Formula SAE Cooling Design:

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Foreword:

This paper was written to help transfer cooling system knowledge across the cycles of the team. Cooling isn't a particularly sexy system to go into so often it would get neglected to the point where overheating (either oil or water) became a burden on the team in competition and testing. In 2016, I spent a lot of time to make sure that wasn't the case with RGP005 (I sorta succeeded: the water cooling was great but the oil cooling didn't work too well). With this paper, I aim to make sure no future team member has to go through what I had to again.

Thanks to Lane for his work on and help with oil cooling. Thanks to Josh for his help with radiator shroud design. If there is anything else that you guys (Lane, Thad, Josh, or any later team/cooling/engine leads) think should be added to this paper feel free to add it. Really, please do. Add your names to the author list on the title page, and maybe a note in here on what you changed or added.

Also, feel free to distribute this to other teams that want it. Competitiveness shouldn't be determined by cooling systems. That kind of failure is no fun at all and isn't a good learning experience.

Intro

The following is a summary of how I think the cooling system should be designed for a Formula SAE car. Unfortunately, we were short on time, so I didn't actually design RGP005's this way.

What is the Cooling System?

The job of the cooling system is, essentially, to keep the car running. As such, it is incredibly important to get right. However, since it's not a particularly fun or flashy part of the car, a lot of teams don't pay any attention to it. A bad system might not make too much of a difference for acceleration, skidpad, or autocross but it makes endurance and testing very difficult. Just look at RGP003 or RGP004, we spent more time trying to keep those cars from overheating than anything else while testing.

Additionally, the University of Toronto FSAE team studied the effect of coolant temperature on engine torque on pg. 25 of this paper: https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf. They came up with the graph below.

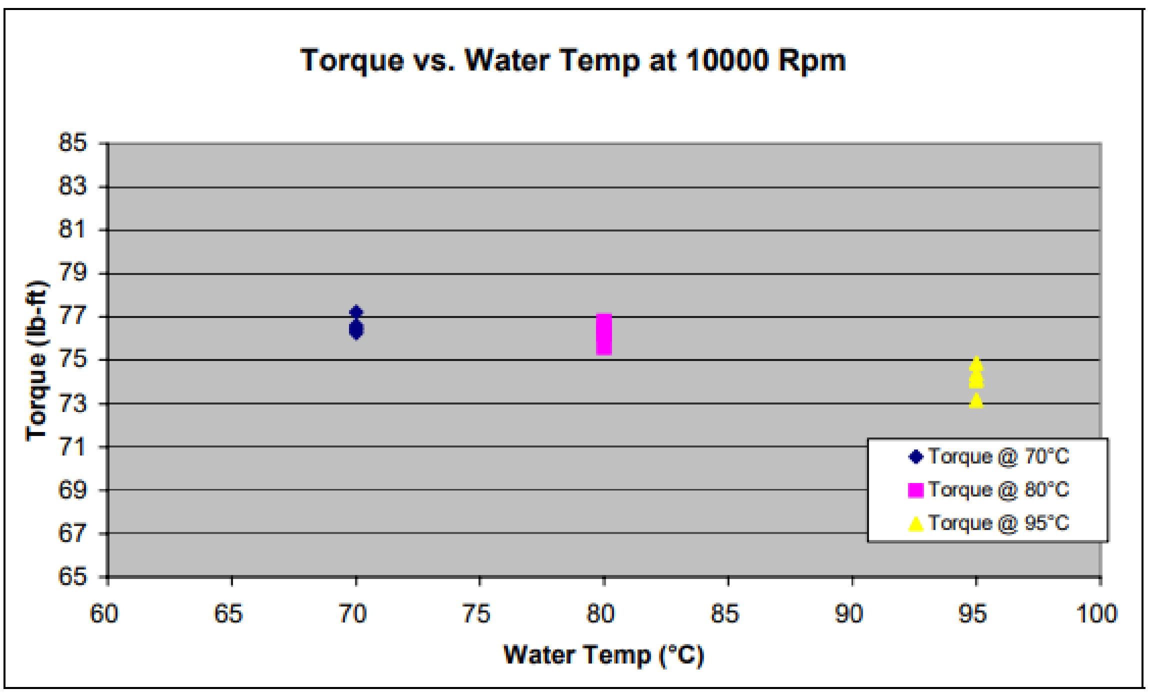


Figure 3.8 Torque vs. Water Temperature

Figure 1. Engine Torque vs. Coolant Temperature

The above graph shows that as the temperature increases the torque goes down significantly, especially near the boiling point. Every lb-ft counts in Formula, so keeping the engine at the optimal temperature is very important. That's where the cooling system comes in.

