Investigation into the Optimisation of the Heat Transfer through Ritherdon Cabinets

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1. Abstract

This paper describes an investigation was carried out by Ritherdon & Co. to determine how best to optimise the heat transfer out of Ritherdon cabinets.

Experiments were carried out using ventilated cabinets and sealed cabinets containing a 400W heating element. Up to four 19W fans were used to circulate air around and extract air from the system to determine the most effective arrangement. Each arrangement was tested over the course of a day and repeated once to obtain reliable results. The average inside cabinet temperature was measured continuously using eight thermocouples, the surface temperature was measured at 90 points, 6 times per test to calculate an average, and the ambient temperature was measured continuously using an ambient temperature sensor, all of which were used to calculate convective heat transfer coefficients. Air flow and temperature in and out of the cabinet was measured and used to produce a heat and mass balance around the cabinet.

The following conclusions were made from the experimental data:

- It was found that there was a limit to the overall heat transfer coefficient of approximately 4.1 W/m^2K for sealed cabinets.
- Stirring fans were found to have a similar effect to extraction fans when running in a sealed cabinet, despite the extraction fans running directly against a sealed surface.
- Pure natural convection was found to be as effective as the use of a single stirring fan for a ventilated cabinet.
- Stirring fans were found to have a negative effect when used in conjunction with extraction fans for a ventilated cabinet.
- The lowest temperature difference was found to be 20°C, using two extraction fans at the top sides of the cabinet.

2. Introduction

The Ritherdon RB Cabinet range has a wide range of uses in a number of locations. As a result, the RB Cabinets have to be able to withstand the various environmental conditions that may be imposed upon them in order to function effectively. The RB Cabinet range is used to house hardware ranging from networking equipment to power supplies, all of which generate heat during their use. The overheating of this equipment can result in its malfunction, consequently they are often fitted with a temperature sensor and an upper limit trip to prevent damage to the equipment. The issue this raises is that during the hot season, the higher temperatures and radiation from the sun causes the equipment in the cabinets to overheat, tripping the temperature sensor and turning the equipment off.

To counteract this, mechanisms are often put into place to improve the heat transfer out of the cabinet to reduce the temperatures within. One such measure is the implementation of louvres, or vents, into the design of the cabinet to allow air to pass through. Natural convection causes the hot air within the cabinet to rise and pass out through the top louvres, and cool air replaces it, passing in through the bottom louvres. In addition, small fans were added, placed behind the upper louvres, to facilitate the movement of air and transport of heat out of the cabinet. However, the addition of louvres provides openings through which moisture can pass through reducing the IP rating of the cabinet.

Thermodynamic principals of convection suggest that the heat transfer through a surface can be improved by increasing the air flow across the surface. This carries warm heated air away from the surface and replaces it with cooler air, resulting in a higher local temperature differential which increases heat transfer. The use of a number of stirring fans within a non-ventilated cabinet may be enough to cause this heat transfer without compromising the IP rating.

3. Aims

The aims of this investigation are to determine the effect that different parameters of an RB cabinet have on the heat transfer out of the cabinet. The parameters tested include the location of the fans, the number of fans used, and whether or not air is allowed to pass in and out of the cabinet.

4. Method

In order to carry out this experiment, a special RB cabinet was designed with 14 banks of 3 louvres on each side. The louvres not in use were sealed such that the position of the active louvres could be varied. The cabinet was heated using two 200W HVR Pentagon Anti-Condensation Heaters. The temperature within the cabinet was monitored using two HOBO Onset UX120-014M 4-Channel Temperature Loggers, for a total of 8 channels. The temperature probes were arranged in three rows, suspended on three lengths of wire running lengthways through the cabinet. This allowed for the generation of a temperature profile of the inside of the cabinet, as well as an 8-point average cabinet temperature for each second. The temperature measured by each probe was found to show noise and other variation, therefore an average was taken over approximately 10 minutes for each reading. 600 readings are taken every 10 minutes for each of the 8 channels, constituting approximately 4800 values used to calculate each average cabinet temperature measurement.

The surface temperature of the cabinet was measured using an infrared temperature gun. The cabinet surface was divided into sections and the temperature of each section was measured for a total of 90 temperatures. This was used to create a temperature profile of the surface of the cabinet, from which a 90-point average could be calculated. Taking these readings took 10 minutes on average and was used as the length over which the average internal cabinet temperature was calculated.

Ambient temperature was measured using the ambient temperature sensor on the temperature logger. Readings were taken at an interval of 1 second and an average was taken over the same 10-minute time period described above.

The absolute temperature of the cabinet and the cabinet surface was dependent on the ambient temperature, and so differential temperatures were used as a more objective measure of performance. For each set of readings, the differences between the internal temperature and the surface temperature, the surface temperature and the ambient temperature, and the internal temperature and the ambient temperature were calculated. Readings for each set of conditions were taken 6 times over the course of a day, at approximately the same time each day, and averages of all the differential temperatures were calculated for each day of experimentation. Each experiment was carried out twice, and the average for each set of experimental parameters was calculated.

The number of fans used was varied throughout the investigation. The model of fan used was the ‘ebm-papst’ 230V AC axial fan and all the fans were wired so that they could be activated and deactivated externally without having to open the cabinet. Fans 1 and 2 were positioned on either side at the bottom of the cabinet, in-front of the banks of louvres but angled upwards at 45 degrees towards the centre of the cabinet for circulation. Fans 3 and 4 were mounted on fan brackets on either side at the top of the cabinet directly in front of the banks of louvres.

Airflow in and out of the cabinet was measured using an DT-8800 Hot-Wire Thermo-Anemometer. The mean air speed was taken over each louvre over 20 seconds and was used to calculate an average for each bank of three louvres. This was done six times per test over the course of the day. These values were then averaged giving an overall average speed for each vent for each test. The temperature of each louvre was measured using a temperature probe to calculate a difference between the intake and the exhaust.

