The use of CFD to improve the performance of a chilled multi-deck retail display cabinet

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Abstract

Maintaining food temperatures below critical values is the key to maximising the high quality display life of chilled foods. Studies were carried out to see if computational fluid dynamic (CFD) modelling could be used to rapidly identify the changes that would be required to an existing multi-deck display cabinet so that it would meet a higher test specification. Implementing the changes on a Pastorfrigor MV 200TP display cabinet reduced the average power consumption from 1.37 to 1.29 kW as well as significantly reducing the number of test packs which spent any time above 4^{o}C, from 12 to 1.

Key words: Retail display; Airflow; Computational fluid dynamics (CFD), Modelling, Air curtain.

1. Introduction

In the UK, sales of chilled and frozen food in retail outlets was £83.68 billion in 2002 [1] and most is sold from refrigerated display cabinets. Being able to maintain the temperature of this food is of vital importance to retailers to ensure optimal food quality, safety and shelf life [2]. It has been shown that mean food temperatures between chilled multi-deck cabinets can range from -1°C to +16°C [3]. This range causes food manufacturers problems when defining shelf life and results in shelf lives that are either unduly cautious or potentially risky.

Most retail display cabinets within Europe are tested to the European testing standard, EN441 [4, 5, 6, 7]. Within EN441-6 [6] chilled cabinets are described as M1 if all the temperatures of test packs are maintained between –1 and 5°C, M2 if between –1 and 7°C or H if between 1 and 10°C. A further, more stringent, temperature classification M0 is often used in the UK to describe cabinets that maintains the temperature of all the test packs between 1 and 4°C.

The M0 classification was introduced exclusively for cabinets that display meat. By reducing the maximum temperature by 1 K, the storage life of fresh beef can be extended by approximately 1.5 days. Currently few cabinets conform to the M0 classification. A database of European cabinets recently collated by the authors contained over 45 integral multi-deck cabinets that were classified as M2, H1 or H2. Only one cabinet had the M0 category rating.

Open display cabinets are one of the weakest links in the chilled food chain [8] and large (>5 K) temperature differences are found in most cabinets. This is due to the technical difficulties in reducing the difference between the lowest temperature packs, which are usually, sited at the rear of the cabinet and the highest temperature packs, sited at the front of the cabinet. In the majority of multi-deck retail display cabinets the evaporator is in the base of the cabinet and fans blow air through the evaporator and up a duct at the rear of the cabinet. Air exits the duct through holes or slots in the cabinet rear grilles and into the cabinet. Air is also ducted above the ceiling and through a slot or honeycomb grille placed at the front of the cabinet canopy, termed the air-off grille. The purpose of the air-off grille is to create a vertical air curtain from the front of the cabinet canopy to a grille placed at the front of the cabinet well (termed the air-on grille). The air curtain creates a non-physical barrier between the cold air in the cabinet and the ambient air outside. Due to the air from the curtain being colder than the surrounding air it will also fall due to buoyancy. As the air curtain falls from the cabinet air-off duct, the curtain entrains cold air from inside the cabinet (entered through the rear grille) and warm air from the test room. The entrainment of warm air from the test room causes the air curtain to become warmer as it falls down the cabinet.

To engineer a cabinet that performs to the M0 specification requires optimal air flow design to reduce air entrainment at the front of the cabinet whilst ensuring that air leaving the rear duct grille is as close to –1°C as possible. Technical problems in the supply of air from the evaporator and the design of the air curtain can result in uneven temperatures across the cabinet (left to right) and too much entrainment of ambient air at the front of the cabinet.

Many authors [9, 10, 11, 12, 13, 14] have shown computational fluid dynamics (CFD) modelling to be a valuable tool to rapidly provide design options to improve airflow within display cabinets. Due to the speed that a variety of scenarios can be predicted, CFD potentially provides the ideal means to determine which design options would provide the level of improvement required to reach the M0 classification.

This paper describes studies carried out to see if CFD could be used to rapidly identify the changes that would be required to an existing M2 classification cabinet to achieve a M0 rating.

2. Materials and methods

2.1 Cabinet

A Pastorfrigor MV 200TP chilled multi-deck retail display cabinet was used in the study (Figure 1). The cabinet was a 2 m long multi-deck chilled retail display cabinet with a single chilled air curtain. The cabinet defrost was off-cycle (refrigeration system switched off to allow any ice build up on the evaporator to melt).

2.2 Standard test

The tests were carried out in a test room conforming to EN441 standards and controlled to climate class III (temperature of 25°C and relative humidity of 60%). The lighting level in the test room was in accordance with EN standards (600±100 Lux at a height of 1 m above floor level) and was provided by fluorescent lighting similar to that, which would be found in most retail outlets. Ambient conditions were monitored by a calibrated thermocouple (Type-T) placed 300 mm to the front of the cabinet and 150 mm above the lower lip of the canopy of the cabinet and a humidity meter (Protimeter DDp.989M) placed in the centre of the room.

The cabinet was positioned in the test room approximately 500 mm from the sidewall. All cabinet settings and controls were operated via the controller integral to the cabinet.

2.2.1 Cabinet loading.

Two hundred and twenty standard 1kg packs and 108, 500g packs, as specified in EN441-4 [4], were placed in the cabinet using the loading pattern specified in EN441-5 [5] for a cabinet intended for the display of sensitive products. Fifty-four of the 500g packs were 'm' packs, which had a calibrated T-type thermocouple inserted into the geometric centre of the pack. Twelve were positioned on each of three shelves and 18 in the well as shown in Figure 2. A power meter (Northern Design PM390) was connected to the stabilised mains electrical supply to monitor and record electrical power.

Tests were carried out of temperature performance (according to EN441-5) and energy consumption (according to EN441-9) [7] over a 24-hour period. Temperature of the air and 'm' packs, relative humidity and power were recorded every minute using a data logging system (Datascan modules, Measurement Systems Ltd.) to an accuracy of ±0.1°C, ±3%RH and ±0.003kW respectively.

