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Performance Evaluation of a 4.5 kW (1.3 Refrigeration Tons) Air-Cooled Lithium Bromide/Water Hot-Water-Fired Absorption Unit

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ABSTRACT

During the summer months, air-conditioning (cooling) is the single largest use of electricity in both residential and commercial buildings with the major impact on peak electric demand. Improved air-conditioning technology has by far the greatest potential impact on the electric industry compared to any other technology that uses electricity. Thermally activated absorption air-conditioning (absorption chillers) can provide overall peak load reduction and electric grid relief for summer peak demand. This paper describes an innovative absorption technology based on integrated rotating heat exchangers to enhance heat and mass transfer resulting in a potential reduction of size, cost, and weight of the “next generation” absorption units. This absorption chiller (RAC) is a 4.5 kW (1.3 refrigeration tons or RT) air-cooled lithium bromide (LiBr)/water unit powered by hot water generated using the solar energy and/or waste heat. Typically LiBr/water absorption chillers are water-cooled units which use a cooling tower to reject heat. Cooling towers require a large amount of space and increase start-up and maintenance costs. However, RAC is an air-cooled absorption chiller which requires no cooling tower. The purpose of this evaluation is to verify RAC performance by comparing the Coefficient of Performance (COP or ratio of cooling capacity to thermal energy input) and the cooling capacity results with those of the manufacturer. The performance of the RAC was tested at Oak Ridge National

Laboratory (ORNL) in a controlled environment at various hot and chilled water flow rates, air handler flow rates, and ambient temperatures. Temperature probes, mass flow meters, rotational speed measuring device, pressure transducers, and a web camera mounted inside the unit were used to monitor the RAC via a web control-based data acquisition system using Automated Logic Controller (ALC). Results showed a COP and cooling capacity of approximately 0.58 and 3.7 kW respectively at 35°C (95°F) design condition for ambient temperature with 40°C (104°F) cooling water temperature. This is in close agreement with the manufacturer data of 0.60 for COP and 3.9 kW for cooling capacity. Future work will use these performance results to evaluate the potential benefits of rotating heat exchangers in making the “next-generation” absorption chillers more compact and cost effective without any significant degradation in the performance. Future studies will also evaluate the feasibility of using rotating heat exchangers in other applications.

INTRODUCTION

The single-effect water/lithium bromide (LiBr) absorption cycle diagram is illustrated in Figure 1 [1]. It has a condenser and an evaporator just like a vapor compression (VC) air conditioner and operates using similar principles. Refrigerant is pressurized, condensed to a liquid, then expanded and eventually completely evaporated in the evaporator producing

cooling (chilled water) [2, 3]. In a LiBr absorption chiller water is used as the refrigerant. Typically a generator, an absorber, and a solution heat exchanger (sometimes called thermal compressor) are used instead of compressor in a VC system. High pressure refrigerant water vapor (steam) is produced in the generator by a burner (direct-fired units) or hot water or steam (indirect-fired units). Waste heat recovery systems [4] or solar systems [5] can be used to heat water to increase efficiencies and lower energy demands. The hot strong LiBr solution flows through the solution heat exchanger on its way to the absorber. The hot water vapor from the generator is taken to the condenser, where heat is removed, condensing the refrigerant to liquid water. The liquid water is then expanded and sent to the evaporator, where it evaporates and removes heat from the chilled water. The chilled water then flows to an air handling unit (AHU) to cool the air. The low pressure water vapor from the evaporator is reabsorbed into the strong LiBr solution in the absorber. Finally, weak LiBr solution is pumped back to the generator passing through the solution heat exchanger [6]. This heat exchanger is used for internal heat recovery by preheating the weak solution to the generator with the hot strong LiBr solution leaving the generator to improve chiller efficiency.

RAC's heat exchangers (heat and mass transfer units) are all encased in a hermetically sealed drum (Figure 2) while rotating at approximately 300 revolutions per minute (rpm). RAC uses rotational forces to form thin films for improved heat and mass transfer rates [7-12]. This allows the unit to remove enough heat to prevent crystallization and operate without a cooling tower. A three-way valve is also used to protect the unit against crystallization. This valve would isolate the heat input to the RAC under the following conditions:

- Heat input temperature is above 108°C (226.4°F);
- Heat input temperature is above 90°C (194°F) but the ambient temperature is below 22°C (72°F) and the chilled water temperature leaving RAC is below 10°C (50°F);
- When the chilled water temperature leaving RAC is below 5°C (41°F) to avoid refrigerant (water) freeze.

The rotation also allows for special pumps to be used that convert the kinetic energy of the rotating fluid to pressure energy, therefore no additional motors are needed for solution circulation. Because the drum is rotating the unit relies on rotating seals for chilled, cooling, and hot water. The cooling water uses a condenser coil and fan to dissipate heat into the environment [13]. Although some absorption chillers cost more to operate and are twice as expensive (first cost) as their electric vapor compression counterpart, newer technology is helping to reverse this [14]. Cost can be cut by avoiding the cost of a cooling tower and using waste energy to dramatically decrease the payback period opening up possibilities to expand their marketing potential. Waste-heat driven and solar driven absorption cooling systems are found to be an environmentally friendly way to produce cooling and reduce electricity usage and CO₂ emissions [15]. This type of system would also reduce the need for new electric transmission and electric distribution

infrastructure to meet increasing power demands particularly during the cooling periods.

EXPERIMENTAL EQUIPMENT

The RAC unit (Figure 3) is evaluated inside an environmental chamber allowing performance evaluations in a controlled environment (constant outdoor temperatures) at steady state. An 18 kW electric heater was used to produce hot water at a constant controlled temperature. This was used to simulate hot water generated by solar and/or waste heat applications. An oversized 5-ton (17.6 kW) AHU was used in this study. Typically the air flow rate of AHU is approximately 400 scfm/ton (3.2 m³/min/kW) or nominal 2000 scfm (57 m³/min) for a 5-ton (17.6 kW) unit which is much larger than the nominal 520 scfm (15 m³/min) for a 1.3-ton (4.5 kW) unit. This oversized AHU would allow tests over a wide range of air flow rates from approximately 600 scfm (17 m³/min) to 2200 scfm (62 m³/min). During the tests the following parameters were monitored:

- Ambient temperature inside the environmental chamber;
- Chilled, cooling, and hot water temperatures at the inlet and outlet of the RAC using immersion thermistors;
- Chilled, cooling, and hot water flow rates through the RAC using Coriolis mass flow meters;
- Air temperatures at the inlet and outlet of the RAC condenser coil and after the RAC condenser fan using duct averaging thermistor;
- Rotational speed device measuring the rpm of the RAC drum;
- Electric power consumed by the RAC (includes chilled and cooling water pumps, condenser fan, controls, and drum motor);
- Air temperatures at the inlet and outlet of the AHU using duct averaging thermistors;
- Chilled water temperatures at the inlet and outlet of the AHU using immersion thermistors;
- Air flow rate through the AHU using a multi-point, self-averaging Pitot traverse station with integral air straightener-equalizer honeycomb cell, capable of continuously measuring fan discharges or ducted airflow.