Each experiment was carried out over the course of approximately 24 hours. The cabinet was set up at the required conditions the afternoon of the day before and was allowed to equilibrate overnight. The six sets of readings were then taken over the course of the next day at regular intervals, from 7am to 3pm.

Figure 1 – Experimental setup

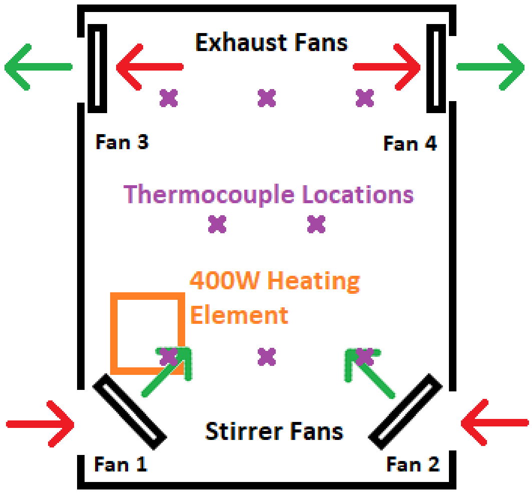

Figure 2 – Experiment diagram showing approximate fan positions, air-flow direction (red is intake, green is exhaust), thermocouple location and heating element location.

5. Theory

There are three methods of heat transfer in nature: conduction, convection, and radiation. Conduction describes the vibration of atoms as a result of heat causing nearby atoms to vibrate allowing heat to pass through a material. Convection describes the circular movement of air as a result of heat changing its density. Radiation describes the emission of heat in the form of electromagnetic waves.

Fourier's Law is typically used to calculate the conduction heat transfer through a surface:

$$q = \frac{k}{x} A \Delta T \tag{1}$$

Where q = Heat Transfer (W), k = Thermal Conductivity (W/mK), x = Material Thickness (m), A = Heat Transfer Area (m^2), ΔT = Temperature Difference (K), $\frac{k}{x}$ = Heat Transfer Coefficient (W/m^2K).

Fourier's law can also be amended to account for the convection portion of the heat transfer by modifying the heat transfer coefficient:

$$q = h_C A\Delta T, \ \frac{1}{h_C} = \frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o} \quad (2)$$

Where h_C = Overall Conduction/Convection Heat Transfer Coefficient (W/m^{2}K), h_i = Inside Air Convection HTC (W/m^{2}K), h_o = Outside Air Convection HTC (W/m^{2}K).

The Air Convection Coefficients vary as a result of the characteristics of the air close to the surface of the object, mainly velocity. Stainless steel has a thermal conductivity of approximately 30.5 W/mK and the steel used to make the cabinet is 2mm thick. This returns a very small value for the conductivity component of the overall heat transfer coefficient (6.56×10^{-5} m^{2}K/W) compared to the air convection components and can therefore be neglected. This leads to the assumption that the conduction of heat through the steel is such that the outer and inner surfaces have the same temperature.

The heat transferred from the heating element to the inside cabinet surface is equal to that transferred from the outside cabinet surface to the environment, therefore Equation 2 can be split to express the effects of the heat transfer on the inside and the outside of the cabinet giving the following heat balance:

$$q = h_C A\Delta T_{i:a} = h_i A\Delta T_{i:s} = h_o A\Delta T_{s:a} \quad (3)$$

Where h_i = Inside HTC (W/m^{2}K), h_o = Outside HTC (W/m^{2}K), h_c = Overall HTC (W/m^{2}K), $\Delta T_{i:a}$ = Inside/Ambient Temperature Difference (K), $\Delta T_{i:s}$ = Inside/Surface Temperature Difference (K), $\Delta T_{s:a}$ = Surface/Ambient Temperature Difference (K).

The Stefan-Boltzmann Law describes the thermal electromagnetic radiation emitted from a black-body, proportional to its absolute temperature raised to the 4th power. A black-body is a theoretical object or system that absorbs all radiation that falls upon it, however in reality there is always some reflected radiation, and while a body emits radiation, it is also absorbing radiation from other bodies in its immediate environment. The net heat transfer via radiation is calculated using the Stefan-Boltzmann equation below:

$$q_r = \sigma\varepsilon A\Delta T^4 = \sigma\varepsilon A\left[{T_2}^4 - {T_1}^4\right] \quad (4)$$

Where σ = Stefan-Boltzmann Constant (W/m^{2}K^4), ε = Emissivity (1).

The following substitutions can be made into Equation 4 to standardize the formula:

$$\left[{T_2}^4 - {T_1}^4\right] = \left({T_2}^2 + {T_1}^2\right)(T_2 + T_1)[T_2 - T_1]$$

$$\text{Let} \quad h_r = \sigma\varepsilon\left({T_2}^2 + {T_1}^2\right)(T_2 + T_1)$$

$$q_r = h_r A[T_2 - T_1] = h_r A \Delta T \tag{5}$$

Combining Equations 3 and 5 gives the total heat transfer taking into account conduction, convection and radiation:

$$q_T = q_c + q_r = h_C A \Delta T + h_r A \Delta T$$

$$q_T = UA\Delta T \tag{6}$$

$$U = h_C + h_r = \frac{1}{\left(\frac{1}{h_{o,c}}\right)+\left(\frac{1}{h_{i,c}}\right)} + \sigma\varepsilon\left({T_2}^2 + {T_1}^2\right)(T_2 + T_1) \tag{7}$$

The heat transfer was fixed at 400W according to the heat source used within the cabinet, the area was taken to be the surface area of the cabinet. The change in temperature was taken to be the differences between the interior temperature of the cabinet, the surface temperature of the cabinet and ambient temperature outside the cabinet. Equation 6 can be applied to both the inside and outside of the cabinet, as well as across the whole system, to provide the following equation:

$$q = h_i A \Delta T_{i:s} = h_o A \Delta T_{s:a} = UA\Delta T_{i:a} \tag{8}$$

Where h_i = Inside HTC (W/m^{2}K), h_o = Outside HTC (W/m^{2}K), U = Overall HTC (W/m^{2}K), $\Delta T_{i:s}$ = Inside/Surface Temperature Difference (K), $\Delta T_{s:a}$ = Surface/Ambient Temperature Difference (K), $\Delta T_{i:a}$ = Inside/Ambient Temperature Difference (K).