The temperature data was initially analysed to identify regions in the cabinets that were outside the M0 performance specification.

2.2.2 CFD modelling

It was not feasible to create a model of a whole cabinet that included the necessary detail with which to troubleshoot the cabinet performance failings. Instead, predictive models of different regions of the cabinet that had been identified to have problems were created.

These three-dimensional predictive models were created using CFX 5.5.1 (CFDS, AEA Technology), a commercially available CFD code. This uses the finite volume technique and an automatic unstructured mesh generator based on a tetrahedral mesh discretisation. The hardware used to run the models was an Intel Pentium 3 PC (Viglen Genie) running at 650 MHz with 512 Mb RAM. It was prohibitively computer intensive to model turbulence directly and therefore a turbulence model (k-ε) was used. The (k-ε) turbulence model provides a good compromise between numerical effort and computational accuracy.

2.3 Performance optimisation

After the areas with pack temperatures above that required had been identified the overall airflow pattern and that in these areas were investigated using smoke puffers (Hydrogen Sulphide, Drager). Air speed measurements were also made of the air curtain as it exited the grille using a hot-wire anemometer (Testo 425). These data were used to verify the airflow predictions of the CFD model. The CFD model was then used to determine what changes would have to be made to the cabinet to improve air distribution in the areas of interest. The changes identified were then carried out to the cabinet and the cabinet retested.

3. Results and discussion

3.1 Performance prior to modifications (EN441-5)

To achieve the relevant specification the temperatures measured in all of the 'm' packs over the 24-hour period have to be within the temperature range specified. When the temperature data was analysed, no temperatures below –1°C were found and all the temperatures in the 54 packs were below 7°C (Table 1). However, only 42 'm' packs (out of 54) spent the entire test period between -1 and 4°C. The position and the percentage of time spent by these 'm' packs above 4 and 5°C are shown in Table 2. Overall a maximum temperature of 6.9°C was measured in the 'm' pack positioned in the top pack at the right front of the well and occurred during a defrost. A minimum of –1.0°C was recorded in the 'm' pack situated in the top pack at the rear left of the well. The temperatures recorded over the 24 hours at these two positions are shown in Figure 3 together with the overall mean and exposed mean (mean of 'm' packs that can be viewed from the front of the cabinet) of all 'm' packs within the cabinet.

The area of most concern in terms of higher temperatures and time spent at elevated temperatures was located at the centre and right front of shelf 1 and the front edges of the well.

The energy consumed by the refrigeration system, fans and cabinet lights throughout the 24 h test was 118 MJ giving an average power consumption of 1.37 kW. The refrigeration ran for 77% of the test period.

3.2 Performance optimisation.

3.2.1 Air flow visualisation

Airflows within the cabinet were examined using smoke as a tracer. On all shelves a vortex was created above the packs that caused air to circulate within each shelf. Because each shelf within the cabinet was lightly loaded (in accordance with the requirements for loading a cabinet intended for storage of sensitive products), gaps were present between shelves that enabled the vortices to be generated.

Further investigation of the cabinet revealed that the evaporator was not the full width of the rear duct. There was a 110 mm gap between each end of the duct and the evaporator. Air, which exited the evaporator, had therefore to change in direction by 90° to enter the edge of the duct.

3.2.2 CFD modelling

CFD modelling concentrated specifically on two areas of the cabinet that were most likely to produce the regions of high temperature.

1. The flow of air as it left the evaporator and travelled up the rear duct at the corners of the cabinet.

2. The flow of air as it left the air curtain and the rear grille and its interaction with product on the top shelf.

CFD was therefore used to model the flow of air as it exited the evaporator and entered the rear duct. Only the bottom edge of the cabinet was considered, where air from the evaporator was required to fill the dead space previously identified at the edges of the cabinet.

Figure 4a shows streamlines predicted by CFD from the exit of the evaporator and Figure 4b velocity vectors predicted by CFD in a horizontal plane at the height of the first set of holes in the rear grille for the un-modified cabinet. The predictions show that as air leaves the evaporator it moves out to the side to fill the dead space and then travels up the rear duct. In doing so the air spirals up the rear duct at the edge. This type of airflow was likely to result in vortexes as the air entered the cabinet rather than the uniform flow required.

CFD modelling was then used to investigate the effect of a number of modifications including changing the size and position of the evaporator coil and inserting baffle plates into the duct. The predictions indicated that the three modifications most likely to create a uniform flow up the back duct were;

1. Make the evaporator as wide as possible (reducing the length of the dead space)
2. Move the evaporator towards the front of the cabinet and create an angle such that the air would more easily move to the edge of the duct.
3. Insert an angled plate at the bottom of the duct to increase the pressure and even out the flow.

Figure 5a shows streamlines predicted by CFD from the exit of the evaporator and Figure 5b velocity vectors predicted by CFD in a horizontal plane at the height of the first set of holes in the rear grille for the modified cabinet (length of evaporator extended such that there was only a 50 mm dead space at each end of the cabinet, evaporator moved forward by 80 mm, angle to expand air to the edge of the duct and a turning vane). With these modifications the CFD predicts that no vortex will develop.

A second CFD model was created to predict the flow of air as it exited the air curtain grille and travelled down the cabinet. To reduce complexity the full height of the air curtain was not modelled since the main area of interest was to optimise air curtain for the top shelf. The existing air curtain exiting the duct had a measured velocity of 1.5 $m.s^{-1}$ and a temperature of $-1^{o}C$, with the jet pointing vertically downwards. The width of the air curtain was 15 mm.

The CFD model predicted that the air curtain would be bent towards the product and hit the outer corner of the product (Figure 6). A vortex was then created which draws warmer air over the front of the product. The air curtain would also be disrupted bringing warmer air onto the shelves below.

Again CFD modelling was used to investigate the effect of a number of modifications including changing the width and angle of the curtain. Increasing the width of the air curtain to 60 mm whilst keeping the volume flow rate through the air curtain constant was predicted to remove the vortex. This was likely to keep the product cooler and also maintain a better air curtain for the next shelf down (Figure 7).