Descriptions and accuracies of all the instrumentations are provided in Table 1. Pressure gauges for hot, chilled, and cooling water inside the RAC unit were monitored occasionally via a web camera inside the unit. This camera was also used to observe the rotation of the drum inside the unit. This proved very useful for remote monitoring particularly by the manufacturer. Temperatures, flow rates, electric power consumption, and rpm readings were all monitored and recorded via ALC, a web control-based data acquisition system. The data acquisition system calculated and displayed important parameters such as the air flow rate, capacities, and COP.

TEST PROCEDURES

The ambient and hot water temperatures were set and the RAC was powered on. The unit bypassed the hot water (via the three-way valve) until it reached approximately 79°C (175°F) as required for a single-effect water-fired unit. The drum would then begin to rotate and the hot water was diverted to the RAC. Once the drum began to spin it took approximately 30 minutes for the RAC unit to reach steady-state conditions (Figure 4). Variable parameters for the test included AHU air, hot water, chilled water flow rates, and ambient temperatures. After a change in any of these parameters, the unit was allowed ample time to reach steady-state operation. After reaching steady-state, the data were collected for a period of 30 minutes in one minute intervals. The data were then exported into a spreadsheet file that calculated averaged values for each parameter and performed heat balance. The matrix of tests completed is shown in Table 2. Data was also collected by sensors built into the RAC by the manufacturer. These measurements provided by the RAC's instruments were mainly used for controlling the cycle. However, they provided additional information about the performance of individual components within the absorption cycle that was otherwise unattainable.

RESULTS AND DISCUSSIONS

The design point given by the manufacturer is at an ambient temperature of 35°C (95°F) and hot water temperature of 90°C (194°F). The manufacturer's recommended nominal flow rates for hot and chilled water (18 kg/min or 2,400 lb/h and 32 kg/min or 4,200 lb/h respectively). The chilled water temperature was varied by changing the air flow rate through AHU and the cooling water temperature was controlled by changing the air temperature inside the environmental chamber where the RAC is located. The manufacturer rated the RAC with a COP value of 0.67 at chilled water temperature of 18°C (64°F) leaving RAC under nominal conditions described previously [16]. Figures 5-8 show the COP (ratio of cooling capacity to thermal energy input excluding all the electrical power used) of tests conducted at different flow rates and ambient conditions. The uncertainties for COP are determined to be approximately 2.8%. Figures 9-12 show the cooling capacity of the same tests shown in Figures 5-8. The uncertainties for capacities are determined to be approximately 2.0%. The single variable that had the largest effect on the COP was the ambient temperature. Lowering the ambient temperature decreased the overall chilled water temperature and increased the cooling capacity and the COP. Decreased ambient temperature lowered the temperature of the cooling water making the RAC unit more efficient. Increasing the hot water flow rate resulted in an increase in cooling capacity and COP. As for the effect of air flow rate in AHU, the chilled water temperature increased with air flow rate which, in turn, increased the cooling capacity and COP. These observations are in agreement with the manufacturers' data [11]. The maximum average COP obtained was 0.68 at ambient temperature of

28°C (82°F), hot water flow rate of 23 kg/min (3,000 lb/h), and air flow rate of 2,200 scfm (62 m³/min). The lowest average COP of 0.55 was recorded at ambient temperature of 35°C (95°F) and hot water flow rate of 15 kg/min (2,000 lb/h). In this case no significant effect was found with varying air flow rates. Results showed that optimum COP could be achieved at hot water, chilled water, and air flow rates of 23 kg/min (3,000 lb/h), 32 kg/min (4,200 lb/h), and 2,200 scfm (62 m³/min) respectively. A comparison was done between experimental values and manufactures values shown in Table 3. This comparison shows the relationship between the data and by what percentage the two values differ defined as percent absolute difference [%Diff = |(Test values-Manufacture values)|/(Test values) * 100%]. The COP values for the manufacturer were almost always higher than those of the experimental values with % difference less than 6%. When comparing the cooling capacity, the experimental values tended to be slightly higher than that of the manufacturer's data with % difference less than 13%. To determine how much energy is lost during the entire process a heat balance was conducted. The heat balance, calculated by energy (Q) input (Q of generator (hot water) + Q of cooling capacity (chilled water)) minus the energy output (Q of cooling water) divided by the energy input and multiplied by 100%, gave an averaged value of 3.7%. This shows a very good heat balance with only a small amount of energy lost in the process.

A cooling system installation with a RAC unit uses approximately 1.8 kW of power for outdoor fan, pumps, etc. Since typically outdoor fan in absorption chillers uses approximately half of this power input, it was decided to evaluate the effectiveness of the outdoor fan and the heat distribution in the outdoor coil by thermal imaging camera for possible size and power reduction of the outdoor fan and even re-design of the outdoor coil. This camera was set up and used to determine the heat distribution from the condenser coil with an ambient temperature of 35°C (95°F). The results in Figure 13 show that there is a good heat distribution over the surface of the coils for good heat dissipation and the fan providing more than adequate air flow through the coil. Figure 14 shows the location on the RAC that the thermal image was taken.

To study the effect of the thermal input on the RAC performance, a limited number of tests were performed at lower hot water temperature of 85°C (185°F). The results for ambient temperature of 35°C (95°F), nominal hot/chilled water flow rates, and air flow rate of approximately 1,000 scfm (28 m³/min) show, as expected, decrease in both cooling capacity and COP. Cooling capacity on average decreased from 3.7 to 3.0 kW, and COP – from 0.58 to 0.45.