When air is allowed to pass through the cabinet, the mass transfer allows extra heat to escape. This energy is proportional to the difference in temperature of the air entering and exiting the cabinet, as well as the mass flow rate of air through the cabinet. The following equation can be used to describe the process.

$$q_m = \dot{m} C_p \Delta T \tag{9}$$

Where $\dot{m}$ = Mass Flow Rate (kg/s), C_p = Specific Heat Capacity of air (kJ/kgK), ΔT = Change in air temperature from inlet to outlet (K).

In this case, Equations 8 and 9 can be combined to produce the overall heat balance, and can be written as follows:

$$q_T = UA\Delta T_{cab} + \dot{m} C_p \Delta T_{air} \tag{10}$$

6. Results

Table 1 - Experiment Plan. Each experiment is a pair of tests, one ventilated and one sealed. Each test was repeated once and average calculated. 'Sealed' denoted that the cabinet ventilation louvres were sealed off, whereas 'Ventilated' denotes that they were not.

Experiment No.	Airflow	Number of Fans Active	Fans Active
1a	Sealed	0	None
1b	Ventilated		
2a	Sealed	1	Bottom Left (1)
2b	Ventilated		
3a	Sealed	2	Bottom Left (1), Bottom Right (2)
3b	Ventilated		
4a	Sealed	3	Bottom Left (1) and Right (2), Top Left (3)
4b	Ventilated		
5a	Sealed	4	Bottom Left (1) and Right (2), Top Left (3) and Right (4)
5b	Ventilated		
6a	Sealed	2	Top Left (3), Top Right (4)
6b	Ventilated		

Each experiment number represents the use of a different arrangement of fans as detailed in Table 1. Each experiment comprises two tests denoted with suffixes 'a' and 'b'. Each test was repeated once to calculate an average set of results for each test. The tests denoted as 'a' were carried out with the vents sealed, whereas the tests denoted at 'b' were carried out while the cabinet was allowed to ventilate.

*Table 2 - Air flow data from ventilated tests. *Average exhaust temp was weighted based on exhaust flow speed, intake temp was taken as ambient. Air flowrate and energy transfer calculated using intake speeds.*

Experiment	Top-Left Speed (m/s)	Top-Right Speed (m/s)	Bottom-Left Speed (m/s)	Bottom-Right Speed (m/s)	Left Temp Difference (°C)	Right Temp Difference (°C)	Avg. Temp Difference* (°C)	Energy Transfer (W)
1b	0.7	0.6	0.5	0.4	25.4	19.6	22.7	20.7
2b	0.9	0.9	0.6	0.4	15.2	16.4	15.8	15.6
3b	1.1	1.1	0.6	0.7	15.2	16.1	15.6	19.2
4b	5.2	0.2	0.9	0.8	22.3	11.8	21.9	36.1
5b	4.2	5.3	1.2	1.2	19.7	18.4	19.0	45.2
6b	4.4	5.1	1.3	1.2	25.4	20.2	22.6	58.1

The air speed was measured at each bank of louvres for all ventilated experiments. The top-left and top-right vents were exhaust vents, whereas the bottom-left and bottom-right vents were intake vents. The temperatures of the two exhaust vents were measured and used with the ambient temperature measured with the same instrument to calculate individual temperature differences (Left and Right). The average temperature difference was calculated using a weighted average of the left and right temperature differences, weighted using the exhaust speeds. Air mass flow rate was calculated using inlet speeds (see Section 8.4) and used with the average temperature difference to calculate the energy balance.