The CFD predictions also showed that there were benefits in angling the air curtain away from the shelves, and that the optimum angle depends on the width and velocity of the curtain.

3.3 Cabinet modifications

Based on the CFD predictions a number of modifications were carried out to the cabinet by the manufacturers of the cabinet.

A longer evaporator was fitted to the cabinet, which reduced the gap at each end from 110 to 70 mm. The evaporator was repositioned forwards of the duct by 100 mm and an angle was used to gradually widen the duct from the edge of the evaporator to the edge of the cabinet. A wider air curtain grille (with honeycomb) was fitted to the cabinet. This air curtain grille was 60 mm wide and angled by 8^o away from the cabinet. An additional fan was also fitted to the evaporator to provide a more uniform flow through it.

A further improvement was made by FRPERC during testing. This was to place a riser at the rear of the shelf to prevent the test packs blocking the rear air grille.

3.4 Performance after modification (EN441-5)

The cabinet was retested after modifications had been carried out. Throughout the test all 'm' pack temperatures were above at or above –1°C. Fifty-three of the 54 'm' packs spent the entire test period below 4°C. One 'm' pack, positioned at the front top centre of the well, reached the highest temperature of 4.4°C during the defrost period. This pack spent 19% of the test period at a temperature above 4°C. The lowest temperature of –1.0°C was recorded in the 'm' pack situated at the rear right top of shelf 5. The temperatures recorded at these two positions are shown in Figure 8 together with the overall mean and exposed mean of all 'm' packs within the cabinet..

The difference between the percentages of time spent above 4 and 5°C before and after modifications is shown in Table 2. The areas in the cabinet that had been above 4°C in the original test were all reduced below 4°C after modifications. However, the one position that was above 4°C in the modified cabinet had actually increased in temperature compared to the unmodified cabinet (overall mean temperature of 2.1°C in unmodified cabinet and 3.8°C in modified cabinet).

The energy consumed by the refrigeration system, fans and cabinet lights throughout the 24 h test was 111 MJ giving an average power consumption of 1.29 kW. The refrigeration ran for 77% of the test period.

4. Conclusions

An integral multi-deck retail display cabinet originally designed to meet the M2 classification was modified using CFD as a design tool. Improvements suggested by the CFD model were incorporated into the cabinet. Before modification, 12 of the ‘m’ packs within the cabinet spent at least 50% of the 24-hour test period above 4°C. After modification only 1 out of the 54 ‘m’ packs spent 19% of the test period above 4°C. The average power consumption over 24 hours was reduced from 1.37 to 1.29 kW (a reduction of 5%).

The major improvement achieved after modifications to the cabinet was in the reduction in the maximum ‘m’ pack temperatures on each shelf (Figure 9). On shelf 1 and in the well the maximum ‘m’ pack temperatures were reduced by 2.4 K and on shelves 3 and 4 the maximum ‘m’ packs were reduced by 0.9 K. In all cases the maximum ‘m’ pack temperatures were at the front of the cabinet. The modifications carried out therefore had the greatest influence over packs placed at the front of the cabinet whilst still maintaining pack temperatures at the rear of the shelves above the minimum requirement of –1°C.

In the unmodified cabinet the right side tended to be warmer than the left and all packs above 5°C were located in either the right side of the cabinet or at the front of shelf 1. This was due to the evaporator being located further from the right end wall than the left end wall due to the evaporator connections and manifold being on the right side of the cabinet. The modifications carried out corrected this problem and actually reduced the temperatures of packs in the right side of the cabinet below those in the left. Some unevenness in temperature of packs in the right and left sides of the cabinets remained after the modifications but this may have been more due to the air flow across the front of the cabinet ($0.2\pm0.1\ ms^{-1}$ as prescribed in EN441). This air was directed from the left side of the cabinet and this was a likely cause of mixing between the air curtain and ambient air resulting in slightly higher packs temperatures in the left of the cabinet.

The use of CFD to understand the problem and test possible solutions was invaluable in improving the cabinet. Many authors have proved CFD's benefits to predict air flow in display cabinets, however, this work has generally been carried out during research projects lasting a number of months or even years. The benefit to the display cabinet manufacture is to get results quickly (within a couple of weeks). It was therefore not practical to make a CFD model of the whole cabinet; areas that were considered to be a problem were modelled in detail.

A refrigerated multi-deck display cabinet is an extremely sensitive device with very complicated unstable flow and is therefore a difficult test for which CFD to prove itself. The authors believe that a combination of CFD modelling, experience of display cabinets and testing facilities were invaluable in improving the display cabinet in a short time period.

Number of packs within the cabinet between:					
Before modification			After modification		
-1 to 7°C	-1 to 5°C	-1 to 4°C	1 to 7°C	-1 to 5°C	-1 to 4°C
54	48	42	54	54	53

Total pack positions = 54

Table 1. The number of packs within the cabinet between -1 and 5 and –1 and 4°C before and after modification.

Position	Unmodified % time >4°C	Unmodified % time >5°C	Modified % time >4°C	Modified % time >5°C
Shelf 1, bottom centre front	100	51	0	0
Shelf 1, top centre front	100	51	0	0
Shelf 1, bottom right front	100	10	0	0
Shelf 1, top right front	91	0	0	0
Shelf 3, bottom right front	98	0	0	0
Shelf 3, top right front 2	100	0	0	0
Shelf 4, bottom right front	100	0	0	0
Shelf 4, top right front	56	0	0	0
Well, bottom left front	98	73	0	0
Well, top left front	91	0	0	0
Well, top centre front	0	0	19	0
Well, bottom right front	100	100	0	0
Well, top right front	100	100	0	0

n.b. All positions of packs not shown in table were below 4°C.

Table 2. The position and the percentage of time spent by ‘m’ packs above 4 and 5°C before and after modification.