There's the why of the cooling system, here's the what: The cooling system consists of 7 main components. The most important, in terms of system performance, are the radiator and water pump. In addition, you have the cooling lines, de-aeration/reservoir, radiator fan, oil cooler, and catch cans. A diagram of the water side of the system is shown below. The oil cooler can be integrated into that, a la CBR600 engines, or it can be separated like the YFZ450R engine.

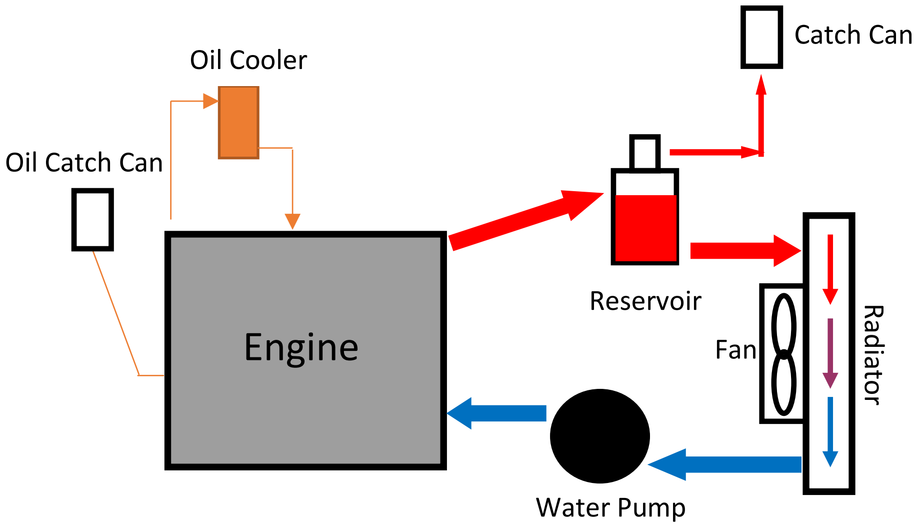


Figure 2. Engine Cooling System w/ external oil cooler

Hot coolant is pulled from the engine through the reservoir and radiator, where it is cooled, into the water pump and back to the engine. The reservoir acts as a reserve of fluid for the system and also as a place for air to escape the coolant. As such, it must be the highest point in the system. I will reiterate that fact several times throughout this paper. The oil cooler is shown as separate from the rest of the system as, in the YFZ450R engine, it was an external radiator. In the CBR600 engine it was a liquid to liquid heat exchanger incorporated into the coolant passage in the engine block. Additionally, the water pump can either be internal or external to the engine.

The primary challenges of the coolant system are to keep the coolant below boiling point and keep the oil in a temperature range where it performs correctly. Bear in mind that, as the system is pressurized, the boiling point will be higher than standard conditions.

So, to summarize: the job of the cooling system is to keep the engine cool enough to keep running. The most important parts of the system for this are the **water pump** and **radiator**.

First Steps

Let's assume that you are part of a young team. You don't have anything designed for cooling yet and you've only got a few months to competition. This is essentially the situation that RGP005 found itself in. The following section is the result of that situation and my advice on how to start out with your cooling system. The end result is a reliable cooling system that will actually work, something that some teams never manage. It may not get you many extra points with the judges but it will keep your car running at FSAE West with air temperatures over 100 degrees (true story, it was consistently above 100 degrees at FSAE Lincoln 2016, lots of teams failed endurance due to overheating but we didn't).

