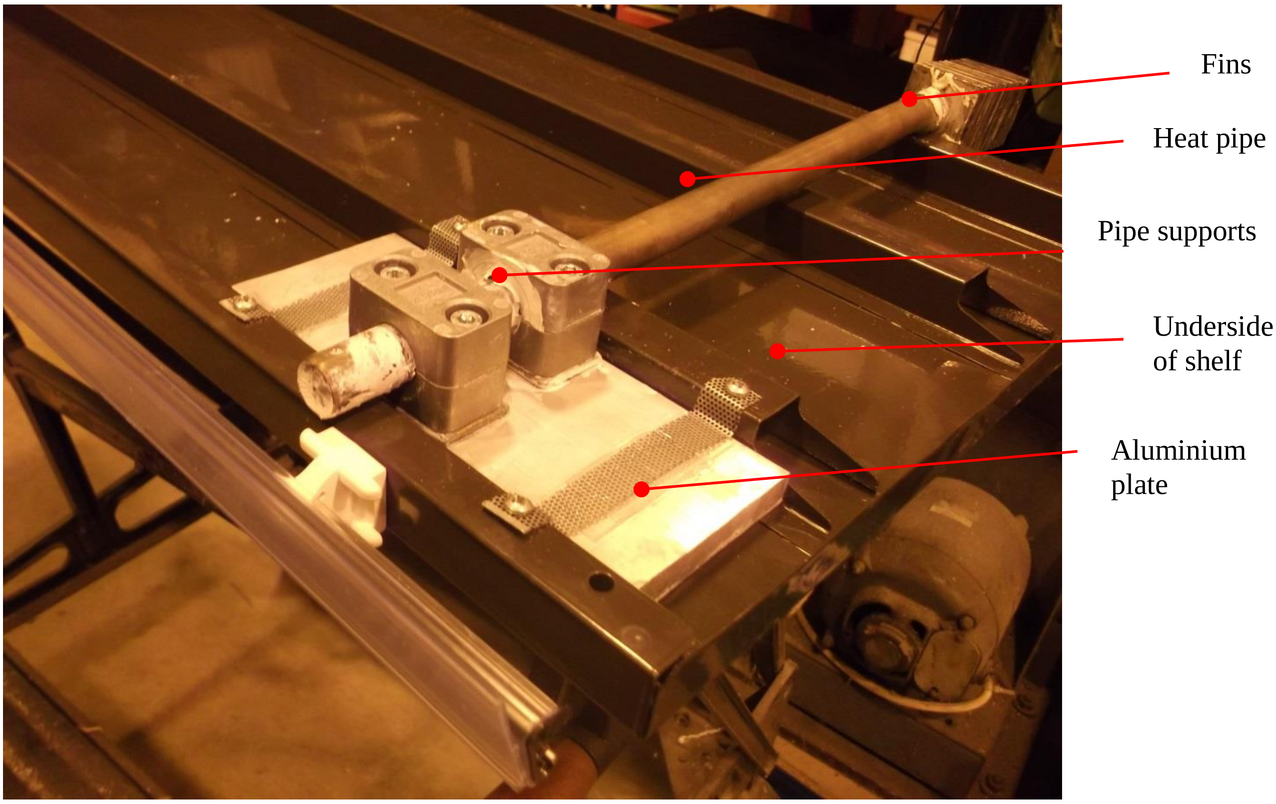

Figure 1. Heat pipe assembly attached to the bottom of the shelf.

A hole was drilled into the back perforated panel under the shelf and the finned end of the heat pipe was inserted.

The cabinet was loaded with a combination of Tylose packs in the centre and ends of the shelves and polyurethane insulation in between. The packs and insulation were loaded as they would be for the EN23953 standard. The cabinet was tested in CC3 conditions (25ºC and 60% RH).

T-type thermocouples were;

- inserted through the perforated rear panel near to the finned end of the heat pipe.
- attached to the front of the heat pipe
- positioned between the shelf and an ‘m’ pack (Tylose pack with thermocouple inserted in the centre)
- positioned in the ‘m’ pack above the shelf.