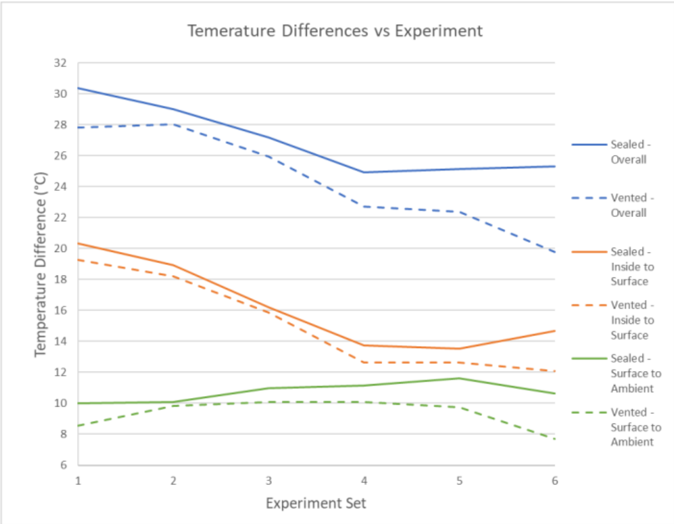

Figure 3 - Temperature Difference for each pair of experiments

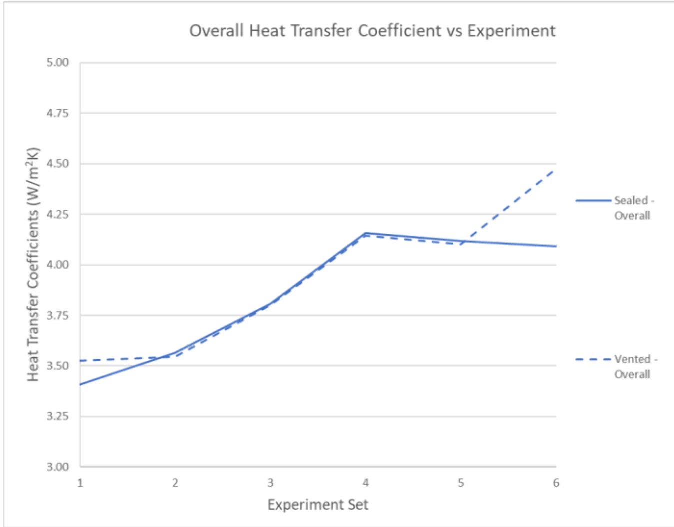

Figure 4 – Overall Heat Transfer Coefficient for each pair of experiments

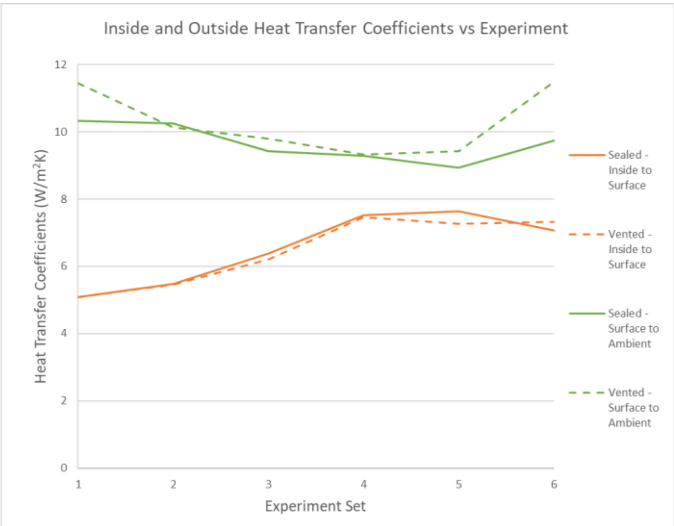

Figure 5 – Inside and Outside Heat Transfer Coefficients for each pair of experiments (Convection and Radiation components combined)

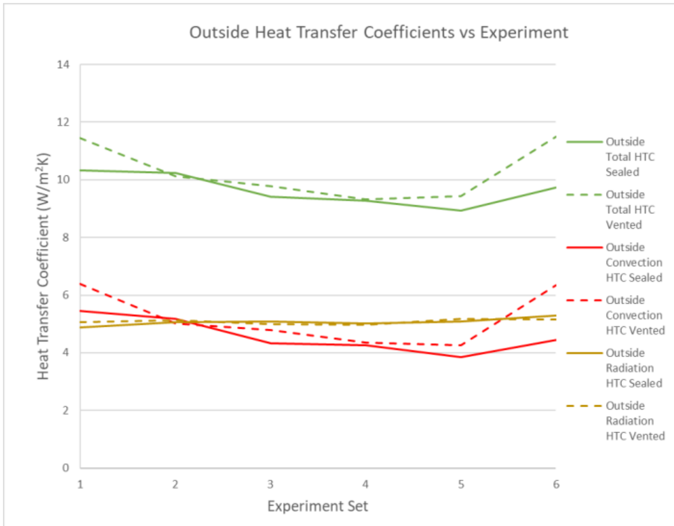

Figure 6 – Outside Convection and Radiation Heat Transfer Coefficients for each pair of experiments

Figure 3 shows the variation in temperature differences across the range of experiments. Each experiment consisted of two tests; the solid lines represent tests performed during which the cabinets were sealed, and the dashed lines represent tests performed during which the cabinets were ventilated. As the performance of the cabinet improves, the overall difference in temperature decreases as this represents a lower cabinet temperature relative to the temperature of the environment.

Figures 4-6 show the variation of the various heat transfer coefficients calculated using the experimental results. These coefficients affect the convective heat transfer through the cabinet walls – the higher the coefficient, the higher the energy transfer, and the lower the inside temperature. Like in Figure 3, solid lines represent sealed tests and dotted lines represent ventilated tests.

Top Face

17A		23.5	20.9	14.5	12.9	12.1		
Left Face		16.7	16.5	15.1	13.5	12.1	Right Face	
14.9	15.5	17.1	17.7	16.5	14.1	12.5	12.5	11.5
14.5	13.9	15.3	16.5	14.5	12.7	11.1	12.5	11.5
14.7	12.5	15.1	16.5	14.5	11.9	10.7	11.1	9.7
24.7	15.7	13.7	14.5	11.9	9.3	8.5	8.9	8.1
2.9	2.5	5.7	7.5	7.3	5.3	4.1	3.1	4.1
		4.5	5.7	4.7	4.1	2.7	Front Face	
		2.9	2.1	2.7	2.3	2.3		
		Bottom Face ^						
		8.5	9.5	11.1	14.1	13.9		
		6.1	6.1	6.5	8.9	10.7	Average	9.9
Back Face >		5.1	4.7	5.5	8.9	12.3	Range	23.2
		3.5	3.1	5.3	12.3	11.3	Max	24.7
		1.5	1.7	2.3	2.7	2.5	Min	1.5

Figure 7 – Sample Heat map of sealed non-circulated cabinet Experiment 1a

18A		21.6	18.8	13.0	11.2	10.4		
		15.0	15.0	13.4	12.0	10.6		
17.2	13.8	15.2	16.2	14.8	12.6	11.0	11.4	12.4
12.4	11.2	13.8	14.6	13.0	11.4	9.2	10.6	9.6
13.0	11.0	14.0	14.6	13.2	10.2	9.4	9.0	7.4
22.2	13.8	12.8	12.2	9.6	7.8	7.2	6.4	6.2
1.0	0.0	3.6	5.6	4.8	3.4	2.4	0.4	1.4
		3.0	3.6	3.2	2.4	1.6		
		1.2	0.6	0.8	0.6	0.6		
		8.4	9.0	9.4	12.6	13.6		
		5.4	4.6	5.2	7.2	9.0	Average	8.4
		3.8	3.4	4.0	8.8	10.6	Range	22.4
		1.6	0.2	2.8	9.2	9.0	Max	22.2
		0.0	0.0	-0.2	0.6	0.6	Min	-0.2