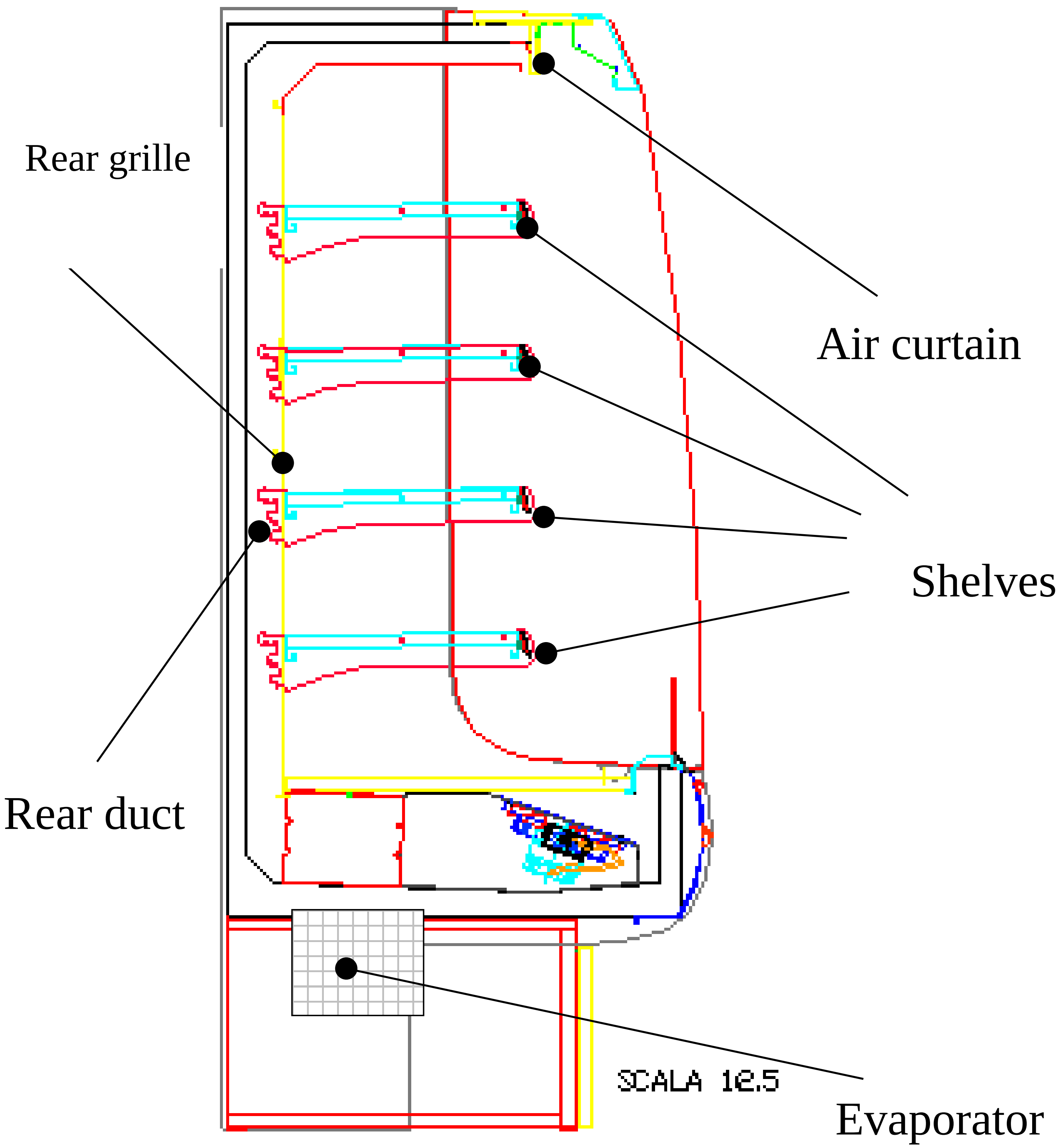

Figure 1. Vertical section of display cabinet.