4. EXPERIMENTAL RESULTS

To see the effect of the heat pipe, the temperatures were recorded for a period with the heat pipe connected, then the heat pipe was disconnected and temperatures allowed to stabilise before reconnecting it again

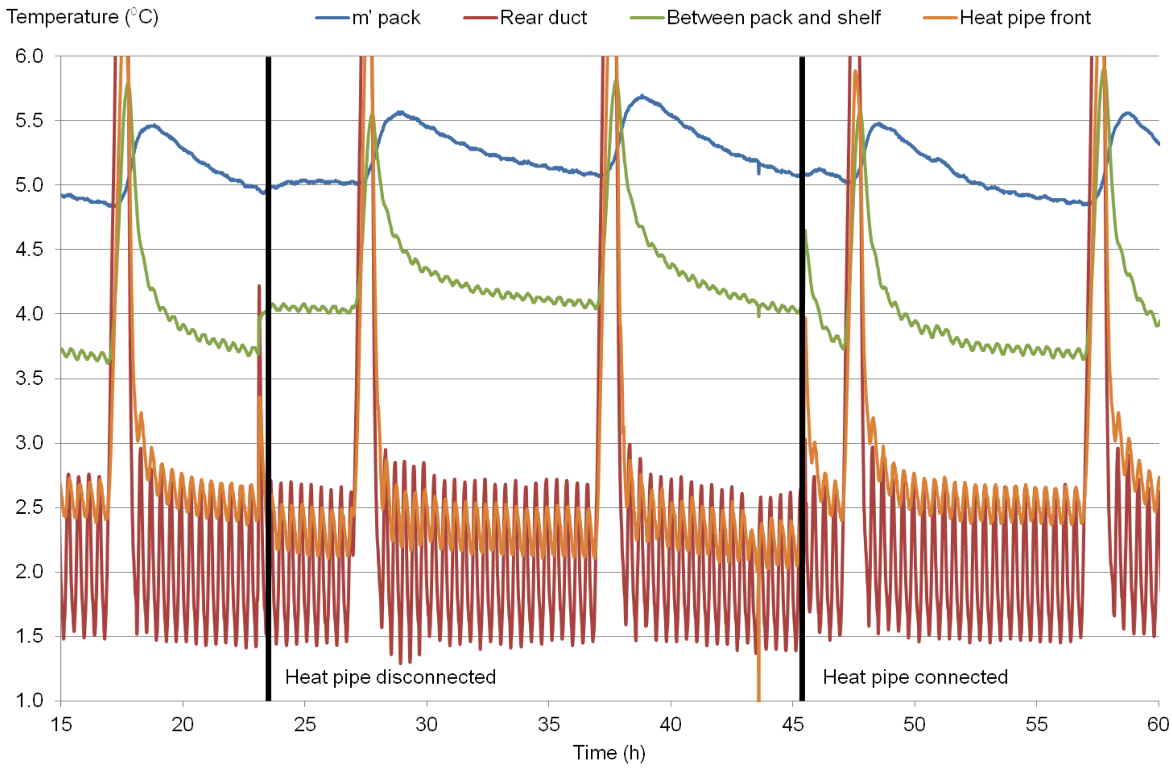

Figure 2. Temperatures measured during a test with originally heat pipe connected, then disconnected, then connected again.

With the heat pipe connected the 'm' pack above it reached a minimum temperature of 4.9ºC (at the end of a cycle). Without the heat pipe the same pack reached a temperature of 5.1ºC. Therefore the heat pipe improved the temperature of the 'm' pack above it by 0.2 K. A greater reduction in temperature was seen between the pack and shelf, where the minimum temperature reduced from 4.1 to 3.6ºC, a 0.5 K reduction. The temperature of the front of the heat pipe reduced when it was disconnected from the shelf from a minimum of 2.4 to 2.1ºC, this was because the heat pipe was not being warmed by the shelf.

There was a large temperature difference between the 'm' pack and the front of the heat pipe (2.4 K). The temperature difference between the 'm' pack and shelf was half way between the temperature of the front of the heat pipe and the 'm' pack internal temperature, showing that there was the same level of thermal resistance between the heat pipe and shelf as between the shelf and centre of the 'm' pack.