Figure 8 – Sample Heat map of ventilated non-circulated cabinet Experiment 1b

17E		16.1	13.1	8.5	11.1	14.3		
		14.5	12.7	9.5	10.5	11.3		
15.9	11.5	9.7	11.3	12.7	11.3	10.1	10.3	14.9
12.1	12.5	11.9	12.5	12.1	11.7	9.9	9.9	8.7
14.7	14.3	15.1	17.1	14.1	11.9	10.7	10.9	9.5
26.9	17.7	18.3	20.1	16.5	13.5	13.1	13.3	12.1
9.1	7.7	14.5	16.9	13.5	13.5	12.3	10.1	10.1
		10.1	10.1	10.5	10.9	9.7		
		9.1	8.1	11.3	10.3	8.5		
		10.1	11.5	10.3	9.5	13.1		
		6.7	7.5	8.5	8.1	11.1	Average	11.3
		5.3	4.7	6.3	7.1	9.3	Range	22.2
		7.7	4.9	5.9	9.7	12.5	Max	26.9
		6.5	5.9	6.1	7.9	8.7	Min	4.7

Figure 9 – Sample Heat map of sealed circulated cabinet Experiment 5a

18E		14.6	11.8	8.6	11.0	13.0		
		13.6	11.8	9.8	10.0	11.0		
15.4	9.4	10.4	12.0	12.0	12.0	9.4	9.6	14.4
10.6	11.8	12.2	12.2	11.8	11.2	9.2	9.2	7.6
13.4	12.2	15.2	16.4	13.8	11.4	10.4	8.8	8.4
24.6	16.0	17.2	18.6	15.4	12.6	11.8	11.8	11.0
7.6	4.6	13.0	15.4	12.4	12.0	11.0	7.4	10.2
		9.8	9.8	10.2	10.4	9.0		
		7.8	7.4	10.2	9.4	7.8		
		10.0	10.4	9.8	8.8	11.4		
		6.0	7.0	7.4	7.0	9.4	Average	10.5
		5.4	4.8	6.0	6.8	9.2	Range	20.0
		7.2	5.0	6.0	10.0	12.8	Max	24.6
		6.4	5.8	6.2	7.6	8.8	Min	4.6

Figure 10 - Sample Heat map of ventilated circulated cabinet Experiment 5b

7. Discussion

7.1. General Trends

Figure 3 shows the variation in temperature differences across the range of experiments. Each experiment consisted of two tests; the solid lines represent tests performed during which the cabinets were sealed, and the dashed lines represent tests performed during which the cabinets were ventilated. As the performance of the cabinet improves, the overall difference in temperature decreases as this represents a lower cabinet temperature relative to the temperature of the environment.

From Experiments 1-5, the number of fans was increased by one each time, and it can be seen in Figure 3 that the temperature difference decreases. In Experiment 6, only the top two fans were active, as is the standard configuration in Ritherdon cabinets. For the sealed tests represented by the solid line, this indicated that the heat transfer through the cabinet wall was aided by the forced convection provided by the fans as there is no other means of escape for the heat.

Figure 3 suggests that there may be a limit to the increase in heat transfer possible in a sealed cabinet, as the temperature difference (solid blue line) plateaus at approximately 25°C. However, it is possible that the use of more fans or a different spatial arrangement may yield better results.

Figure 3 also shows that venting the cabinet produces a consistent decrease in the overall temperature difference between Experiments 1-5. The decrease is less in Experiments 2 and 3, where the active fans were positioned in the bottom left and right next to the vents and angled 45 degrees upwards. These stirrer fans were intended to circulate air around the cabinet, and in this position the fans may not have been effective in drawing the air into the cabinet from the vents. Figure 3 shows that for Experiment 1, venting the cabinet produced a larger temperature drop than for Experiments 2 and 3, despite having no active fans. Venting during Experiments 4 and 5 produced a larger temperature drop, and venting during Experiment 6 produced the largest temperature drop.

7.2. Surface Temperature Distribution

Figures 7-10 show the temperature distribution on the surface of the cabinet broken down into 90 quadrants during Experiments 1 and 5. The lower detached section in each Figure represents the back face of the cabinet. The temperatures shown are the difference between the absolute temperature of each quadrant and the ambient temperature recorded, along with the average for each data set. Figures 7 and 8 show that the range of temperatures for non-circulated cabinets is large as shown by the presence of greener and redder areas, whereas Figures 9 and 10 show a more even temperature distribution, as indicated by the increased presence of orange sections. This is indicative of the hotter gas being in contact with more of the metal which may have aided heat transfer. Venting the cabinet in each case did not produce a significant change in the temperature distribution, aside from an overall temperature decrease, demonstrated by the average values. Experiments 5a and 5b exhibited a higher surface temperature than Experiments 1a and 1b, however the overall temperature difference between the inside and outside of the cabinets was found to be lower. This will be explained in more detail in Section 7.8.2.

It can be seen that the back face of the cabinet does not heat up as much as the front and sides, due to the placement of the plywood backboard impeding heat transfer in this direction. There is a 5mm gap between the backboard and the rear face of the cabinet which may further prevent heat transfer, however it can be inferred that some air makes its way to this space in the top right corner due to the higher temperatures measured there. Forcing airflow into this space may further increase the effective heat transfer area and produce a lower overall temperature difference.

7.3. Experiments 1 and 2

Experiment 1 was used as a baseline, producing a high temperature difference that the proceeding tests could be compared with to assess their performance against a configuration with no additional heat removal measures. This baseline was found to be 30°C for a sealed cabinet and 28°C for a ventilated one.

