RM26 EV Thermal Management System Design

By Matthew Galarza

Rensselaer

Motivation

The growing trend towards an environmentally-friendly and energy-efficient society has shifted the focus of automotive manufacturers from IC engines to battery-powered electric motors.

As a result, the Rensselaer Motorsport team will be transitioning to an EV car for the upcoming year which will bring about new requirements for effective cooling of electronic components.

Specifically:

- Electric Motor
- Electronic Speed Controller (ESC)
- Accumulator (Battery cells)

Project Goals

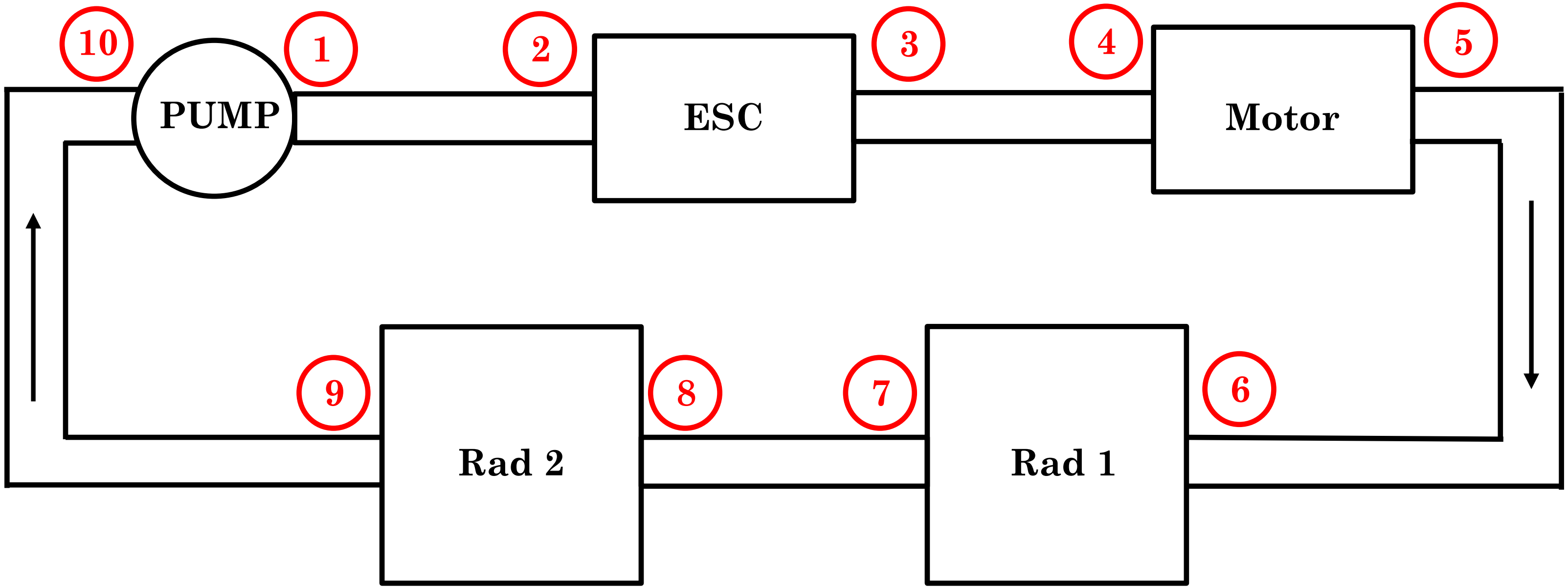
Design, simulate and, improve thermal management system for the RM26 vehicle with the following objectives:

- Maximize heat transfer rate based on current available systems
  - Determine if new systems are required to achieve cooling metrics
- Reduce vehicle weight and drag from cooling systems
- Improve operating temperatures of devices

Develop a robust modeling system to provide insight into vehicle performance in varying operating conditions, timeframes and system altercations.