CONCLUSIONS

This study resulted in a complete performance map of the RAC, although additional tests should be run to test extremes and discover the limits of the RAC. Evaluation showed that our experimental values were in good agreement with the manufacturer's values for the RAC. The ambient temperature

affects the efficiency of the unit, operating less efficiently in warmer environments, causing the COP to decrease as ambient temperatures increase. An increase in COP was also found in both 28°C (82°F) and 35°C (95°F) ambient temperatures when the hot water flow rate was increased from 18 kg/min (2,400 lb/h) to 23 kg/min (3,000 lb/h). This shows the possibility of obtaining a higher COP value if higher water temperature was supplied to the unit. Decrease in hot water temperature supplied to the RAC resulted in reduction of both cooling capacity and COP. The chilled water capacity increased as the air flow rates thru AHU increased, for both 28°C (82°F) and 35°C (95°F) ambient temperatures, showing that more heat was able to be transferred out of the air when there was more air flow available, therefore increasing the cooling capacity. Additional testing as well as comparison to other absorption chillers without a rotating heat exchanger will show the added performance in the heat exchanger itself as well as the feasibility of future use of a rotating heat exchanger in other applications. Additional variables such as higher and lower ambient temperatures, water flow rates, and variable RAC drum rotational speeds can be tested to discover limits of the RAC. The manufacturer is currently working on a “second-generation” unit with higher cooling capacity and improved COP.

Future studies will use the results of these performances to evaluate the potential benefits of rotating heat exchangers and the feasibility of using rotating heat exchangers in other applications.

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Table 1. Major test instrumentation and measurement accuracies used for performance evaluation of the RAC unit.

Measurement	Sensor	Range	Accuracy
Temperature	Immersion thermistor	-67 to 302°F (-55 to 150°C)	±0.4°F (±0.2°C) (32 to 158°F or 0 to 70 °C)
Average Temperature	Duct averaging thermistor	-67 to 302°F (-55 to 150°C)	±0.4°F (±0.2°C) (32 to 158°F or 0 to 70 °C)
Air flow	Fan Evaluator*	0 to 2,500 cfm (0 to 71 m ³ /min)	±2%
Water flow	Coriolis mass flow sensor	0 to 5,000 lb/h (0 to 38 kg/min)	±0.1%
Rotational speed	Portable tachometer	0 to 500 rpm	±0.5 rpm
Electric power	Watt transducer	0 to 5 kW	±0.5% of full scale

* A multi-point, self-averaging Pitot traverse station with integral air straightener-equalizer honeycomb cell, capable of continuously measuring fan discharges or ducted airflow.

Table 2. Test plan used for performance evaluation of the RAC unit at hot water temperature of 90°C (194°F).

	Air flow rate, scfm (m ³ /min)							
	600 (17)		1,100 (31)		1,700 (48)		2,200 (62)	
	Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)	
	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)
Ambient temperature, °F (°C)	95 (35)							
Hot water flow rates lb/h (kg/min)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)
		3,000 (23)		3,000 (23)		3,000 (23)		3,000 (23)
		2,000 (15)		2,000 (15)		2,000 (15)		2,000 (15)

	Air flow rate, scfm (m ³ /min)							
	600 (17)		1,100 (31)		1,700 (48)		2,200 (62)	
	Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)		Chilled water flow rate, lb/h (kg/min)	
	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)	3,200 (24)	4,200 (32)
Ambient temperature, °F (°C)	82 (27.8)							
Hot water flow rates lb/h (kg/min)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)	2,400 (18)
		3,000 (23)		3,000 (23)		3,000 (23)		3,000 (23)
		2,000 (15)		2,000 (15)		2,000 (15)		2,000 (15)

Table 3. Experimental vs. Manufacturer’s data for COP and cooling capacity (% Difference is the percentage by which the experimental values differ from the manufacture’s data).

CHW Supply Temp* °F (°C)	CW Temp to the absorption unit** °F (°C)	Manufacture Quoted COP	Test-COP	% Difference
54.9 (12.7)	95.4 (35.2)	0.64	0.62	3.2
55.6 (13.1)	95.5 (35.3)	0.64	0.63	1.6
57.2 (14.0)	95.9 (35.5)	0.66	0.63	4.8
58.3 (14.6)	96.1 (35.6)	0.67	0.64	4.7
58.6 (14.8)	104.7 (40.4)	0.56	0.54	3.7
61.0 (16.1)	105.6 (40.9)	0.58	0.61	4.9
62.1 (16.7)	104.0 (40.0)	0.60	0.58	3.4
62.4 (16.9)	105.4 (40.8)	0.59	0.56	5.4
66.7 (19.3)	107.4 (41.9)	0.63	0.65	3.1
68.2 (20.1)	107.6 (42.0)	0.61	0.62	1.6
CHW Supply Temp* °F (°C)	CW Temp to the absorption unit** °F (°C)	Manufacture Quoted Capacity RT (kW)	Test-Capacity RT (kW)	% Difference
54.9 (12.7)	95.4 (35.2)	1.4 (4.8)	1.5 (5.3)	9.4
55.6 (13.1)	95.5 (35.3)	1.4 (4.8)	1.6 (5.5)	12.7
57.2 (14.0)	95.9 (35.5)	1.5 (5.2)	1.6 (5.6)	7.1
58.3 (14.6)	96.1 (35.6)	1.5 (5.4)	1.6 (5.8)	6.9
58.6 (14.8)	104.7 (40.4)	0.9 (3.3)	0.9 (3.2)	3.1
61.0 (16.1)	105.6 (40.9)	1.0 (3.4)	1.0 (3.6)	5.6
62.1 (16.7)	104.0 (40.0)	1.1 (3.9)	1.1 (3.7)	5.4
62.4 (16.9)	105.4 (40.8)	1.1 (3.7)	1.0 (3.6)	2.8
66.7 (19.3)	107.4 (41.9)	1.3 (4.6)	1.4 (4.9)	6.1
68.2 (20.1)	107.6 (42.0)	1.3 (4.7)	1.3 (4.6)	2.2

* Chilled water supply temperature leaving the RAC unit.

