Boeing Heat Exchanger

Finalized Testing Plan

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1. Design Requirements Summary

The customer requirements specified by the client and the engineering requirements developed by the team must be tested to see if the design meets all performance targets. Each customer and engineering requirement is detailed below.

CR1: The liquid coolant going into the radiator must be cold enough from the heat exchanger that when it conducts heat transfer to the air it will drop its temperature to a felt degree.

CR2: This system models the Apache Helicopter vapor compression system which will use HFO-1234yf which is a combustible refrigerant so a firewall will need to be put in place to isolate the cockpit from the refrigerant.

CR3: The liquid-to-liquid heat exchanger must meet this maximum sizing requirement. No weight constraint is specified.

CR4: Since the client requires the design of a demonstrator, they have requested clear housing to make the internal design of the heat exchanger visible.

CR5: The client would like to see the demonstration of the heat exchanger in person, so the system must be easy to transport and can be set up and operational within 1 hour.

CR6: The heat exchanger must continue to expel cold coolant to the radiator for a duration of 30 minutes.

ER1: The system must channel cold air to an observer's hand. As such, the design must be able to bring the fan air temperature as low as possible. At minimum, the air temperature should be at least 5 °C below room temperature, assuming the ambient temperature is 20 °C.

ER2: The entire system must be easily transportable for the purposes of transferring from NAU to the Boeing facility in Mesa, AZ. Thus, all components should fit within a compact volume. When packed, the system should fit within a volume of 1 m^3. Additionally, the client defined a maximum area of 6"x6"x18" for the liquid-to-liquid heat exchanger, which represents an additional volume constraint specific to that subsystem.

ER3: The client specified that the system must operate for at least 30 minutes without melting all the ice within the system. As such, the design should be fully functional for more than half an hour without failure.

ER4 An important consideration for heat exchanger design is the amount of head losses in the form of pressure drop. The client listed a specified pump that supplied 45 psi of pressure head. Given this limit, the team set the maximum allowable pressure loss to be 40 psi.

ER5: The team has a budget of $5,000 provided by Boeing with an additional $1,000 in the form of a VA grant. All testing equipment, prototyping, and material costs must collectively be below the $6,000 of funding available. To appropriately allocate the budget, the material cost of the system should be less than $1,000, excluding expenditures for ice.

ER6: The liquid-to-liquid heat exchanger is the main component to be designed. Since the team is unable to control the efficiency of the radiator (coolant-air heat exchanger), the liquid-to-liquid heat exchanger should be as efficient as possible. The team has defined a minimum effectiveness of 50% with a target of 60%.

2. Testing Plan

2.1 Top Level Testing Summary

List all the tests that you will be performing and map your Design Requirements in a table look like the one below. Not all these requirements make sense to test, since some are design limits. ERs and CRs like the volume requirement and the presence of a firewall have no real way to be tested and the system was designed to inherently meet these requirements. However, the team devised three experiments to test parameters that are not readily known, such as heat exchanger effectiveness or head loss. These experiments and their relevant design requirements are briefly summarized in Table 1 below.

Table 1: Summary of Experiments

Experiment/Test	Relevant DRs
Exp 1 – Inlet/Outlet Temperature Test	CR1, ER1, ER3, ER6
Exp 2 – Pressure Drop	ER4
Exp 3 – Sealing Tests	CR6, ER3

Experiment 1 involves testing the heat transfer of the system. Experiment 2 focuses on head losses through the heat exchanger. Experiment 3 tests the quality of the seals used at all fittings and connections.

2.2 Detailed Testing Plans

Each of the experiments will be conducted under normal operating conditions. This gives the team information regarding how the design will perform compared to the expected performance from calculations.

2.2.1 Inlet/Outlet Temperature Test

Experiment Summary

The temperature test will check the effectiveness of the liquid-to-liquid heat exchanger and the overall system. CR1 will be tested by measuring the coolant temperature at the inlet and outlet of the radiator. Temperature measurements of the radiator inlet and outlet will be taken to ensure the air flow is colder than the ambient environment (ER1). The temperatures of the liquid-to-liquid heat exchanger inlets and outlets will be used to calculate the heat exchanger's effectiveness (ER6). The temperature of the water expelled into the ice water tank will be used to determine the time it takes to melt the ice in the tank (ER3).