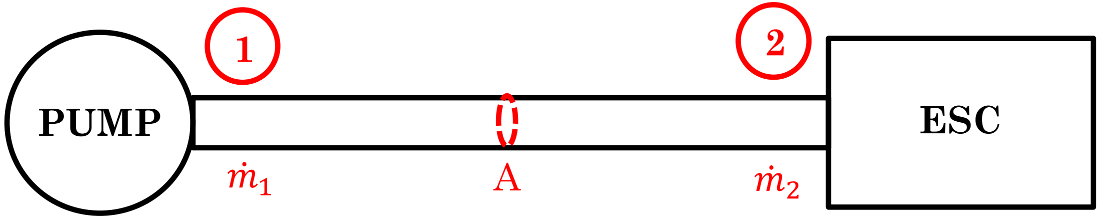
Modeling Schematic – Variable

The thermal system will be modeled as a closed loop circuit with specific positional numbers:



Pressure Drop Analysis

Pipe Flow Analysis



Between control volume flows, friction losses are account to predict mass flow rate changes:

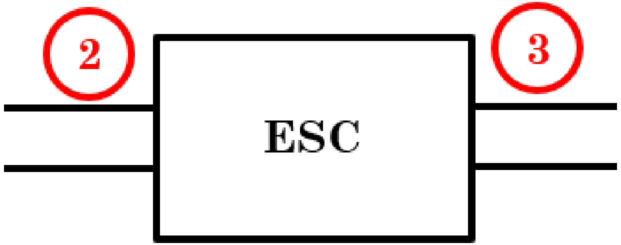
Pressure Drop in Circular pipe:

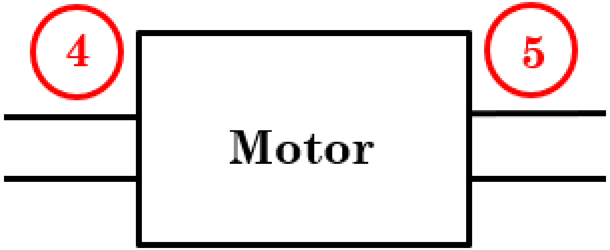
$$\Delta P_{1\rightarrow 2} = f\left(\frac{L}{D}\right)\left(\frac{pV^2}{2}\right)$$

Friction Coefficient – Colbrook Equation:

$$f = \frac{0.25}{\left[\log\left(\frac{\epsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

Component Flow Analysis





The ESC is the Cascadia PM100DX which features a pressure drop of 4.2kPa.

The motor used is the Emrax 228 CC which features a pressure drop of 9 kPa.

This is important for pump selection, as pump must maintain flow despite pressure losses.

Radiator Flow Analysis

No pressure drop information was known about the radiators and therefore physical testing was completed.

By using inlet and outlet pressure of the radiator, we were able to determine a pressure drop of 20.68kPa.

System Flow Analysis

For a pipe network in series, total pressure loss is the summation of all pressure drops in the line.

The total pressure loss calculation can be found below:

$$\Delta P_{total} = \Delta P_{1\to 2} + \Delta P_{ESC} + \Delta P_{3\to 4} + \Delta P_{motor} + \Delta P_{5\to 6} + \Delta P_{Rad1} + \Delta P_{7\to 8} + \Delta P_{Rad2} + \Delta P_{9\to 10}$$

Assuming uniform pipe material, roughnesses and similar radiators:

$$\Delta P_{total} = \Delta P_{pipes} + \Delta P_{ESC} + \Delta P_{motor} + \Delta P_{Rads}$$

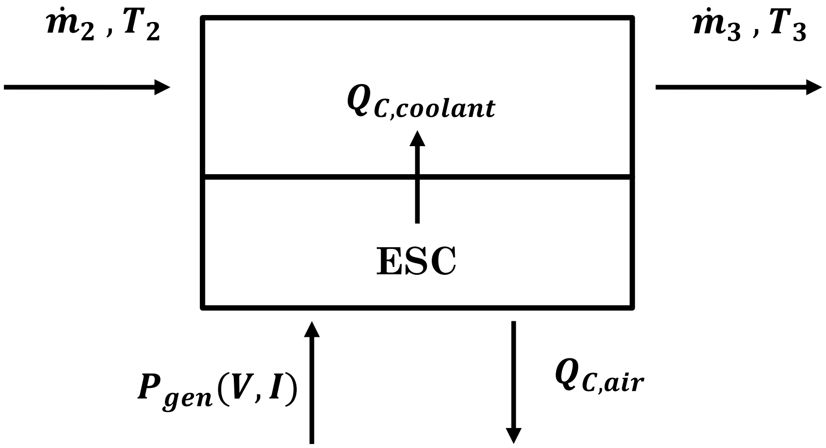
$$\boxed{\Delta P_{total} \approx 161.368\ kPa}$$

The total pressure drop will dictate the pump selected for the vehicle as the pressure and flow rate must be maintained despite the losses.