Radiator:

Here goes: radiator first. The easiest way to do this is to just use the radiator that came with your engine; after all, somebody with a lot more time and money than you could ever have picked that radiator. This choice assumes that you haven't made any major changes to the engine so that it makes more power. Since most teams make less power than stock (thanks restrictor) this is the easiest and cheapest way to pick a radiator. Unfortunately, the stock radiator is usually a lot heavier than the other options. That's the price you pay for saving money.

The next option is to use a custom radiator. Generally, these will be much lighter and somewhat more efficient than the stock radiator. Anyways, you're pretty much going to be forced to use a custom radiator if you've made significant improvements to your engine. So, rough radiator sizing… the rule of thumb (at least according to the internet) is that an engine sheds roughly 30% of its power output into the cooling system as heat. Of course, this depends on efficiency and a bunch of other factors so it's not entirely accurate… that's why it's only a rule of thumb… So, since this relationship is linear, it means that if your engine is making 20% more horsepower you're gonna need a 20% more powerful radiator. Radiator heat-transfer rate is a factor of a bunch of different things, but the biggest factor is the core area. The heat output is roughly a linear function of core area… so with 20% more engine power you'll probably want to get a 20% bigger radiator than stock.

If you've decided to get a custom radiator and you've used your engineering judgement (that's what you call it for the tech judges at least) to size the radiator, you've got to go and order one. You could go and buy one from your local autozone, (do it! It's hilarious to see the one or two cars at competition with road car radiators) or you could get one custom made. The two companies that I've ordered from before are C&R Racing and Saldana Racing. Both will make you custom radiators pretty much any way you'd like them. I've found that Saldana radiators are generally cheaper and lighter than C&R, so I recommend going with them but if that doesn't work out C&R is definitely a good option too. If you decide to go with Saldana you'll want to submit an inquiry form on their website (http://www.saldanaracingproducts.com/customradiator.html). First, you'll have to decide whether you want a cross-flow or down-flow radiator and whether you want it to be single or double-pass.

Single vs Double-pass means whether you want to the coolant to only flow in one direction from one side of the radiator to the other or if you want it to flow in one direction across one half of the radiator then flow from the other chamber back to the first side of the radiator. See the pictures below for an explanation.