The temperature difference between the front of the heat pipe and the air in the rear duct was approximately 0.5 K showing that the heat pipe was working effectively.

4. THERMAL IMAGE

A thermal imaging camera (Fluke TiR32) was used to ascertain boundary condition data for a CFD model (described later) and also to validate the CFD predictions.

Figure 3 shows the thermal image for a test where the heat pipe was connected and disconnected from the underside of the shelf. The images were taken at similar points in the refrigeration cycle (towards the end of a refrigeration cycle). However, it was not easy to take images at exactly the same point in the cycle, therefore the actual temperatures measured between images are not directly comparable, it is more important to consider the differences in temperatures within the same image.

The heat pipe was approximately the same temperature when connected and disconnected from the shelf (3.7 to 4.3ºC). The heat pipe is shown to be colder than the shelf it is attached to, however, only by about 0.5 to 1 K Therefore the benefit of the heat pipe to cooling the shelf is limited. The reduction in 'm' pack temperature of 0.2 Kmeasured by thermocouples matches the data from the thermal images.

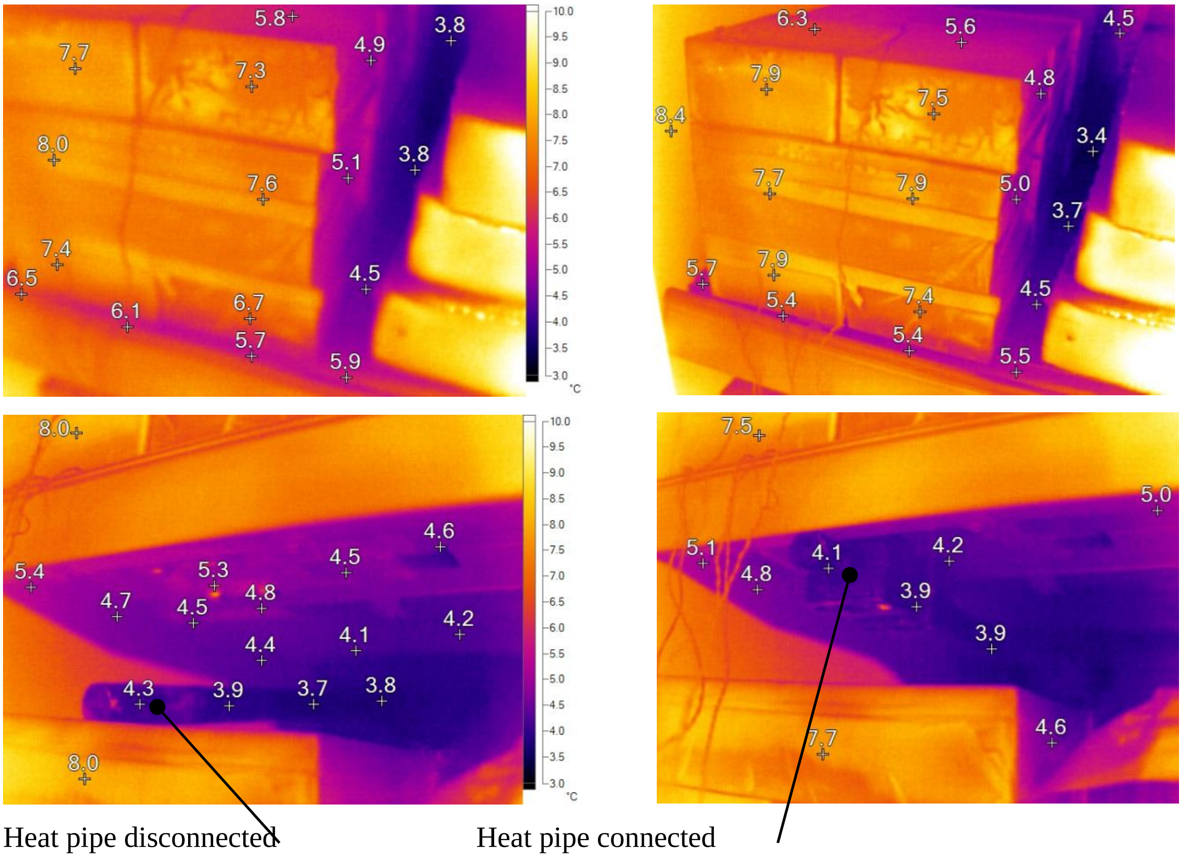

Figure 3. Temperatures shown by the thermal imaging camera when the heat pipe was connected and disconnected to the underside of the shelf.

5. PREDICTIVE MODEL