Control Volume Analysis

ESC Control Volume – Heat Transfer

A more complex analysis is not possible without physical testing, however, a steady-state analysis is generated for the time-being:



Desired: $\frac{dE_{st}}{dt} = mc_p dT = P_{gen}(V, I) - Q_{C,air} - Q_{C,coolant}$

Assumption: $P_{gen}(V, I) = Q_{C,air} + Q_{C,coolant}$

ESC Control Volume – Heat Transfer

Inspection of ESC gives insight into potential internal black box cooling network:

HVIC 2.1 board with OLEA® FPCU T222 mounted on PM100 inverter

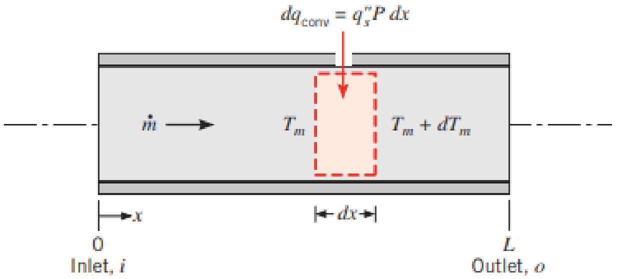
Likely a single-loop cooling block, known as a cold plate

ESC Control Volume – Heat Transfer

An assumption of consistent heat flux from the plate will be assumed as water will flow relatively quickly through the ESC block and therefore stagnation is unlikely:

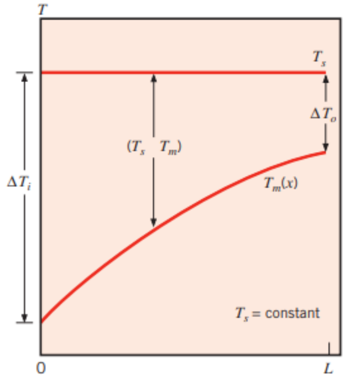
Assuming convection from air is small:

$$\frac{dE_{st}}{dt} = mc_p dT = P_{gen}(V, I) - Q_{C,coolant}$$



Assuming steady-state:

$$P_{gen}(V, I) = Q_{C,coolant}$$



where:

$$Q_{C,coolant} = \dot{m}_3(u_3 + P_3V_3) - \dot{m}_2(u_2 + P_2V_2) = mc_p(T_{m,3} - T_{m,2})$$

ESC Control Volume – Heat Transfer

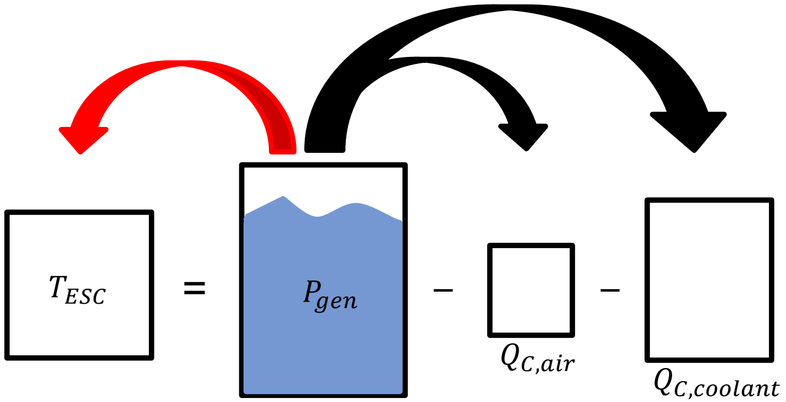
Estimated efficiency of the ESC gives us an equation for the heat generation of the ESC:

Assuming efficiency of η: $P_{gen}(V, I) = (1-\eta)VI = (1-\eta)I^2 R_{internal}$