** Cooling water return temperature (cooling water to the absorber and condenser) entering the RAC unit.

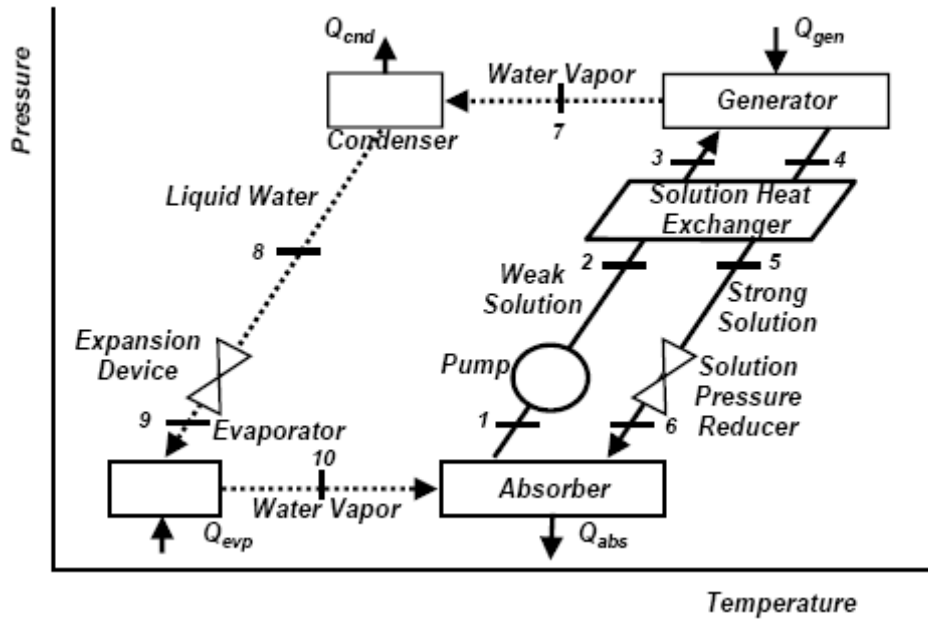


Figure 1. Single-effect water/LiBr absorption cycle diagram.

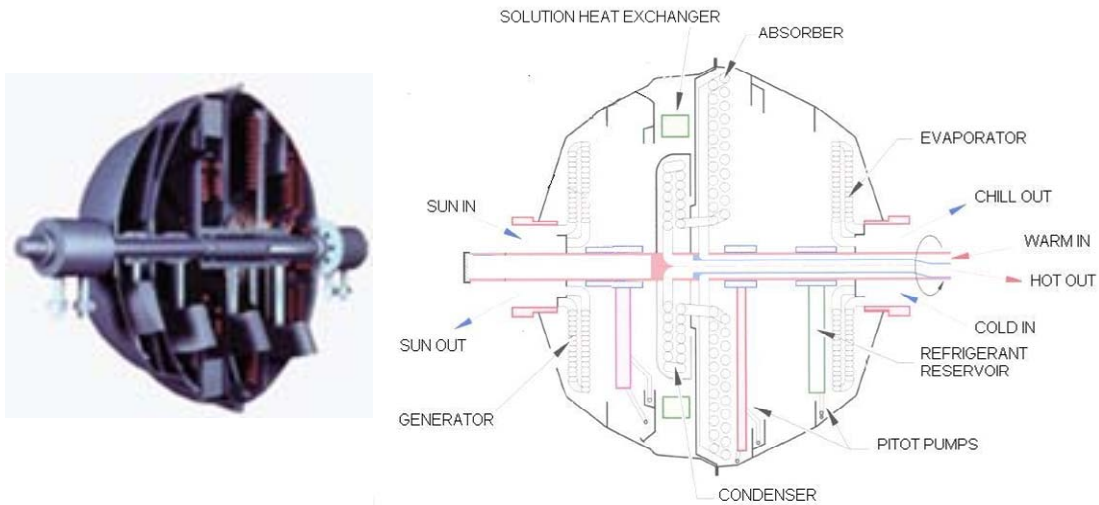


Figure 2. RAC heat exchangers in sealed drum.



Figure 3. Picture of RAC unit.

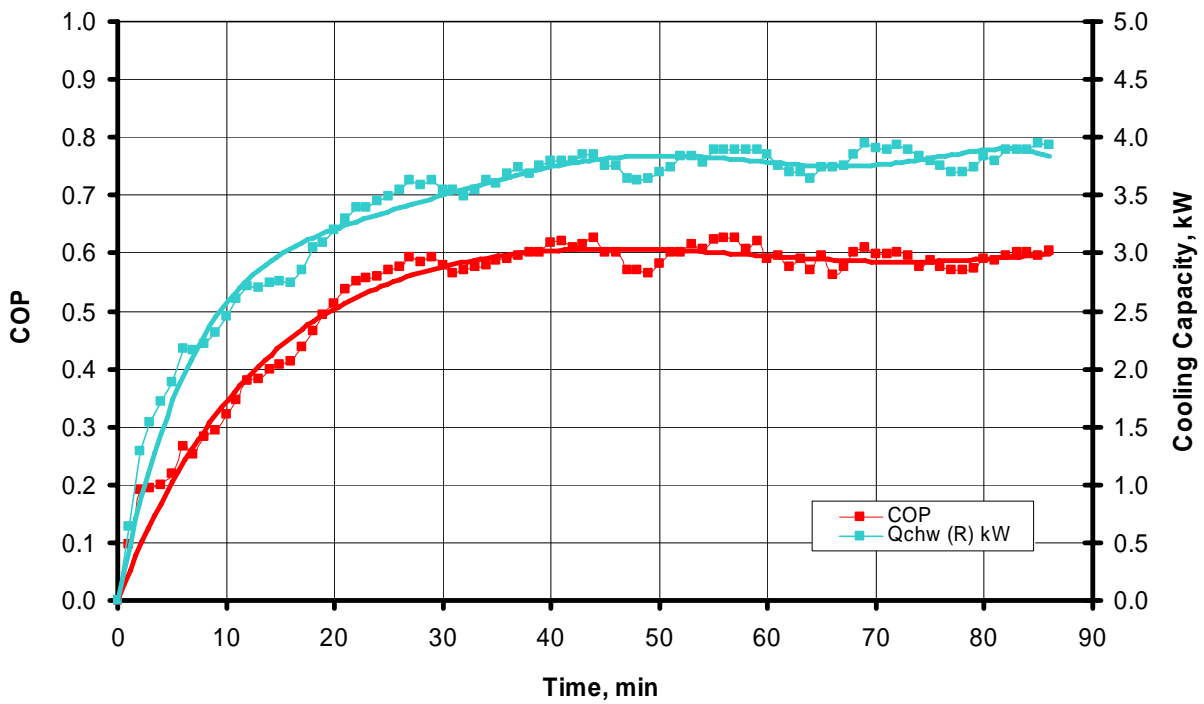


Figure 4. Startup of RAC unit (cooling capacity and COP).