An Ansys Fluent (Version 14.5) CFD model was used to predict the effect of a heat pipe attached to the underside of the shelf. The model was steady state, with heat transfer to the surfaces of the materials being predicted by setting a heat transfer coefficient and free stream temperature. Fluid flow was not modelled, only conductive heat transfer through the solids. The thermal conductivities of the solid materials are shown in Table 1.

Table 1. Thermal conductivities of the materials in the CFD model

Material	Thermal conductivity (W/mK)
Heat pipe	5000
Shelf and pipe bracket	202
Tylose	0.5

The boundary conditions of the surfaces used in the model are shown in Table 2.

Table 2. Surface boundary conditions used in the CFD model

Surface	Free stream Temperature (ºC)	Heat transfer coefficient (W/m^{2}K)
Finned (cold) end of heat pipe	3	32,800 (this is large to take into account the increased surface area of finning)
Front of packs	10	15
Rear and top packs	3	5

Shelf	3	5
Rest of heat pipe	3	5

Figure 4 shows temperature contours predicted with and without a heat pipe. Although the no heat pipe image shows a heat pipe, it thermally has no effect (heat transfer coefficient at the finned end is set to 0). The heat pipe is shown to provide cooling to the shelf, with the temperature of the shelf under the pack 4.2ºC with no heat pipe and 3.5ºC with a heat pipe.

The 'm' pack above the heat pipe was predicted to be at a centre temperature of 4.3ºC with, and 4.8ºC without the heat pipe. Therefore the heat pipe was predicted to reduce the 'm' pack temperature by 0.5 K