Final Equation for ESC: $T_{m,o} = T_{m,i} + (1-\eta)\dfrac{VI}{\dot{m}c_p}$

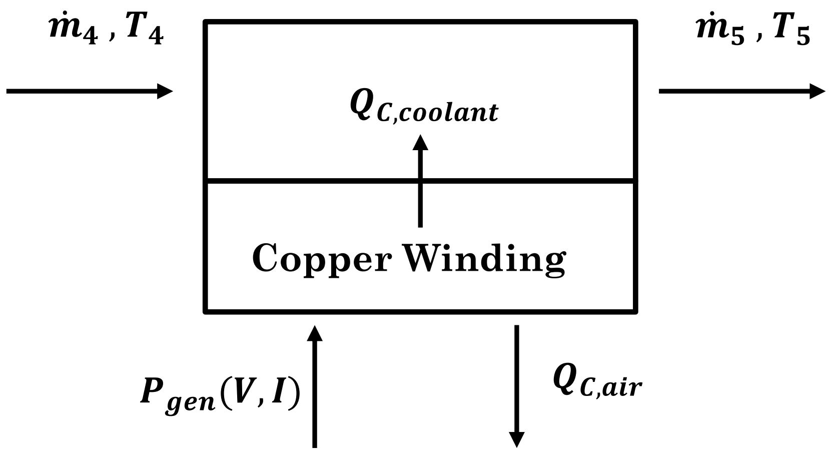
Requirements for further accuracy:

1. Function relating heat available (from P_{gen}) to temperature change of ESC
    - Understanding of ESC thermal resistance or function generated through testing
2. Accurate knowledge of ESC internal cooling
    - Full measurements or schematic of cold plate with tubing



Motor Control Volume – Heat Transfer

A more complex analysis is not possible without physical testing, however, a steady-state analysis is generated for the time-being:

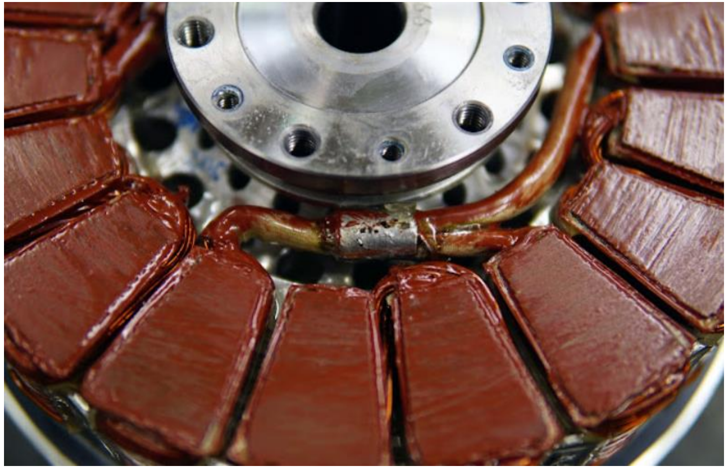


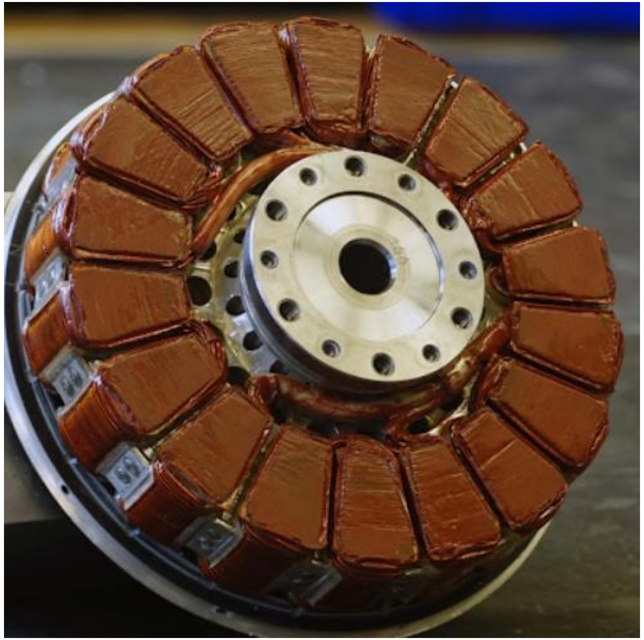
Desired: $\frac{dE_{st}}{dt} = mc_p dT = P_{gen}(V, I) - Q_{C,air} - Q_{C,coolant}$