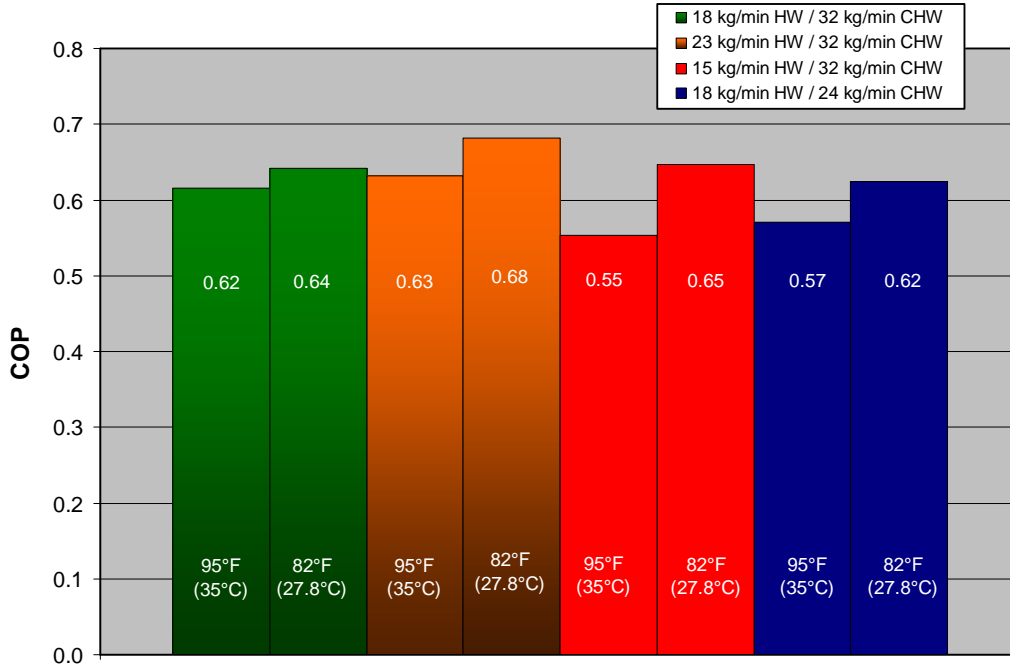


Figure 5. Coefficient of Performance of RAC unit at 2200 scfm (62 m³/min) air flow thru AHU.

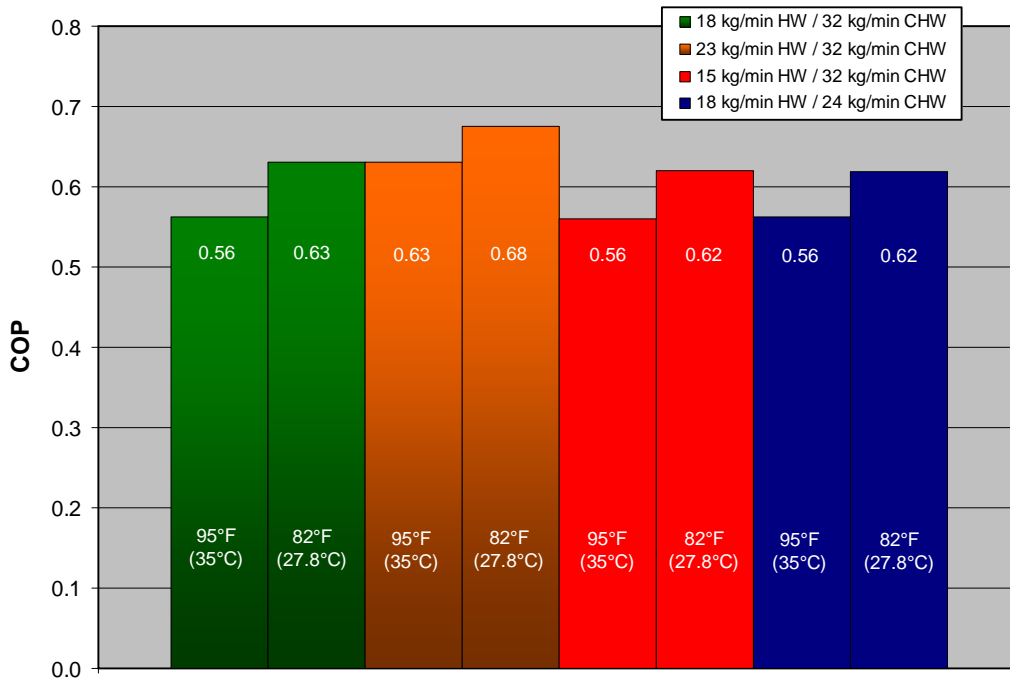


Figure 6. Coefficient of Performance of RAC unit at 1700 scfm (48 m³/min) air flow thru AHU.

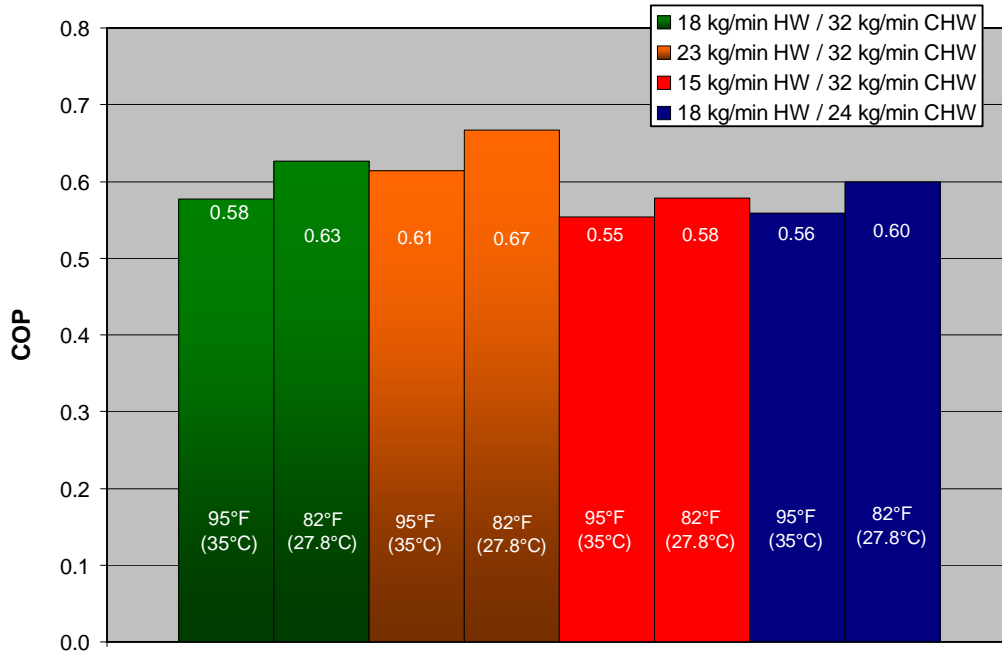


Figure 7. Coefficient of Performance of RAC unit at 1100 scfm (31 m³/min) air flow thru AHU.