Single-Pass Radiator: **Double-Pass Radiator:**

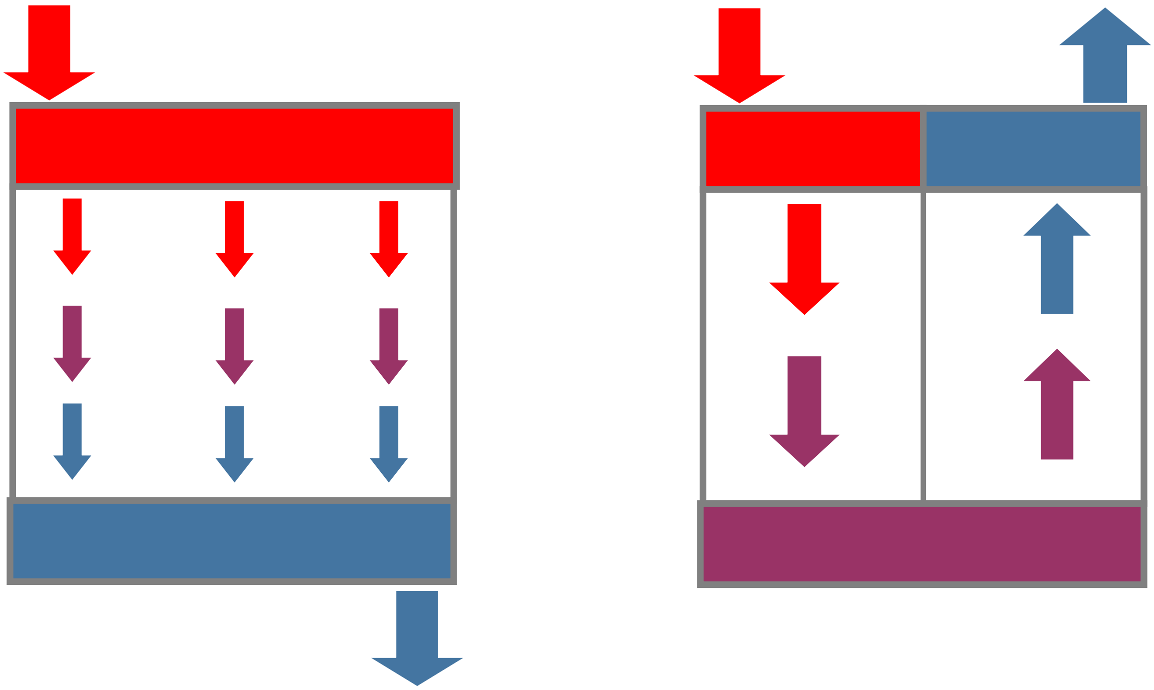


Figure 3. Single vs Double Pass Radiators

You can pick between using a single or double pass radiator. Personally, I think that the single pass radiator is going to be slightly better. First, it will be lighter as you won't have the walls between the two passes. Secondly, my engineering judgement (educated guess) says that it will be slightly more effective at heat-transfer as it will have more area at a higher temperature (if you look at the above pictures 1/3rd of the single pass radiator is red whereas only 1/4th of the double pass is). However, if having the inlet and outlet on the same side makes your packaging a lot easier it could be worth using a double pass radiator. Unfortunately, my engineering judgement in this case is probably wrong. University of Toronto performed testing of a single vs double pass radiator (pgs. 26-29 of this paper: https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf). They present this table suggesting that with low air flow speeds, double pass is significantly more effective than a single pass.

	Single Pass	**Double Pass**	**Delta**
Ambient Air Temp	-4°C	-4.5°C	0.5°C
Starting Water Temp	100°C	101°C	1°C
Steady State Water Temp	**98°C**	**64.5°C**	**33.5°C**

Figure 4. Toronto Radiator Study

Personally, I would take this table with a grain of salt. I can't believe that the double pass transfers 17.5 times more energy than the single pass radiator. However, it certainly is possible that it is more effective.

Next, you'll pick if you want a cross-flow or down-flow radiator; which really only matters if you have a cap on the radiator. However, since your reservoir can double as a filling point you don't need a cap.

Then, click "more" to take you to the design submission screen, as shown below.