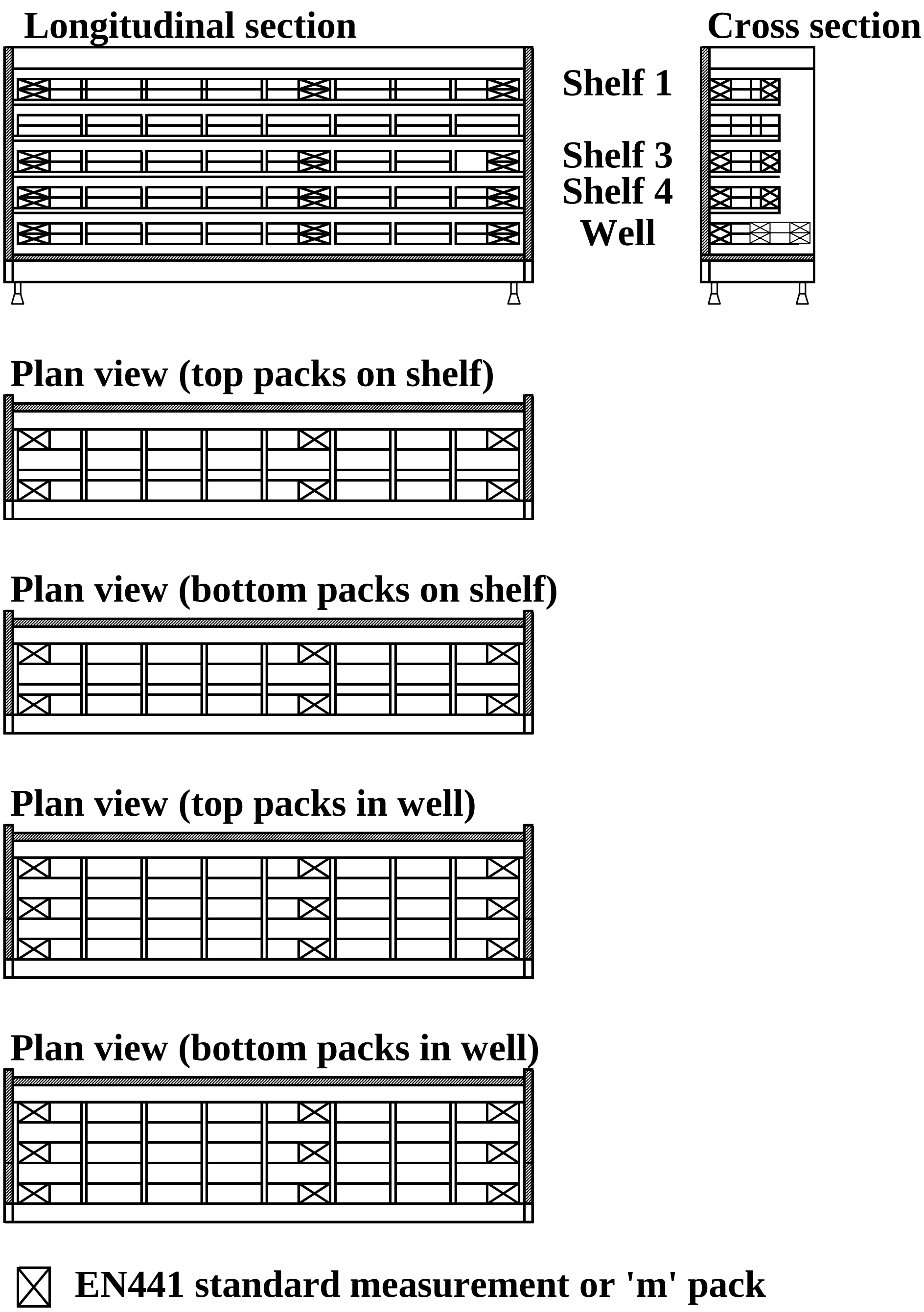

Figure 2. Loading of cabinet showing positions of measurement or ‘m’ packs.

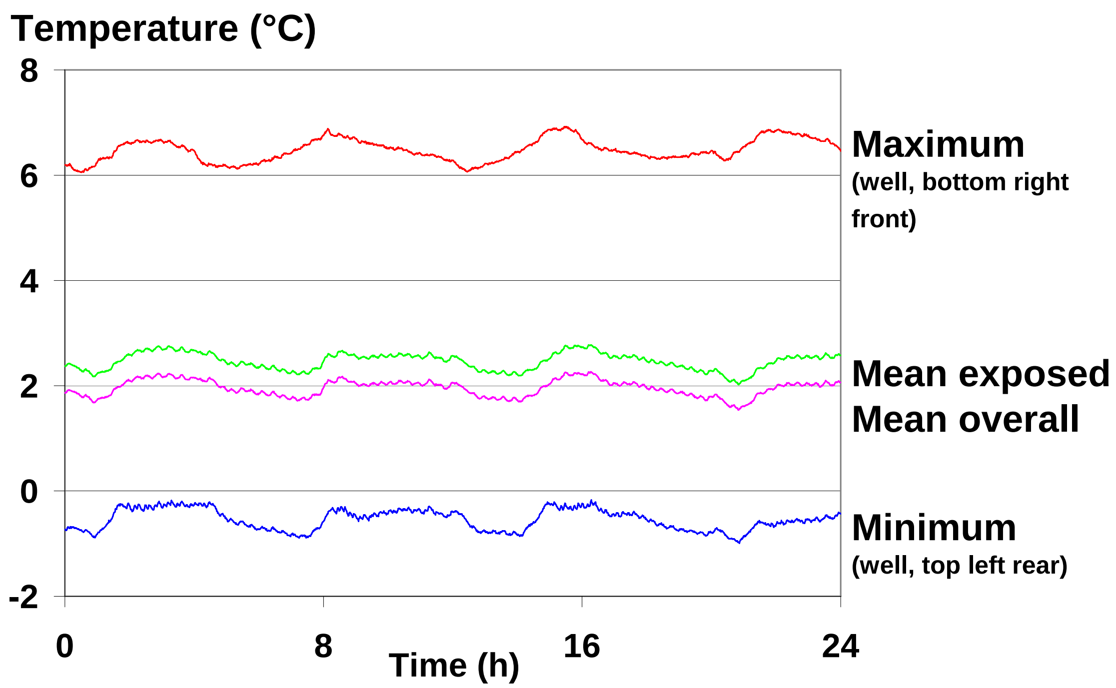

Figure 3. Temperatures recorded over 24 hours at the position of the maximum and minimum temperature together with the overall mean and exposed mean (mean of ‘m’ packs that can be viewed from the front of the cabinet) of all ‘m’ packs within the cabinet before modification.

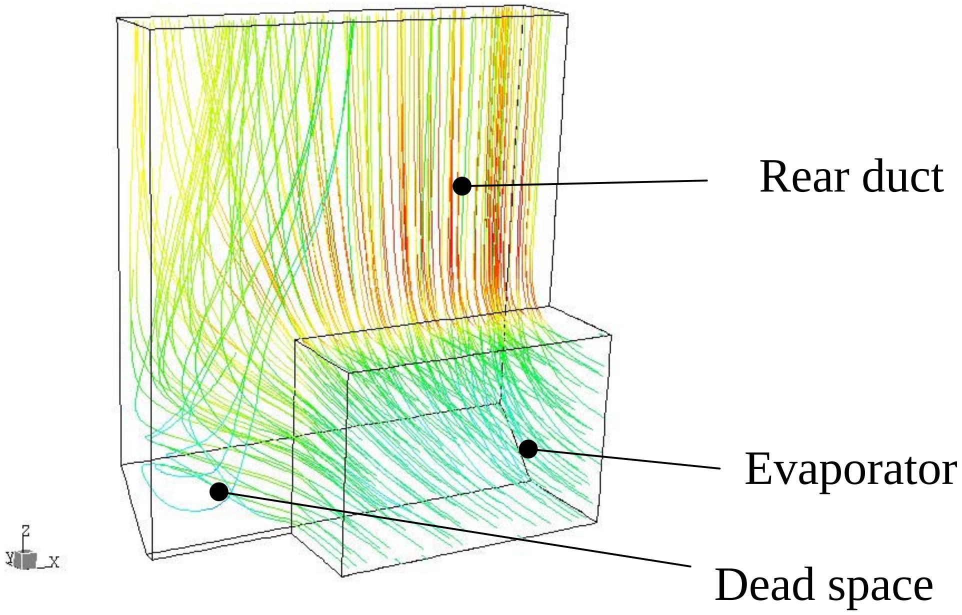

Figure 4a. Streamlines predicted by CFD from the exit of the evaporator for the un-modified cabinet.