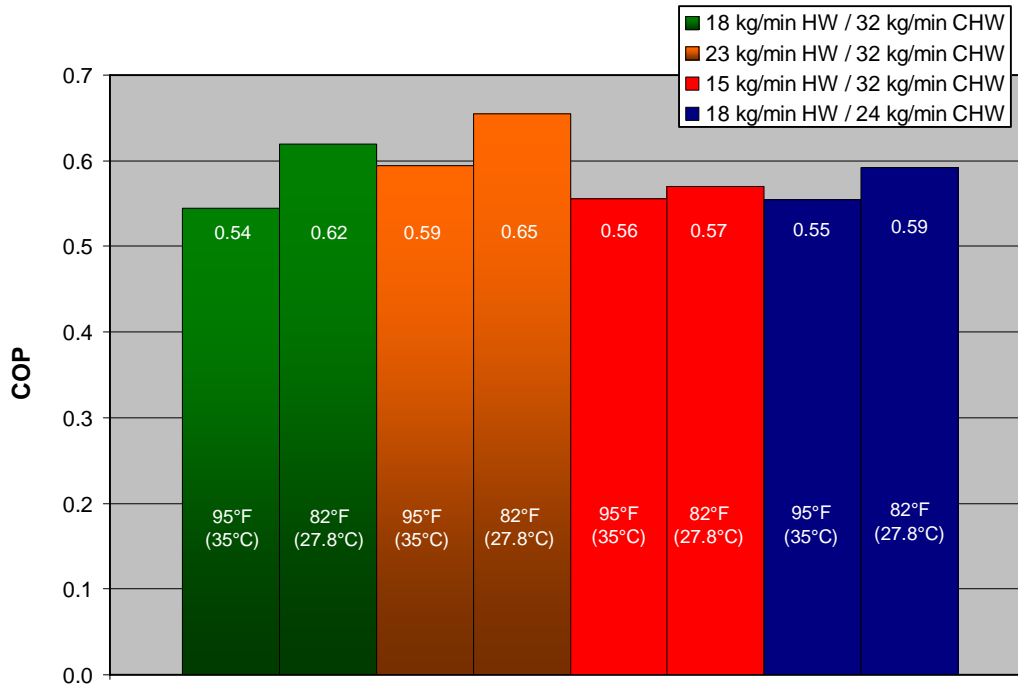


Figure 8. Coefficient of Performance of RAC unit at 600 scfm (17 m³/min) air flow thru AHU (approximate nominal AHU air flow required for 1.3-ton or 4.5 kW chiller).

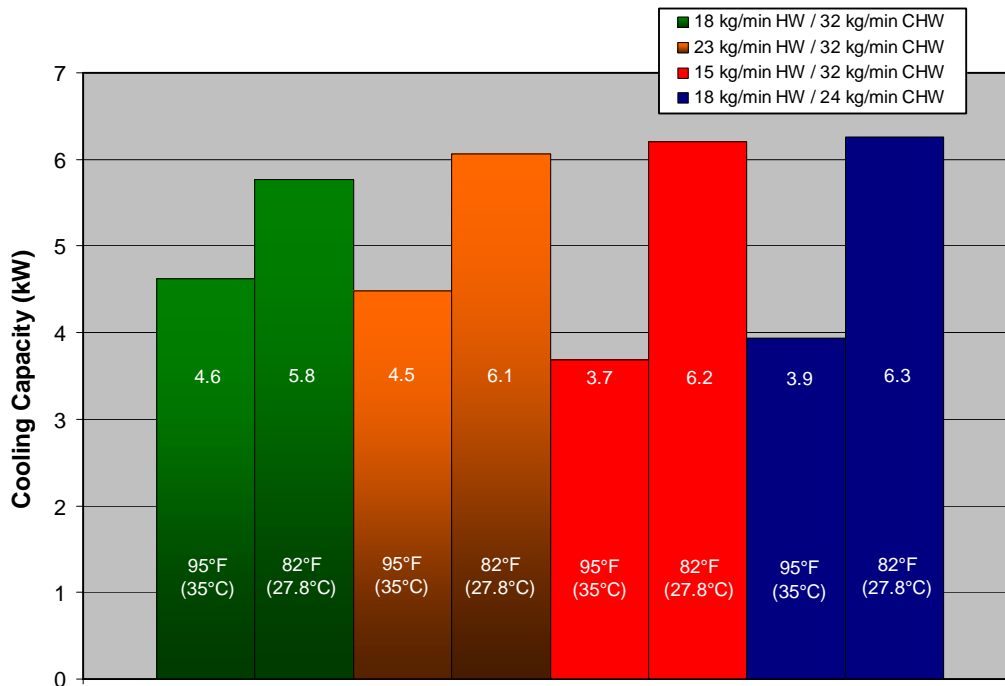


Figure 9. Cooling Capacity of RAC unit at 2200 scfm (62 m³/min) air flow thru AHU.