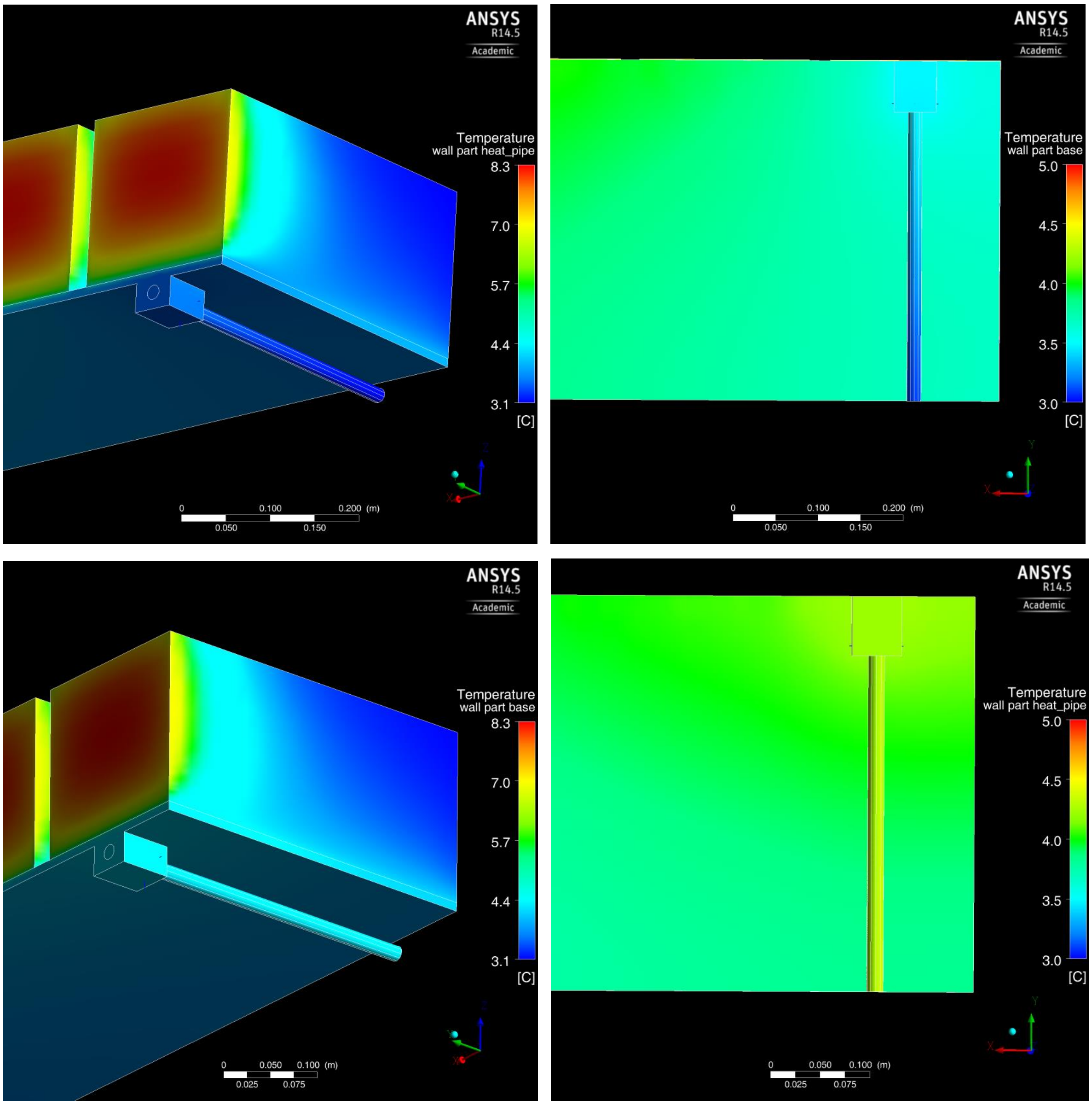

Figure 4. Temperature contours with (top) and without a heat pipe (bottom). Diagrams on left show a view from the front and underside of shelf. Diagrams on right show a view from the underside of the shelf.

6. GLASS DOOR CABINET CONCLUSIONS

A heat pipe has been shown to benefit the 'm' pack closest to it (front of shelf near end wall) by reducing its temperature by 0.2 K This is lower than the predicted reduction of 0.5 K This difference is probably due to the surface heat transfer boundary conditions. Instead of having a fixed free stream temperature and heat transfer coefficient, it would probably be more accurate to model the air flow over the packs and the heat transfer to the front of the packs caused by radiation.

Heat pipes do not have the expected benefits, either predicted or measured. The reason for this is that the temperature of the shelf is only slightly higher than the heat pipe (when the heat pipe is not attached). Therefore, attaching the heat pipe can only reduce the shelf temperature by a small amount.

It is possible to increase the number of heat pipes on the shelf, however, CFD predictions showed the benefits of this were very small.

If there was a much larger temperature difference between the air in the rear duct and the front of the shelf, heat pipes would have a larger effect. This is more likely in an open fronted cabinet where air is entrained into the air curtain and towards the rear of the shelves.

6. MULTI-DECK CABINET

Thermal imaging was carried out on a multi-deck cabinet with sloping shelves and low loading (as used for sensitive products). This particular cabinet was unable to operate within the required temperature classification, as temperatures were too high.

Thermal imaging showed a much larger temperature gradient on the shelf than the glass-doored cabinet tested earlier. Surface temperature from front to back ranged from approximately 6 to 9ºC (Figure 5).