This test will use eight NPT threaded thermocouples inserted near the inlets and outlets of all major components (holding tanks, heat exchanger, radiator). These thermocouples will be connected to a Pico TC-08 data logger and PicoLog DAQ software to collect temperature data. These temperatures will be used to calculate effectiveness for the system and the temperature of the airflow.

Procedure

1. Connect thermocouples to TC-08.
2. Start PicoLog and enable all channels, setting sample interval to 100ms.
3. Power on pumps and fans to start the system.
4. Wait for temperatures to reach steady state operation.
5. Calculate the effectiveness of the heat exchanger.
6. Calculate the temperature of the outlet air.

Results

The target effectiveness for the heat exchanger is 60%. The following fundamental equations are how the team calculated the theoretical efficiency.

$$\varepsilon = \frac{\text{q}}{\text{qmax}}$$

$$\varepsilon = \text{efficiency}\; q = heat\ transfer \quad q_{max} = \text{max}\, heat\ transfer$$

The following equation gives the theoretical heat transfer:

$$\text{q} = (\text{Thi} - \text{Tco})/\text{Req}$$

$$T_{hi} = High\ Teperature \quad T_{co} = Cold\ Teperature\ R_{eq} = Thermal\ Resistance$$

To get the cold side heat transfer, the team will assume the temperatures of the inlets and outlets to be 0 °C and 20 °C respectively for the ice water side and the thermal resistance will be for water. The following equation was used to find the maximum heat transfer via the coolant.

$$\text{qmax} = \text{Cm}(\text{Thi} - \text{Tco})$$

$$C_m = Specific\ Heat\ Capacity$$

The team used similar assumptions knowing the temperatures of the inlets and outlets from the previously used NTU method and found the heat transfer via the hot side. These calculations resulted in an effectiveness of about 0.62, or 62%. The full math and values can be found in the team's past presentations as well as in the mathematical model. This expected value is within the teams' expectations, so if the assumptions hold true, the design should reach the target effectiveness. The team also needed to find the temperature from the outlet of the radiator to blow onto a judge's hand. Using the fundamental equations for the efficiency of the heat exchanger, the following equation was devised.

$$T_{air,out} = T_{air,in} - \varepsilon * (T_{air,in} - T_{coolant,in})$$

Since air has a lower heat capacity than the coolant, air outlet temperature was dependent solely on efficiency and inlet temperatures. The air coming out of the radiator was calculated to be about 13.77 °C which is below the 15 °C target temperature.

This experiment also determines the amount of ice that is needed to meet DRs CR1, ER1, and ER3. This was achieved by calculating the total energy the ice needed to absorb to last for 30 minutes. The following equation was used to find the amount of energy needed for the ice to bring the initial water down to 0 °C.

$$\mathrm{m} = \mathrm{V} * 3.79 = 22.7\mathrm{kg}$$

$$V = Volume \quad m = mass\ of\ water$$

$$E_i = \mathrm{m\ x\ hc\ x\ (Ti - Tf)} = 1{,}903.8\mathrm{kJ}$$

$$E_i = Initial\ Energy \ \ h_c = Specific\ Heat \ \ T_i = Initial\ Temp \ \ T_f = final\ Temp$$

Then, the amount of energy that was being brought into the system from the heat exchanger was calculated.

$$\mathrm{m} = 0.2527\ \mathrm{x}\ (1800) = 454.86\ \mathrm{kg}$$

$$\mathrm{Em} = \mathrm{m\ x\ hc\ x\ (Ti - Tf)} = 25130\ \mathrm{kJ}$$

The total of these two energies is the amount of energy absorbed by the ice.

$$\mathrm{Ef} = \mathrm{Ei} + \mathrm{Em} = 27034\ \mathrm{kJ}$$

The following equation gives the total number of energies the ice can absorb based on sensible and latent heat.

$$Q_{total} = Latent + Sensible = 374 \frac{kj}{kg}$$

$$m_{ice} = \frac{E_f}{Q_{total}} = 72.3\ kg\ or\ 159.6\ lbs\ of\ ice$$

To operate for 30 minutes, 160 lbs. of ice is needed to keep the ice bath at constant temperature. The experiment will give a better approximation of this amount, but this gives a good estimate for the required amount of ice.