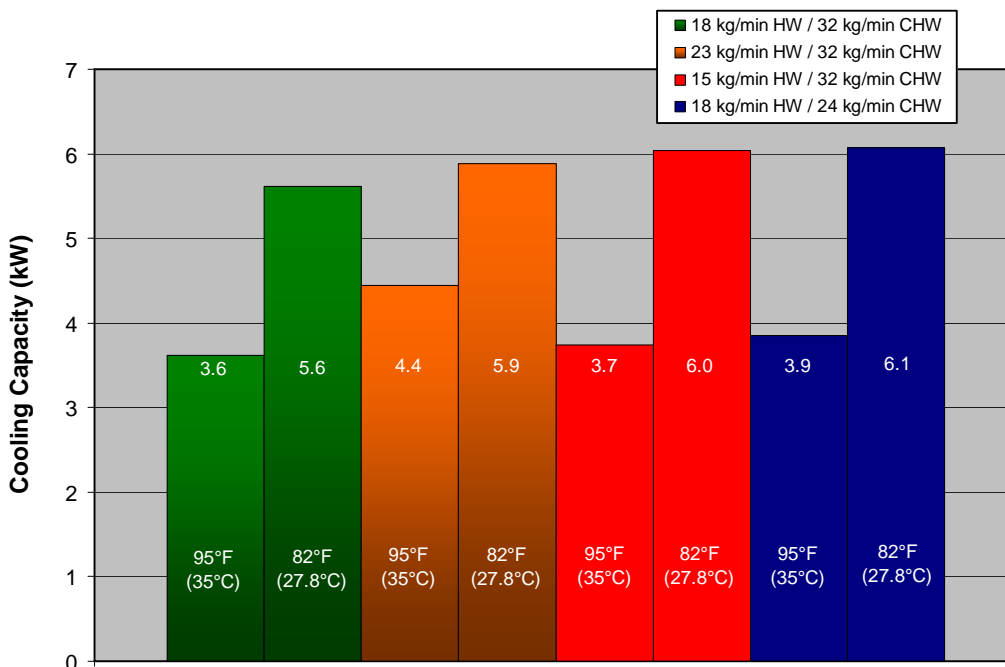


Figure 10.

Capacity RAC unit at 1700 scfm (48 m³/min) air flow thru AHU.

Cooling

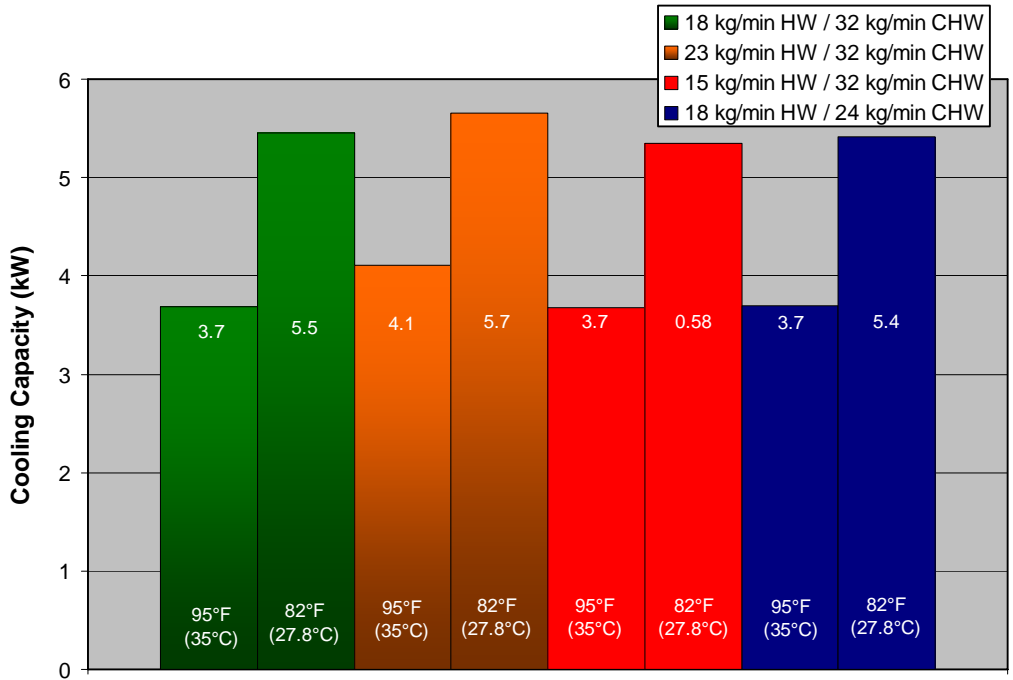


Figure 11. Cooling Capacity of RAC unit at 1100 scfm (31 m³/min) air flow thru AHU.

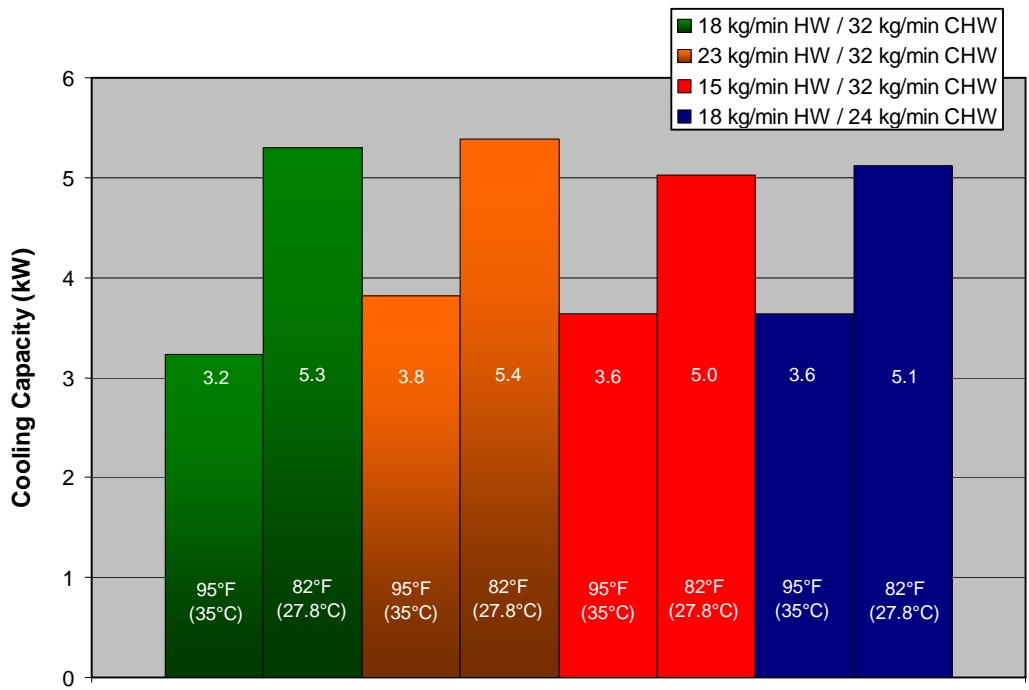


Figure 12. Cooling Capacity of RAC unit at 600 scfm (17 m³/min) air flow thru AHU (approximate nominal AHU air flow required for 1.3-ton or 4.5 kW chiller).