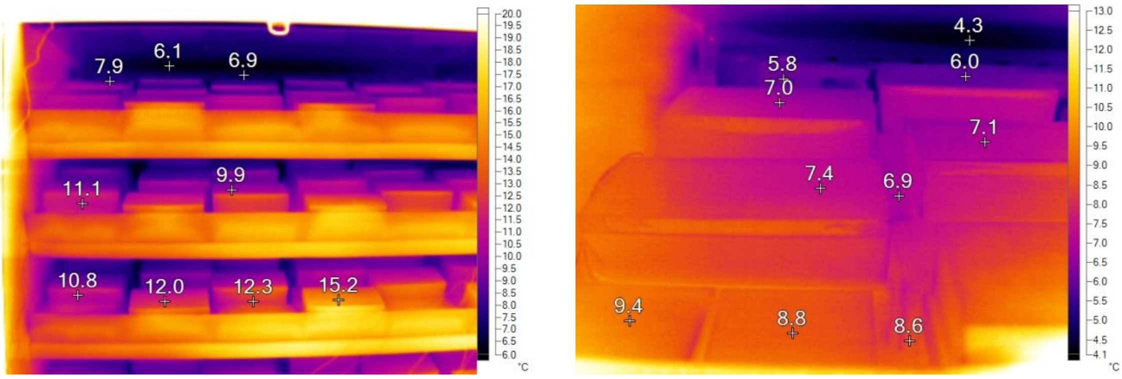

Figure 5. Temperatures shown by the thermal imaging on an open cabinet with sloping shelves.

Boundary conditions for the CFD model were set such that they gave temperatures in the CFD model which were similar to those in the thermal image (Table 3). The CFD model was run with and without the heat pipe operating.

Table 3. Surface boundary conditions used in the CFD model of an open cabinet.

Surface	Free stream Temperature (ºC)	Heat transfer coefficient (W/m^{2}K)
Finned (cold) end of heat pipe	4	32,800 (this is large to take into account the increased surface area of finning)
Front of packs	15	30
Rear	4	20
Top packs	4	5
Shelf	Adiabatic	0
Rest of heat pipe	Adiabatic	0

The temperature of the shelf underneath the 'm' pack was predicted to be 7.9ºC with no heat pipe and 5.3ºC with a heat pipe (Figure 6).

The 'm' pack above the heat pipe was predicted to be at a centre temperature of 8.6ºC without and 6.9ºC with the heat pipe. Therefore the heat pipe was predicted to reduce the 'm' pack temperature by 1.7 K

This is over 3 times the benefit of that predicted for the glass door cabinet. However, the previous prediction overestimated the benefit on 'm' pack temperatures by a factor of 2.5. If the same over-prediction is assumed it may be expected that the 'm' pack temperatures would reduce by 0.7 K.

The benefit of heat pipes on the underside of a shelf is clearly more significant if there is a larger temperature gradient from front to back. Therefore heat pipes will be of more benefit in open fronted than glass door cabinets.