The sealed temperature difference decreases from Experiment 1 to Experiment 2, whereas the ventilated temperature difference remains constant. This suggests that while the active fan (bottom left, angled 45 degrees upwards towards centre) does improve heat transfer through the walls due to convection, it may at the same time hinder the heat transfer caused by ventilation, resulting in a net-zero change between Experiments 1b and 2b. Table 2 shows that the energy removed from the cabinet via the vents decreases by 5 Watts between Experiments 1b and 2b due to the reduction in temperature difference between the inlet and the outlet. This suggests that spreading the heat energy around the cabinet, while improving convection heat transfer, also means that the temperature of the air leaving the cabinet is lower than it would otherwise be, reducing the temperature difference and consequently the energy leaving the cabinet.

7.4. Experiments 2 and 3

Between Experiments 2 and 3 the ventilated temperature difference begins to decrease while the sealed temperature difference continues its descent. Table 2 shows an increase in air intake through the bottom right vent by 0.3 m/s for the ventilated test, but no change in the air temperature difference. The energy removed by air increases by approximately 5 Watts. At this point, the energy removed from the cabinet via ventilation is very similar to the energy removed in Experiment 1b with no active fans, indicating that the reduction in temperature difference between Experiments 1b and 3b is due entirely to the increase of the convection heat transfer coefficient.

7.5. Experiments 3 and 4

Between Experiments 3 and 4 the gap between the solid and dashed lines increases, indicating that activating the top left fan has a greater effect with regards to temperature difference than the bottom fans, when the cabinet is ventilated. Table 2 shows that between Experiments 3b and 4b, the bottom left and right vent intake speeds increase by 0.3 m/s and 0.1 m/s, the average air temperature difference increases by 6°C and the energy removed increases by 17 Watts. The top fans are positioned right in front of the vents and draw air from inside the cabinet towards them, then expelling the air out through the louvres. This is a much more effective method of encouraging air flow through the cabinet, and also has a positive convective effect as can be seen from the continued temperature decrease for the sealed test.

7.6. Experiments 4 and 5

Between Experiments 4 and 5, Figure 3 shows no significant change in the overall temperature differences. For the sealed tests this suggests that a limit may have been reached with regards to the convective heat transfer coefficient. Table 2 shows that for the Experiments 4b and 5b, air flow increases by 0.3 m/s and 0.4 m/s for the left and right lower vents respectively, however the average temperature difference decreases by 2.9°C. This results in 9.1 Watts more energy being removed from the cabinet. The inside heat transfer coefficient reduces slightly, keeping the temperature difference constant.

7.7. Experiment 6

Figure 3 shows that for Experiment 6a, for a sealed cabinet, using the top two fans positioned just behind the vents produces a similar temperature difference as using the bottom two fans angled upwards at 45 degrees for a sealed cabinet (Experiment 3a), approximately 25°C. Once ventilated however, the configuration in Experiment 6 produces a much larger drop in temperature difference, the lowest temperature difference encountered in this investigation, measured at 20°C.

When comparing Experiments 5b and 6b, it can be seen that the use of the stirring fans in addition to the exhaust fans in fact hindered performance. Table 2 shows that in Experiment 6b, 12.9 Watts more energy was removed from the cabinet by the fans, likely owing to the increased outlet temperature caused by reduced mixing, as the air speeds were similar. The use of the bottom two fans in addition to the top two may have interrupted the flow of air through the cabinet hindering heat transfer through the vents.

For a sealed cabinet, the addition of the bottom two fans caused no significant temperature change. Perhaps the convection 'limit', as previously described, had been reached, and the use of addition fans could no longer produce additional heat transfer through convection, as it was shown to decrease slightly in Figure 4. However for the ventilated cabinet, the internal convection coefficient was shown to increase significantly. This lowered the surface temperature, shown in Figure 3.

This would suggest that for ventilated cabinets the priority should be ensuring a clear path for air to quickly pass through the cabinet with minimal mixing, whereas for sealed cabinets the priority should be ensuring as much mixing as possible with as few fans as possible.

7.8. Heat Transfer Coefficients

Figure 4 shows the heat transfer coefficients calculated using Equation 8 for sealed cabinet tests and 10 for ventilated cabinet tests. These values represent the heat transfer via convection through the walls of the cabinet. The overall heat transfer coefficient increases with an increase in active fans, plateauing at approximately 4.1 W/m^2K for 2, 3 and 4 active fans during sealed tests. The heat transfer coefficients for the ventilated and sealed experiments closely mirror one another suggesting that venting the cabinet did not improve heat transfer due to convection apart from a slight positive deviation at zero fans in Experiment 1 and for two fans in Experiment 6 (top left and top right fans active). This would mean that turning on the first fan in Experiment 2b did cause a decrease in the convective heat transfer coefficient while the cabinet was ventilated as mentioned in Section 7.3, and venting the cabinet while the top two fans were active caused the heat transfer coefficient to increase as mentioned in Section 7.7.

7.8.1. Inside Heat Transfer Coefficient

Figure 3 also shows the temperature difference between the interior to surface, and the surface to ambient. Across all the experiments, the addition of fans generally decreases the inside temperature difference due in part to the increased convection moving the heat around the cabinet. The heat transfer through a material is proportional to the temperature difference across the material. Increased convection replaces cooler air at the inside surface of the cabinet that has already transferred its heat with hotter air that has just picked up heat from the heating element. This increases the temperature difference between the inside air and the surface, increasing the heat transfer coefficient. However, the overall heat transfer is fixed at 400W, therefore according to Equation 8, the increased inside heat transfer coefficient will cause the temperature difference between the inside air and the cabinet surface to decrease. The variation in this heat transfer coefficient is shown by the orange lines in Figure 5.

7.8.2. Outside Heat Transfer Coefficient

Figure 3 shows that the surface to ambient temperature difference increases between Experiments 1-5 and decreases during Experiment 6. The movement of air on the outside is not affected by the fans on the inside of the cabinet meaning that there is no change in convection, and the overall heat transfer through the cabinet is constant. Therefore, according to Equation 8, for sealed cabinets, neither the outside temperature difference nor the outside heat transfer coefficient should change. However, Figure 5 shows that the outside heat transfer coefficient does vary with the arrangement of fans. This phenomenon could be explained in a number of ways, and more detail is provided in Section 8.1.