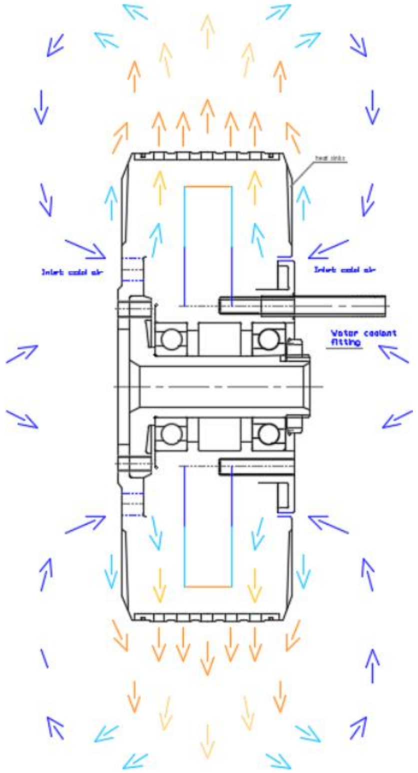
Assumption: $P_{gen}(V, I) = Q_{C,air} + Q_{C,coolant}$

Motor Control Volume – Heat Transfer

Inspection of motor internals gives insight into potential cooling network:

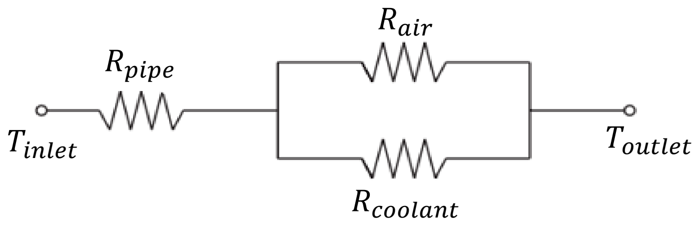


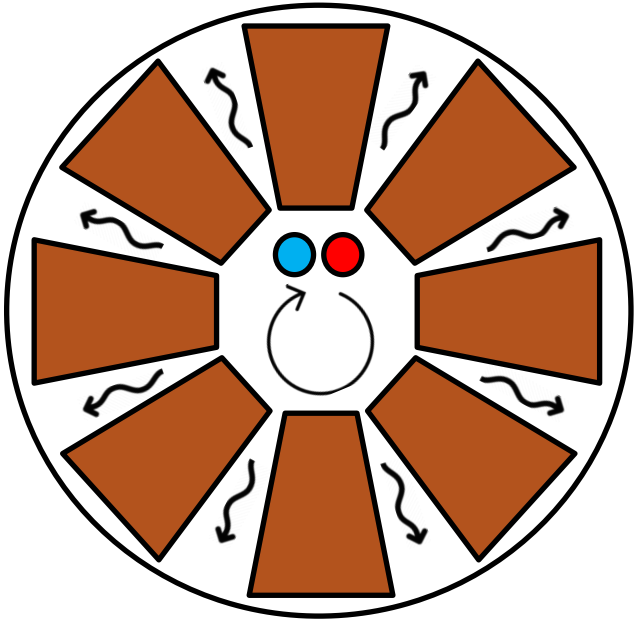




Motor Control Volume – Heat Transfer

Unclear what the cooling specifications of the motor are and it is desirable to have some benchmark testing to provide better insight into cooling network:





- Inlet - Outlet

According to the manufacturer, about 1/3 of heat is dissipated through air and 2/3 is dissipated through cooling fluid.

This is an acceptable approximation initially during the steady-state case, however, this will change as more data is provided.