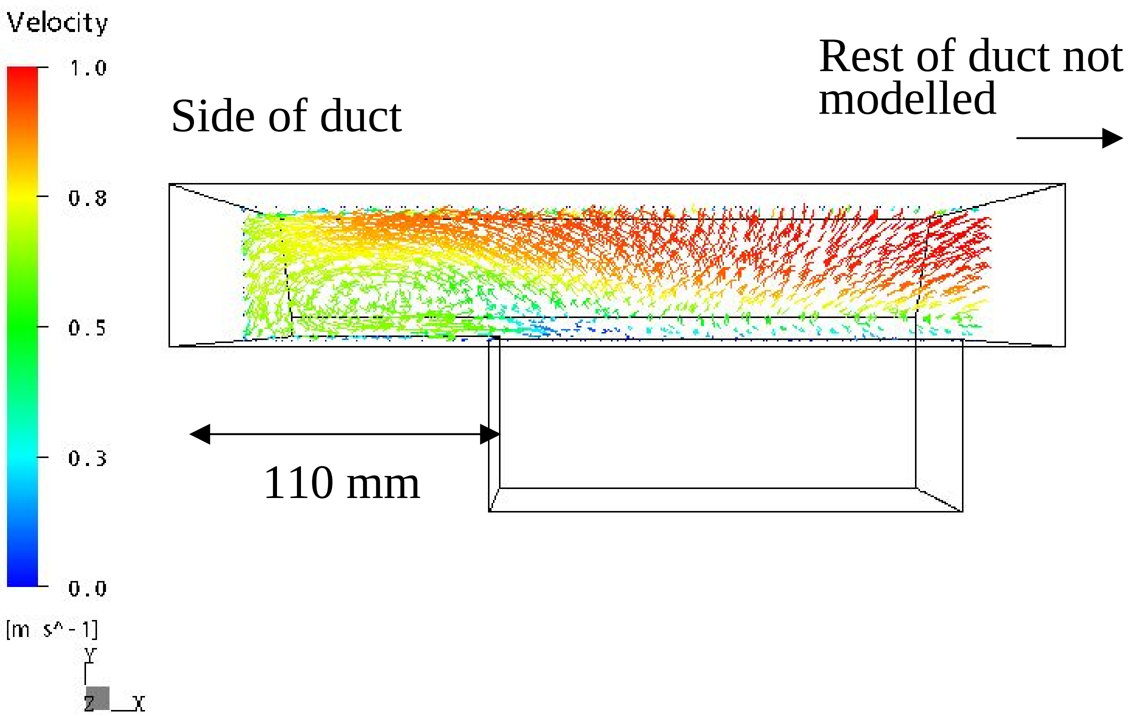

Figure 4b. Velocity vectors predicted by CFD in a horizontal plane at the height of set of holes in the rear grille for the un-modified cabinet.

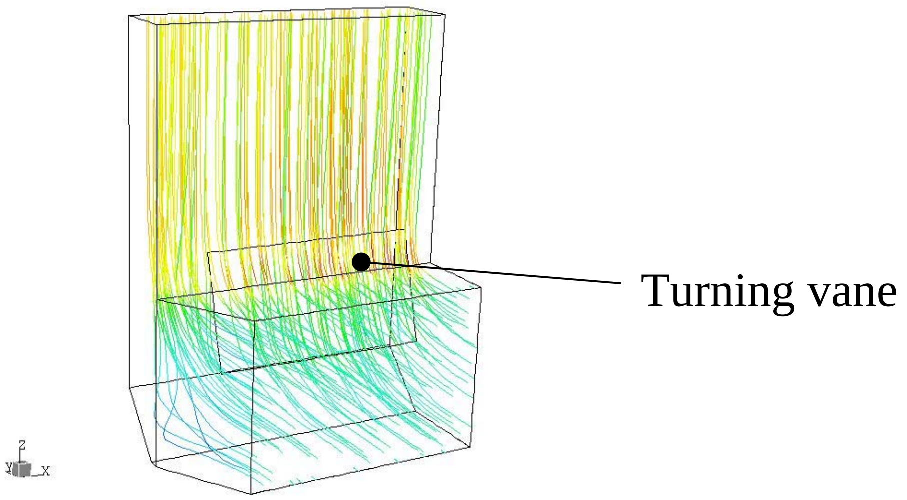

Figure 5a. Streamlines predicted by CFD from the exit of the evaporator for the modified cabinet (length of evaporator extended such that there was only a 50 mm void at each end of the cabinet, evaporator moved forward by 80 mm and angle to expand air to the edge of the duct).