7.8.3. Radiation vs Convection

In Section 5, Equation 7 suggests that the heat transfer coefficient contains a radiation component and a convection component. Equation 7 is derived from the Stefan-Boltzmann equation (Equation 4) which is based on the interchange of radiation energy between an object and its surroundings, using the surface temperature of the object and the ambient temperature for the calculation. This is valid for the cabinet surface and its surroundings, however inside of the cabinet, the radiation interchange takes place between the surface of the resistor heaters and the inside surface of the cabinet. To calculate the radiation component of the inside heat transfer coefficient, the average temperature of the surface of the heaters would have to be known however, this was not possible to measure using the equipment available during this investigation. Attempts to approximate the radiation component using the temperature difference between the air on the inside of the cabinet and the surface of the cabinet produced radiation components larger than the total inside heat transfer coefficient, which is not possible according to Equation 7.

Therefore, only the outside heat transfer coefficient could be separated into its radiation and convection coefficients, these are shown in Figure 6. The radiation component does not vary significantly, and the convection component mirrors the overall outside heat transfer coefficient.

8. Limitations and Error Analysis

During this experiment there were a number of errors that may affected the results obtained. In this section the errors are identified and their effect on the results are assessed.

8.1. Simplistic thermodynamic modelling

As mentioned in Section 7.8.2, it is possible that Equations 7 and 8 are too simplistic to model this experiment as they are meant to represent a unidirectional homogenous flux of heat passing through a 1-dimensional surface, and may not be appropriate for a 3D model with variable heterogenous heat flux. Perhaps the fact that the heat is more evenly spread out within the cabinet causing more of the cabinet surface to heat up causes the total average surface temperature to increase, and it would be more appropriate to calculate heat flux through each quadrant, which would only be possible if both the inside surface and outside surface temperatures of each quadrant of the cabinet could be known at the same time which was not possible with the equipment available. The effect of heat conducting laterally through the metal was also neglected.

The convective heat transfer coefficient is known to be a function of the Nusselt Number, the ratio of convective to conductive heat transfer. For free convective flow, the Nusselt Number is a function of the Raleigh Number, which itself is a function of the temperature difference, which is in turn dependent on the convective heat transfer coefficient. The interdependent nature of these variables could be causing their variation. More in-depth analysis could be used to generate an iterative model capable of solving this problem.

It could also be that the resolution of the temperature measurement on the surface of the cabinet was not high enough, and if the temperature at all points on the cabinet surface could be accurately measured, the calculated average would give a constant outside temperature difference across all experiments.

The equations above are also only valid for a steady state system. During the course of the day the ambient temperature increases steadily, meaning that the system constantly adjusting to a new equilibrium. This was mitigated by taking multiple readings during the day and calculating the average however this could still affect readings between experiments.

8.2. Surface Temperature Measurement

The average surface temperature of the cabinet was measured by dividing the surface into 90 quadrants recording the temperature of each one using an IR temperature gun. The temperature gun is accurate to the nearest 0.2°C giving each reading an uncertainty of ± 0.1°C. The uncertainty of the average is also ± 0.1°C. This error was judged insignificant as the differences between experiments exceeded this, and increasing the resolution would increase the time spent taking measurements, increasing the likelihood that the average temperature would increase significantly along with the ambient temperature during measurement.

There were also small oscillating fluctuations in the measured temperature of each quadrant of approximately ± 0.2°C, likely due to the variation of heat transfer caused by local convection on the inside of the cabinet. No study was performed into this variation therefore the exact effect is unknown, however its effect was not estimated to be significant due to the number of samples taken to calculate each average.

8.3. Thermocouple Temperature Measurement

The average inside temperature was calculated using eight thermocouples, each accurate to the nearest 0.01°C giving each reading an uncertainty of ± 0.005°C. One reading was taken per second per thermocouple, and the averages for each thermocouple were taken over 10 minutes. Many values were used to calculate the average however the thermocouples were arranged in a 3,2,3 formation on a single frontal plane running down the middle of the cabinet. The temperature was assumed to be constant in an axial direction, whereas in reality will vary. Compared to the 90-point average taken on the surface of the cabinet, the 8-point average taken inside the cabinet is an order of magnitude lower and may not be representative of the true average temperature. If a given fan configuration was to affect the axial temperature distribution, it would not be possible to measure using this experimental configuration. The decision to use only 8 points was done on a cost-benefit basis, considering the price of a single 4-Channel Temperature Logger, however this could potentially be the source of some error. The fans also caused the temperature readings to exhibit a significant amount of noise, however this was mitigated by taking the average of 600 readings for each thermocouple to get a representative value.

The ambient temperature was taken using the ambient temperature sensor of one of the 4-Channel Temperature Loggers. This temperature was assumed to not to vary around the cabinet, however this could be the source of some error.

8.4. Air Flow Measurement and Heat Balance

The temperature of the air flow was measured using a steel temperature probe. Ambient temperature was measured and assumed to be equal to the inlet temperatures. The outlet air temperature was measured by positioning the probe at the vent opening and allowing 20 seconds for the reading on the device to settle. Ambient air temperature was measured separately from the ambient temperature measured by the ambient temperature sensor of the 4-Channel Temperature Logger to reduce error in the heat balance of the air flow, as the same method was used to measure both inlet and outlet temperatures. The temperature probe was accurate to 0.1°C giving it an uncertainty ± 0.05°C, which was not judged to have had a significant impact on the air heat balance.