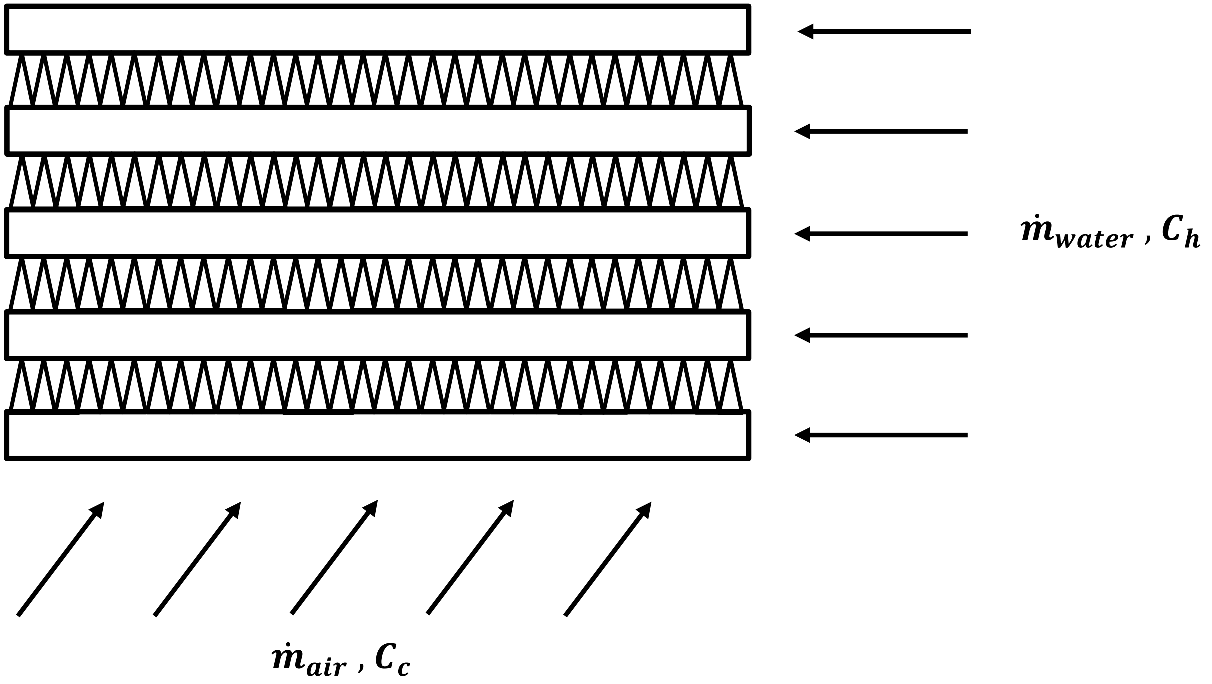
From motor inspections, it can be assumed that air will pass along coils outward and cooling fluid will run along the interior.

Radiator Control Volume – Heat Transfer

Currently available radiators require modeling:

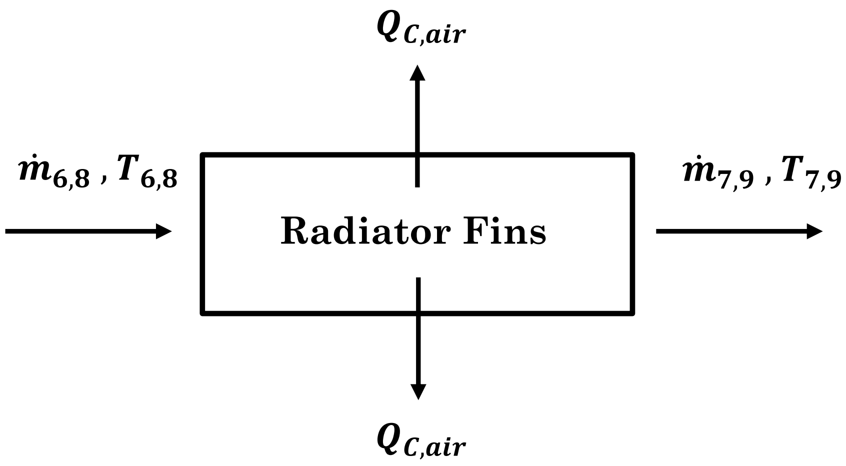
Radiator Control Volume – Heat Transfer

Inspection of the available radiator gives insight into flow pattern. In this case, the radiator is a cross flow, single pass plate fin with small resoviors on either side:



Radiator Control Volume – Heat Transfer

A more complex analysis is not possible without physical testing, however, a steady-state analysis is generated for the time-being:



Desired: $\frac{dE_{st}}{dt} = mc_p dT = Q_{C,air}$

Assumption: $P_{motor+ESC}(V, I) = Q_{C,air}$

Radiator Control Volume – Heat Transfer

The radiator will be analyzed as a heat exchanger for which the heat dissipation will occur through the length of the finned section. As a result, the relationship between the incoming cold fluid, air, will dictate the dissipation of the hot fluid, coolant:

Assuming convection from air is small:

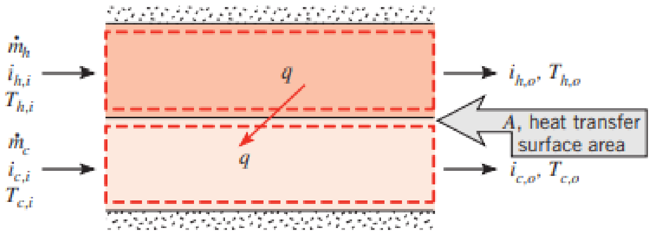
$$\frac{dE_{st}}{dt} = mc_p dT = Q_{C,air}$$

Assuming steady-state:

$$P_{motor+ESC}(V, I) = Q_{C,air}$$

where:

$$Q_{C,air} = \varepsilon C_{min}(T_{h,i} - T_{c,i})$$

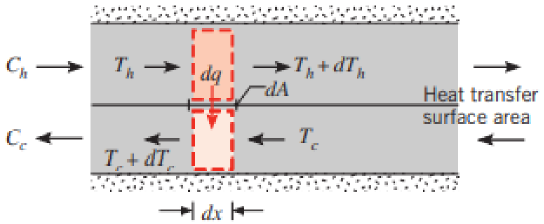


Heat capacity rate, for both cold and hot fluids (Ch and Cc):

$$C = c_p \frac{dm}{dt}$$

Radiator Control Volume – Heat Transfer

Analyzing the radiator as a heat exchanger we utilize an equation to determine the overall heat transfer coefficient, $\frac{1}{UA}$:

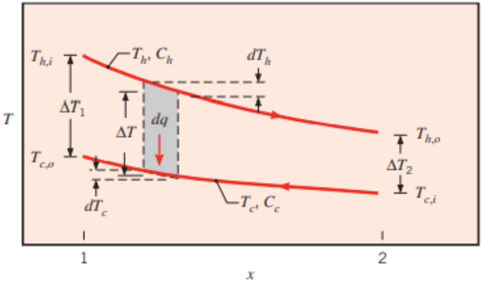


$$\frac{1}{UA} = \frac{1}{(\eta_0 hA)_c} + \frac{R''_{f,c}}{(\eta_0 A)_c} + R_w + \frac{R''_{f,h}}{(\eta_0 A)_h} + \frac{1}{(\eta_0 hA)_h}$$

Finding the NTU value:

$$NTU = \frac{UA}{C_{min}}$$

where Cmin is the smallest heat capacity rate between hot and cold fluid.



The effectiveness relation for a unmixed fluid cross-flow exchanger:

$$\varepsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right) \qquad \varepsilon = 1 - exp\left[\left(\frac{1}{C_r}\right)(NTU)^{0.22}\{exp[-C_r(NTU)^{0.78}] - 1\}\right]$$

Future Plans

Creating test benchmarks for individual black box components or acquisition of run data will allow for the finalization of transient component ODEs. These will then be used with an ODE solver to determine positional fluid and component temperatures.

Thermal state-space equations:

$$\dot{x_{ESC}} = \frac{1}{m_2 c_{p,2}}\{(1-\eta)VI - m_c c_{p,c}(x_3 - x_2) - m_a c_{p,a}(x_2 - x_\infty)\}$$

$$\dot{x_{motor}} = \frac{1}{m_4 c_{p,4}}\{(1-\eta)VI - m_c c_{p,c}(x_5 - x_4) - m_a c_{p,a}(x_4 - x_\infty)\}$$

Common heat exchangers are evaluated at steady-state, therefore, more analysis must be done to generate a transient state-space equation.

Conclusion and Next Steps

Current work has laid out a few conclusions and next steps:

- Based on determined pressure drop values, a pump for the system can be selected
- Steady-state analysis of the system should be generated as a worst-case scenario
- Benchmark testing for components should be attempted to speed along transient analysis
- Some water testing should be done to determine fouling of radiators

Thank You
Questions?

Rensselaer

why not change the world?®