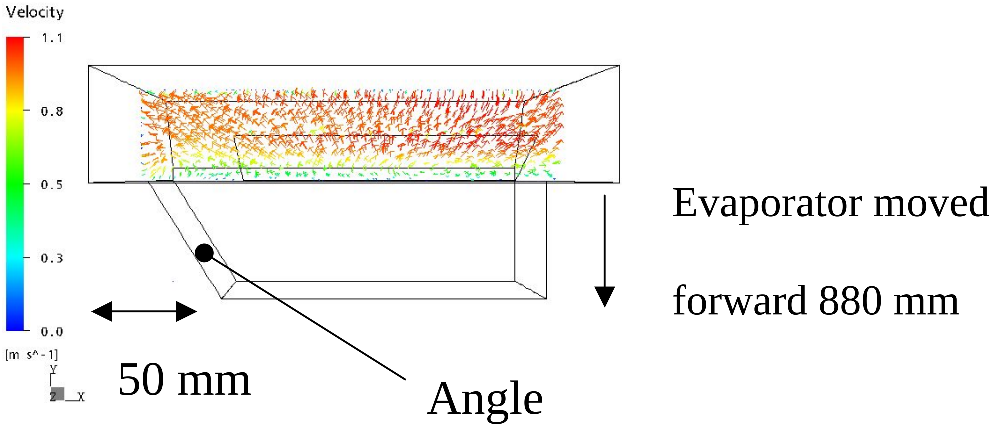

Figure 5b. Velocity vectors predicted by CFD in a horizontal plane at the height of the first set of holes in the rear grille the modified cabinet (length of evaporator extended such that there was only a 50 mm void at each end of the cabinet, evaporator moved forward by 80 mm and angle to expand air to the edge of the duct).

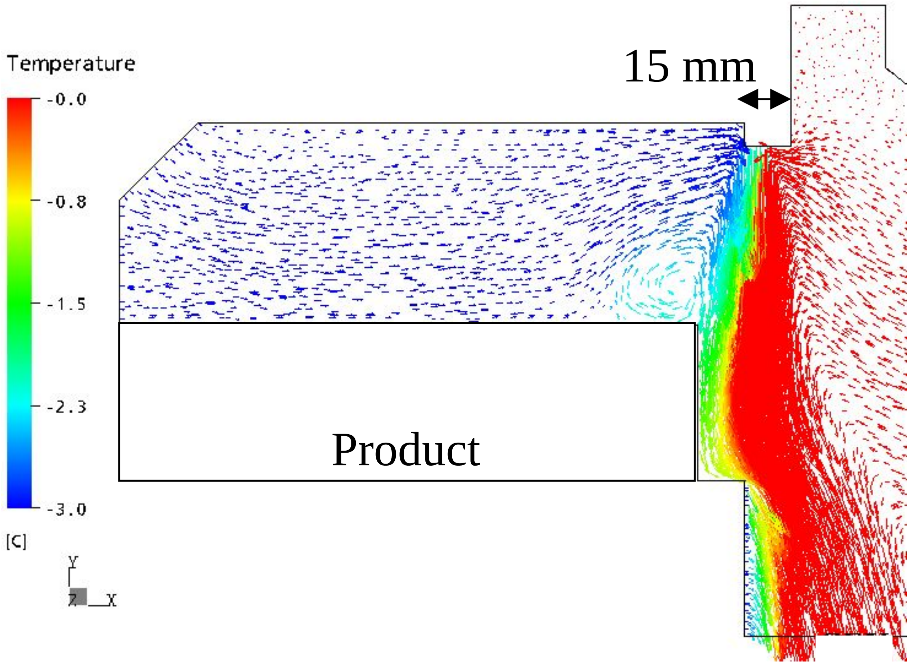

Figure 6. Velocity vectors predicted by CFD in a vertical plane at the top of the cabinet. The length of the vector is proportional to the air velocity, the colour represents the temperature. (air curtain 1.5 $m.s^{-1}$ and 15 mm).

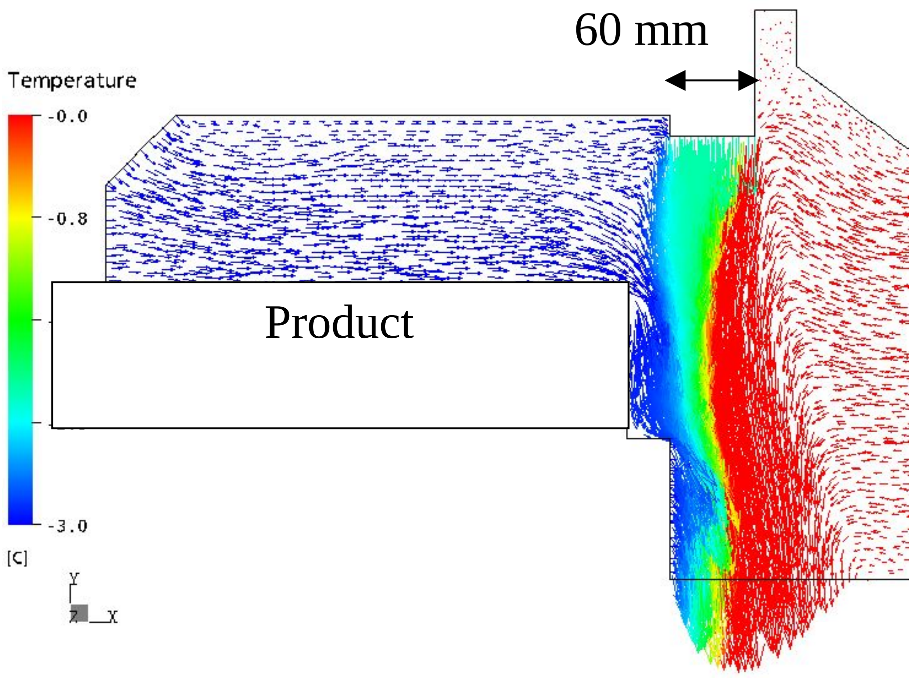

Figure 7. Velocity vectors predicted by CFD in a vertical plane at the top of the cabinet. The length of the vector is proportional to the air velocity, the colour represents the temperature (air curtain 0.375 m.s^{-1} and 60 mm).