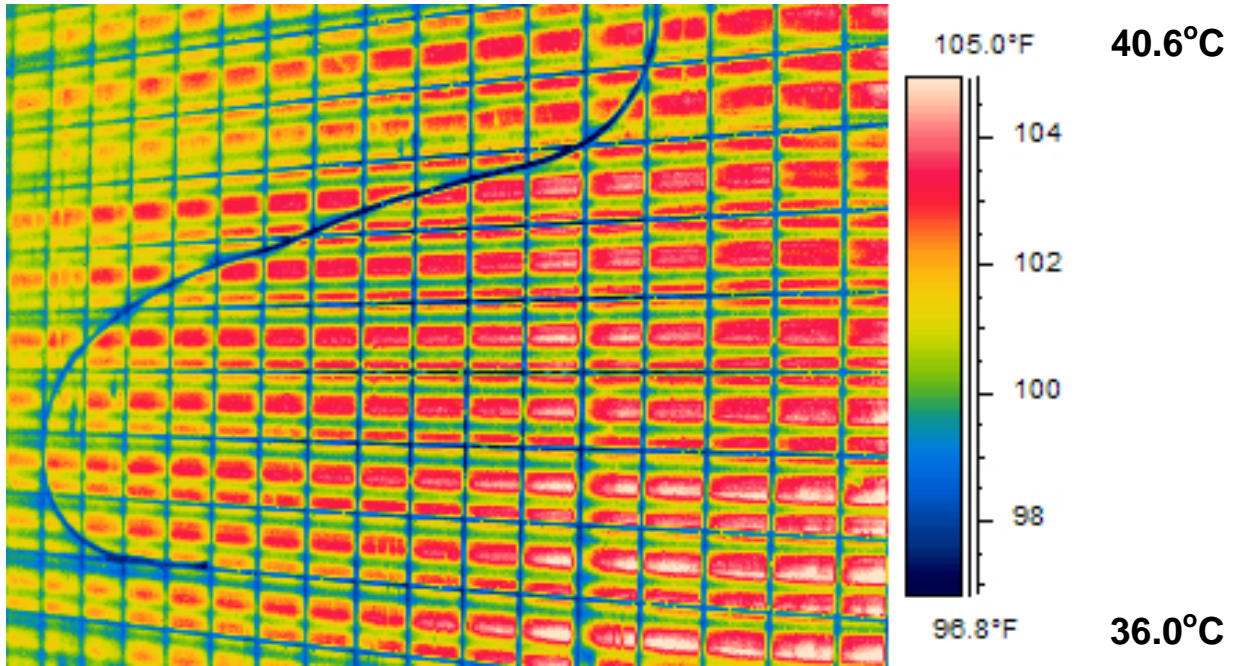


Figure 13. Thermal image of condenser coil.

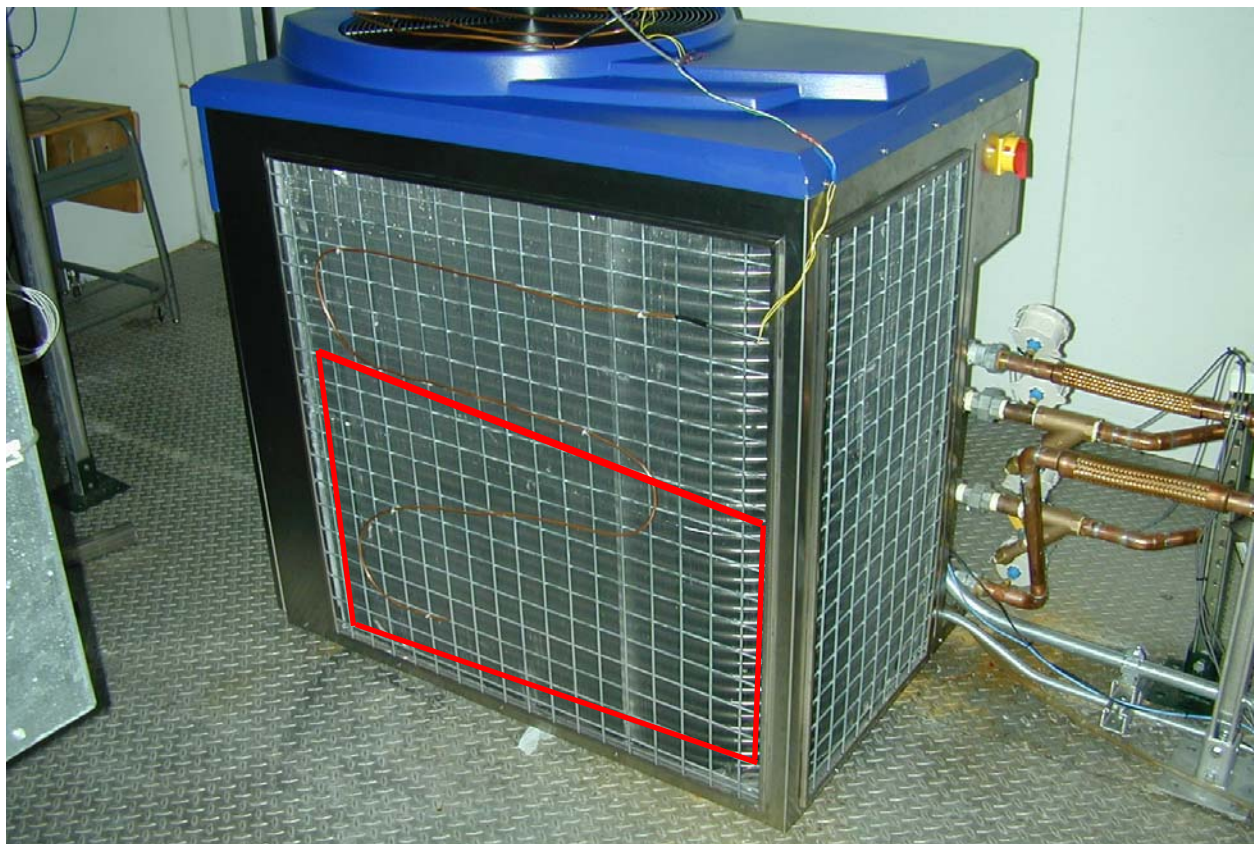


Figure 14. Location on coil used for thermal imaging.