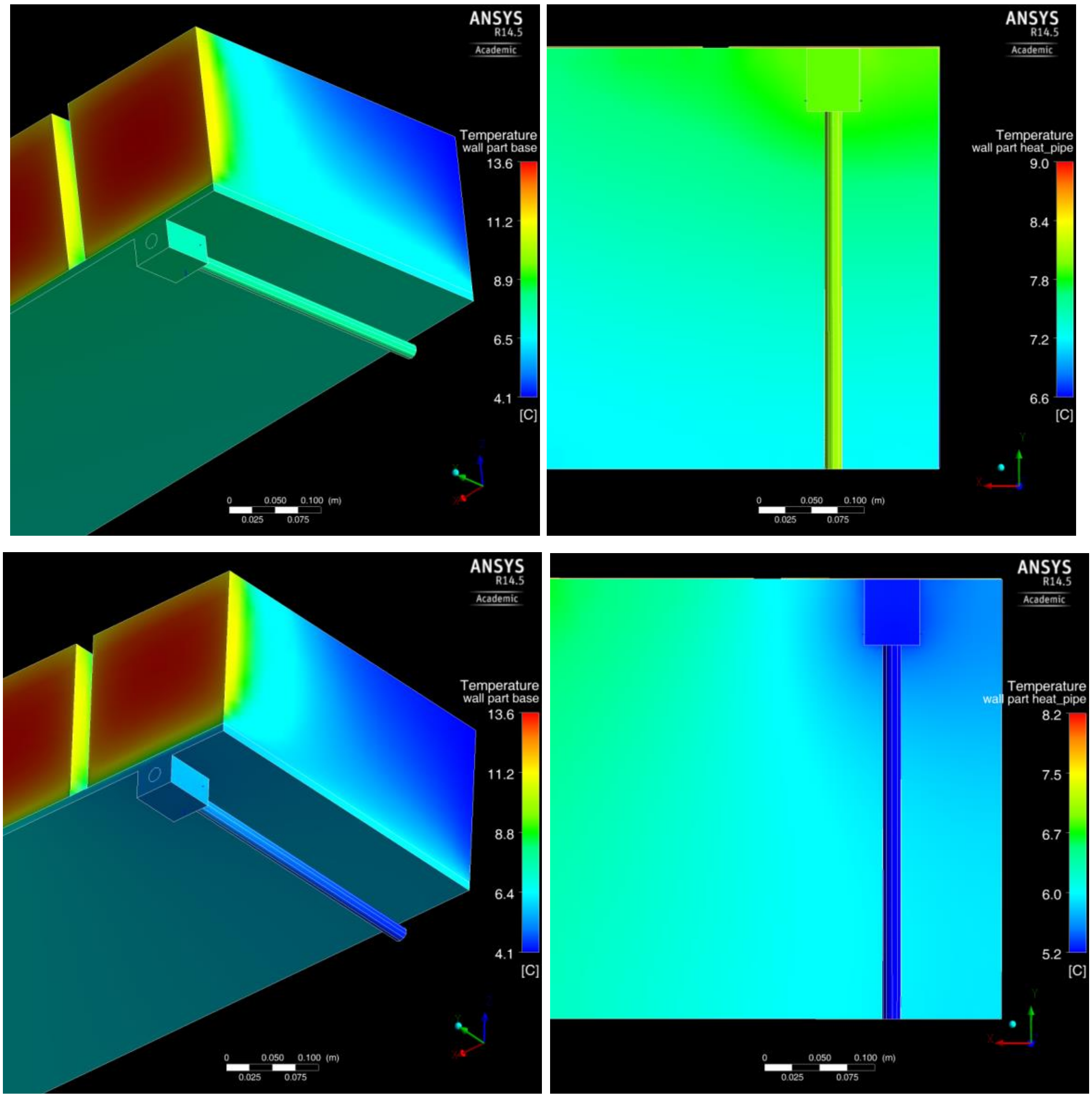

Figure 6.Temperature contours without (top) and with a heat pipe (bottom). Diagrams on left show a view from the front and underside of shelf. Diagrams on right show a view from the underside of the shelf.

7. OVERALL CONCLUSIONS

Heat pipes were predicted and experimentally shown to reduce the maximum 'm' pack temperature by 0.5 K and 0.2 K respectively for a glass door cabinet. For an open fronted multi-deck cabinet the predicted benefit was 2.5 K, although assuming the same level of accuracy in the prediction as for the glass door case, this would reduce to 0.7 K.

Reduction of maximum temperature in the cabinet allows an increase in the set point temperature which will allow a reduction in energy consumption. If we assume the energy consumption of the cabinet is proportional to the temperature difference between the ambient (assume 25ºC) and the average temperature of the air within the cabinet (assume 5ºC), then a 0.2ºC increase in the set point will yield a reduction in energy consumption of 1%. A 0.7 K reduction will yield a reduction in energy consumption of 3.5%. In reality, not all of the energy consumption will be proportional to temperature difference, for example, that due to lighting and fans, so the values given are an over estimate.

The heat pipes were hand made to order at a cost of £82.60 each for 10 units. The number of heat pipes required is dependent on where warm spots may exist on the shelves, however, if we assume only using heat pipes where 'm' packs are located on shelves (not the well) in an EN23953:2005 standard test, this would lead to 9 heat pipes at a cost of £743.40. As this is a significant additional cost of the cabinet, this would only be cost effective if the price could come down dramatically due to mass production.

8. ACKNOWLEDGEMENTS

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