Table 2 shows that the measured inlet and outlet air speeds differ significantly, and do not produce a consistent mass balance if near-constant pressure and density are assumed. For example, Experiment 6b shows an average inlet speed of 1.25 m/s and an average outlet speed of 4.75 m/s, nearly four times the inlet speed. The pressure and density of the air were likely affected just in front of the fan at the outlets. When used to calculate the energy removed from the cabinet, the outlet speeds produced disproportionately large values, however when the inlet speeds were used to calculate the energy removed for each ventilated test, the resultant heat transfer coefficients calculated using Equation 10 were found to be very close to those calculated for their counterpart sealed tests, as shown by the solid and dashed blue lines in Figure 4.

The anemometer was calibrated to a minimum of 1 m/s, however many of the values measured were below this, putting into question the reliability of these measurements. It is unknown to what degree this may affect results, however this would only affect the estimate of energy removed from the cabinet, and not the overall temperature difference.

8.5. Conditions affecting heat balance

With the increasing addition of fans in the cabinet, the energy produced by the fans may become significant. Each fan is rated 19W and any of this energy not used to increase air speed is most likely causing some temperature increase. Fan efficiencies can be used to estimate the energy converted to heat, however these efficiencies assume no obstructions or other causes of pressure drop, such as the louvres, the cabinet and its internals. For this reason the fans were assumed to add no energy to the system, however this may be a cause of the increase in cabinet surface temperature with the addition of fans.

Ideally the cabinet would be protected from sunlight to prevent the addition of energy to the system however this was not possible during this investigation. Throughout the course of each test, the level of sunlight would vary between early morning darkness and bright sunlight, however for each experiment there was found to be no consistent correlation between the weather and the cabinet temperature differences, and any possible effect of time-of-day was mitigated through each test being a full day experiment, starting and ending at the same time each time, and taking each of the six daily measurements at the same time.

An air current was sometimes present in the testing area as it is not sealed off from the rest of the factory. When the main roller door is open and a breeze passes through, it can pass all the way into the testing area, which would change the external convection heat transfer coefficient. This was mitigated by taking averages and repeating each test therefore it was not judged to have had a significant impact on results.

9. Conclusions

9.1. Sealed Cabinets

The addition of fans in a sealed cabinet caused the overall heat transfer coefficient to increase to a limit after which it remained relatively constant at approximately 4.1 W/m^{2}K. This may be the upper limit to which convection can aid heat transfer through the cabinet, however further investigation would be needed to confirm this.

The position of the fans was found to have an effect on the heat transfer through convection, as shown by the sealed cabinet tests. The bottom left and right stirring fans intended for convection were found to somewhat increase the temperature coefficient, but the top two exhaust fans that were essentially running directly against sealed vents were found to induce a higher convection heat transfer coefficient. This also suggests that pulling air up to the top of the cabinet is more effective than blowing air from the bottom the cabinet. Running fans this close to a sealed surface may however cause damage to the fans in the long-term.

9.2. Natural Convection in Ventilated Cabinets

A significant amount of mass transfer occurs through a ventilated cabinet with no active fans. The air movement caused by convection alone removes enough energy from the cabinet through the vents to significantly reduce its temperature, by 2.6°C in this case when compared to a sealed cabinet. This natural convection was found to be more effective in removing energy from the cabinet than with the use of a single stirring fan, which disrupted the air flow through the cabinet and reduced the air temperature difference between the inlet and outlet, reducing energy the removed.

9.3. Forced Convection in Ventilated Cabinets

Energy removed from the cabinet was not found to be solely dependent on air speed in and out of the cabinet suggesting that other factors were at play, such as the air path, temperature distribution and internal convection.

The position of the fans was found to have a significant impact on the mass transfer through the cabinet. Fans positioned to favour convection and the intake of air (bottom left and right) were found to mostly impede mass transfer through the cabinet whereas exhaust fans were found to favour it.

9.4. Ideal Conditions

The best performing configuration was found to be Experiment 6, during which the cabinet was ventilated by two exhaust fans at the top left and right sides of the cabinet. This was because of the uninterrupted mass transfer of air through the cabinet. The upwards direction of the forced air flow aided the natural convection of heat upwards and out of the cabinet. As the heat energy was not evenly spread through the cabinet, the air exhausted was hotter than in the other experiments, which aided energy removal. An average of 58.1 W was removed by the air, 14.5% of the total energy in the system producing a temperature difference of 20°C between the cabinet and the environment, 10°C less compared to the baseline result of 30°C for Experiment 1a for a sealed cabinet with no active fans.

9.5. Errors and Uncertainties

The most significant causes of uncertainty during this investigation were the measurement of the inside cabinet temperature and the ambient temperature due to their low resolution, however they were not found to cast significant doubt over the main conclusions drawn from this investigation.

10. Recommendations and Future Work

For maximum heat removal, the results of this particular investigation show that air from the cabinet should be ventilated outwards from the top of the cabinet, with intakes at the bottom.

In future experiments, attempts should be made to maximise mass transfer through the cabinet while at the same time minimizing pressure drop caused by obstructions, non-linear air paths and clashing air streams. One possibility would be to use intake fans on one side of the cabinet and exhaust fans on the other side to encourage a lateral passage of air through the cabinet. In this configuration the air streams would not clash as they may have in Experiments 2 and 3, the air would not change direction before leaving the cabinet, and the fans would not compete with each other as the exhaust fans did during this investigation, reducing pressure drop and maximizing fan efficiency. The air would also not be mixed, maximizing the temperature difference between the air inlets and outlets ensuring maximum energy removal.

The use of more vents should also be explored. Using all four fans to exhaust air from the system through a different bank of louvres each on one side of the cabinet while intaking air from the same number of banks of louvres on the other side may produce a higher overall air flow, as the total number of open louvres is doubled.

For sealed experiments, further investigation should be carried out to determine whether the internal convection coefficient can be increased beyond the plateau of 4.1 W/m^2K encountered during this investigation. This may be achieved by forcing air behind the backboard, as it was discovered that much less heat is transferred through the back of the cabinet than the front. This increase in effective heat transfer area may further reduce the inside cabinet temperature.