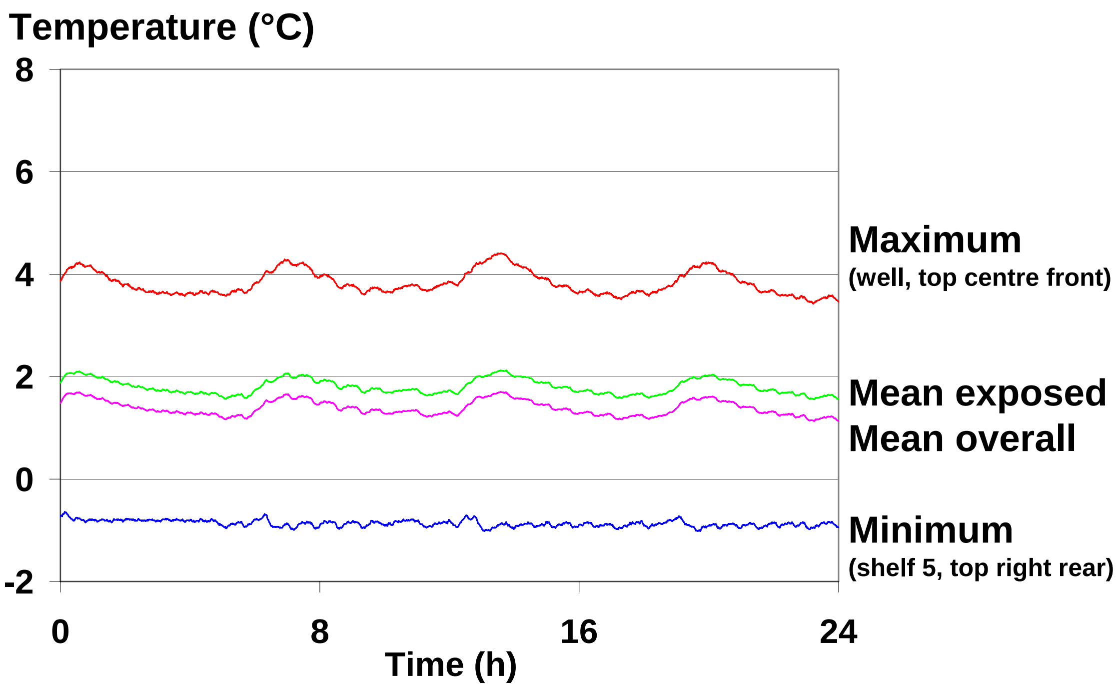

Figure 8. Temperatures recorded over 24 hours at the position of the maximum and minimum temperature together with the overall mean and exposed mean (mean of 'm' packs that can be viewed from the front of the cabinet) of all 'm' packs within the cabinet after modification.

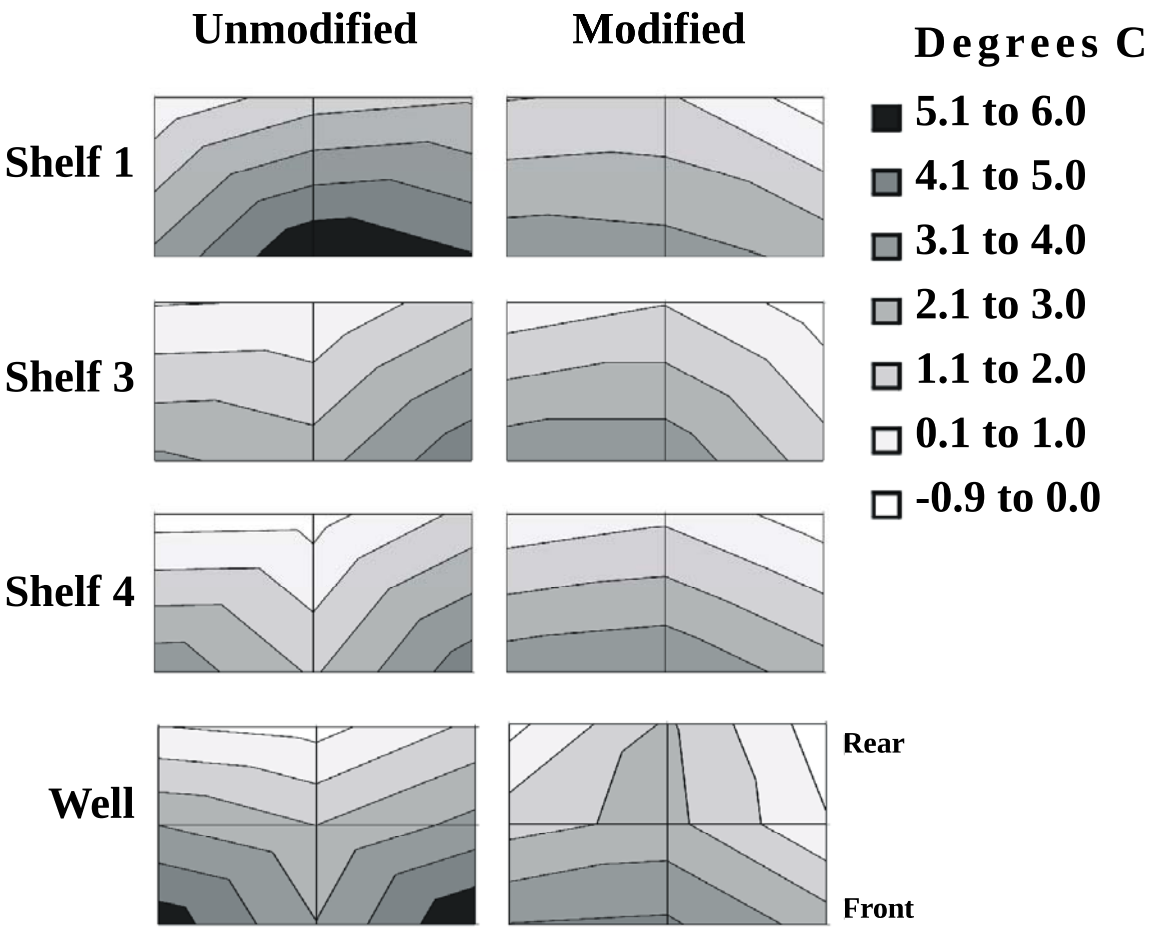

Figure 9. Comparison between temperatures on each shelf in unmodified and modified cabinets. (The figure shows overall maximum temperatures of the 2 ‘m’ packs located at each shelf position over 24 hours).

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