2.2.2 Pressure Drop Test

Experiment Summary

This test will measure the pressure drop across the liquid-to-liquid heat exchanger. The pressure at the inlets and outlets of the heat exchanger will be compared to ensure the head loss is below 40 psi (ER4). Four digital pressure gauges will be connected to the system to measure the inlet and outlet pressures of each fluid moving through the heat exchanger. Pressure loss will be calculated by taking the difference between the inlet and outlet pressures.

Procedure

1. Turn on digital pressure gauges and pumps.
2. Wait until all four pressure gauges have stabilized their readings.
3. Calculate the difference between inlet and outlet pressures for each fluid.

Results

To calculate the theoretical pressure difference across the heat exchanger the friction factor had to be calculated using the following equation.

$$\frac{1}{\sqrt{f}} = -2.0 * \log\left(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re * \sqrt{f}}\right)$$

$f = Friction\ Factor \quad e = pipe\ roughness \quad D = inner\ diameter\ of\ tube$

$$Re\ is\ the\ Reynold's number$$

The team got a friction factor of about 0.0654 with the team's current diameter assumed Reynolds number to make the flow turbulent and the pipe roughness. The team then calculated the pressure difference using the following equation.

$$\Delta p = \rho\left(f * \frac{L}{D} + \frac{V^2}{2}\right)$$

$$\Delta p = pressure\ difference \quad \rho = fluid\ density \quad L = tube\ length$$

$$V = average\ fluid\ velocity$$

The team found the expected head loss should be around 1.2 psi, the allowable head loss for the system would be about 40 psi so the team does not expect any issues with the pressure loss across the heat exchanger but will perform the experiment to validate the equations and solutions.

2.2.3 Sealant Test

Experiment Summary

This test determines where seals have failed. The system will operate continuously for half an hour to ensure that all external seals prevent leaks and that both fluid loops are isolated from each other. Any leaks necessitate system shutdown, so this test will ensure the system can reach the desired operation time (CR6, ER3). There are no variables associated with this test.

Procedure

1. Turn on both pumps to start fluid flows and start 30-minute timer.
2. Check for external leaks in fittings and connections in between plastic tubing and the pumps, testing equipment, heat exchanger, and radiator.
3. Check for external leaks in both heat exchanger end caps (gaskets and O-rings)
4. Check for internal leaks in the heat exchanger. Coolant will be a distinct color from ice water, so leaks will be apparent.
5. Repeat leak checks until 30 minutes have elapsed.

Results

The most important seal in the system is the gaskets used in the heat exchanger end caps. The compression percent needed to be calculated to figure out how much gasketing material to use. The allowable torque of 75% material modulus was found using the following equation.

$$T = K * D * P$$

T = Target Tighten Torque K = Coefficient of friction D = Bolts Nominal Diameter

P = Bolts desired tensile load

Next, the following equation calculated the clamping force using the worst-case scenario of 25% of the calculated force.

$$F = \frac{T}{K} * D$$

F= clamping force

The total clamping force was determined using the sum of the individual clamping forces. With this, the compression percentage can be found with the following 2 equations, treating the gasket as a beam with uniform cross section and uniform material properties.

$$\delta = \frac{F * L_i}{A * E}$$

$$Percent\ compression = \frac{L_i - L_n}{L_i} * 100\%$$

$\delta = displacment$ F=total clamping force L_i= original gasket height

L_n=new gasket height A=Cross sectional area E=Youngs modulus

The expected compression from these equations is 10-60% which falls within the ideal static sealing range for rubber gaskets of 10-50%. These calculations are approximations as many factors can influence the actual clamping force, hence the necessity of testing.

3. Specification Sheet Preparation

Using these experiments, the team will be able to see if the current design meets the specified design requirements. The following tables are templates to communicate which design requirements are currently met by the design. Table 2 shows the customer requirements, whether the design satisfies them, and whether the client finds the design acceptable.

Table 2: Summary of Customer Requirements

Customer Requirement	CR met? (✓ or X)	Client Acceptable? (✓ or X)
CR1 – Air Temperature	TBD	TBD
CR2 – Firewall Installed	✓	✓
CR3 – HXR Volume Limit	✓	✓
CR4 – Clear HXR	✓	✓
CR5 – Portable System	✓	✓
CR6 – 30min Operation	TBD	TBD

The design already satisfies many requirements. The system is segmented by a metal sheet representing the firewall. The heat exchanger is smaller than the 6"x6"x18" maximum size specified by the client. The tube of the heat exchanger is made of transparent acrylic, satisfying the requirement for a clear housing. All components collectively fit within a 1 cubic meter volume, which means that the system is easy to transport. Requirements of the air temperature and operation time are currently unknown but will be determined after testing.

Table 3 shows the engineering requirements, the ER target, the actual value, and whether values meet ER targets or client targets. Since testing has not been conducted yet, the measured/calculated values column contains the expected results from calculations.

Table 3: Summary of Engineering Requirements

Engineering Requirement	Target	Measured/ **Calculated** Value	ER met? (✓ or X)	Client Acceptable? (✓ or X)
ER1 – Low Air Temp	< 15 °C	13.77 °C	✓	TBD
ER2 – Small System Volume	< 1 m^3	TBD	✓	TBD
ER3 – High Operation Time	> 30 min	TBD	TBD	TBD
ER4 – Low Pressure Drop	< 40 psi	1.2 psi	✓	TBD
ER5 – Minimized Cost	< $1000	~$854	✓	TBD
ER6 – High HXR Effectiveness	> 60%	62%	✓	TBD

Currently, the design is expected to meet most engineering requirements. The expected temperature of the airflow is below the set target of 5 °C below room temperature. The actual volume of the system when packed has not been physically calculated, but by inspection, is below the target volume. Pressure drop across the tube side of the heat exchanger is well below the allowable pressure drop determined by the pump performance. Current material costs for the system, excluding testing equipment, is less than the $1,000 allocation set by the team. Effectiveness determined by heat transfer equations is near the target 60 % effectiveness. The operation time of the system will be determined through testing.

4. QFD

The QFD links the team's engineering requirements to the requirements specified by the client. For reference, the full QFD is shown in Appendix A. The results of Experiments 1 and 3 directly impact whether CR1 and CR6 are met.

Experiment 1 tests ERs 1, 3, and 6 which according to the QFD, are correlated with CR1. Since the client requires cool air to be blown out of the radiator, the temperature of that air (ER1) clearly affects how well the system can meet this requirement. Similarly, heat exchanger effectiveness (ER6) affects how cold the coolant becomes when it enters the radiator, changing how much heat transfer can occur between the coolant and the air. This test also helps the team determine how long the system will operate (ER3) before all the ice is melted. Thus, the operation time given by the amount of ice used determines how long the system can continuously cool air.

Experiment 3 tests ER3 which is linked to CR6. This test on the sealants for the required operation time demonstrates that the system can operate without failure for the time specified by the client. If the seals hold for the duration of the experiment, the team will know that the system is durable enough to operate long enough to satisfy this client need.

5. Conclusion

The developed experiments give a good insight into the performance parameters that are still unknown in the design. The initial results of this testing will indicate if the current design meets client needs or if modifications need to be made before final project presentation and client handoff. A final round of testing after all necessary modifications will demonstrate the final performance metrics of the design and whether the client is satisfied with the product.

Appendix A: QFD

System QFD

Project: Boeing Heat Exchanger
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#	Technical Requirement	1	2	3	4	5
1	Low Air Temperature					
2	Small System Volume	-3				
3	High Operation Time	-3				
4	Low Pressure Drop		-3			
5	Minimized Cost	-3	3	-3		
6	High HXR Effectiveness	9	-6	-6	6	-9

Legend	
A	Current Apache System
B	Boeing 777 System
C	GM Environmental Control System

#	Customer Needs	Customer Weights	Low Air Temperatue	Small System Volume	High Operation Time	Low Pressure Drop	Minimized Cost	High HXR Effectiveness	*1 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*
			Technical Requirements						**Benchmarking**				
1	Fans should channel cool air to judge's hand	5	9		6			9				C	AB
2	Inlet and outlet lines must pass through 'firewall'	3		3			3		AC		B		
3	Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6			N/A		
4	Clear Housings	3	3			3	3	3	ABC				
5	Portable for demonstration	3		9	3		6		ABC				
6	System must operate for 30 minutes	2	3		9		3	6					ABC
	Technical Requirement Units		°C	m^3	min	PSI	USD	%					
	Technical Requirement Targets		<15	<1	>30	<40	<1000	>60					
	Absolute Technical Importance		60	63	57	36	51	84					
	Relative Technical Importance		3	2	4	6	5	1					