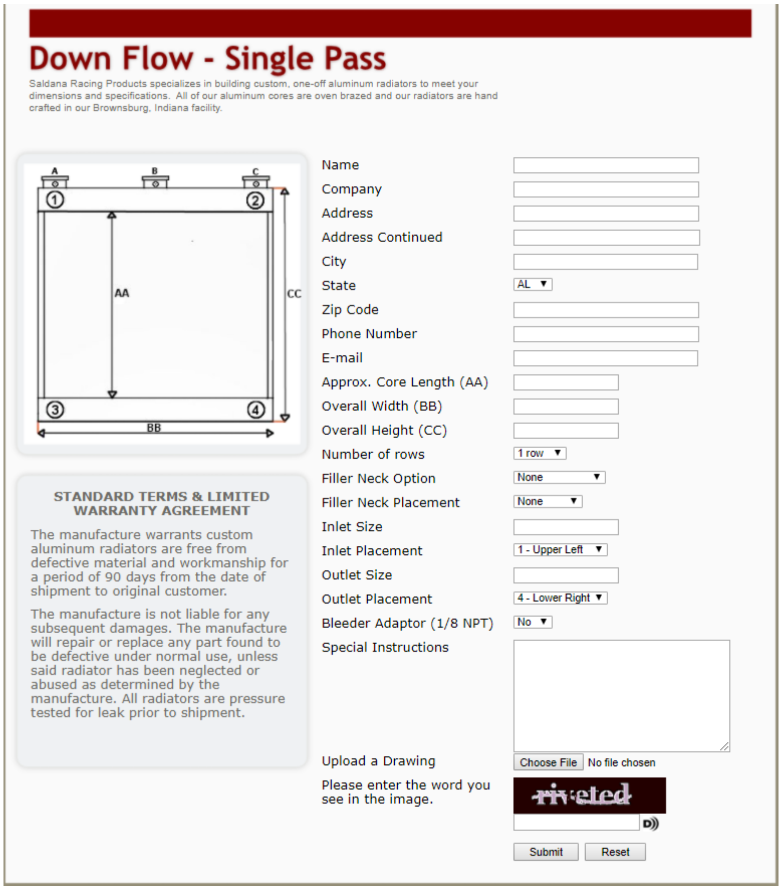


Figure 5. Saldana Submission Form

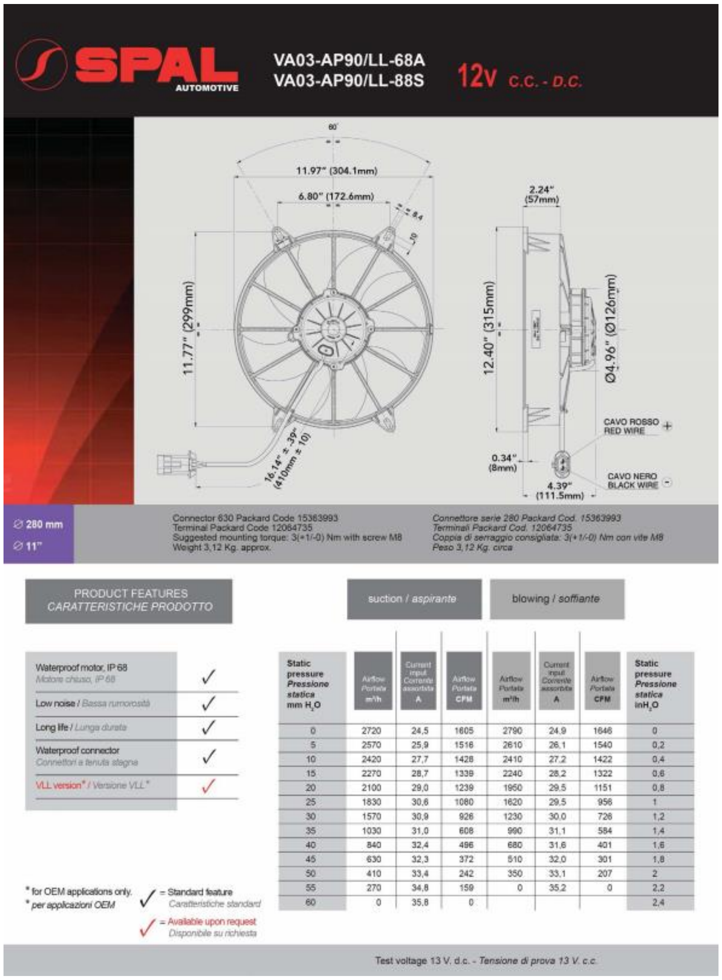
After you enter in the contact info, there are a bunch of choices to be made. The important ones are number of rows, inlet and outlet placement, and the dimensions. Number of rows governs how thick the radiator will be. I recommend that you go with 1 row so that it will be lightest and get the best airflow through it. I recommend going with an inlet and outlet diagonal from each other so that you get more even flow across the radiator. Once you've entered all the information, click submit. You will be contacted by a representative from Saldana to proceed with the development of the radiator.

Fan:

The next step is to pick a radiator fan. There are two parameters you need to consider when you specify a fan: diameter and direction. Once those two have been picked, you can then choose from among the fans that meet those specifications by optimizing three factors: airflow, weight, and current draw.
Diameter: Pretty much you want something the same size or a bit bigger than your radiator as long as

you can package it. So, if you have a 10” x 10” radiator core you should go with roughly a 12” diameter fan. Direction: pretty much you only want to go with a pulling fan as it won’t block the inlet of the radiator when not running. That brings us to optimization. The end goal of this is to get the fan that will have the most airflow without being too heavy or drawing too much current.

On the extreme end of the spectrum, you have a fan like the one we called Brutus.



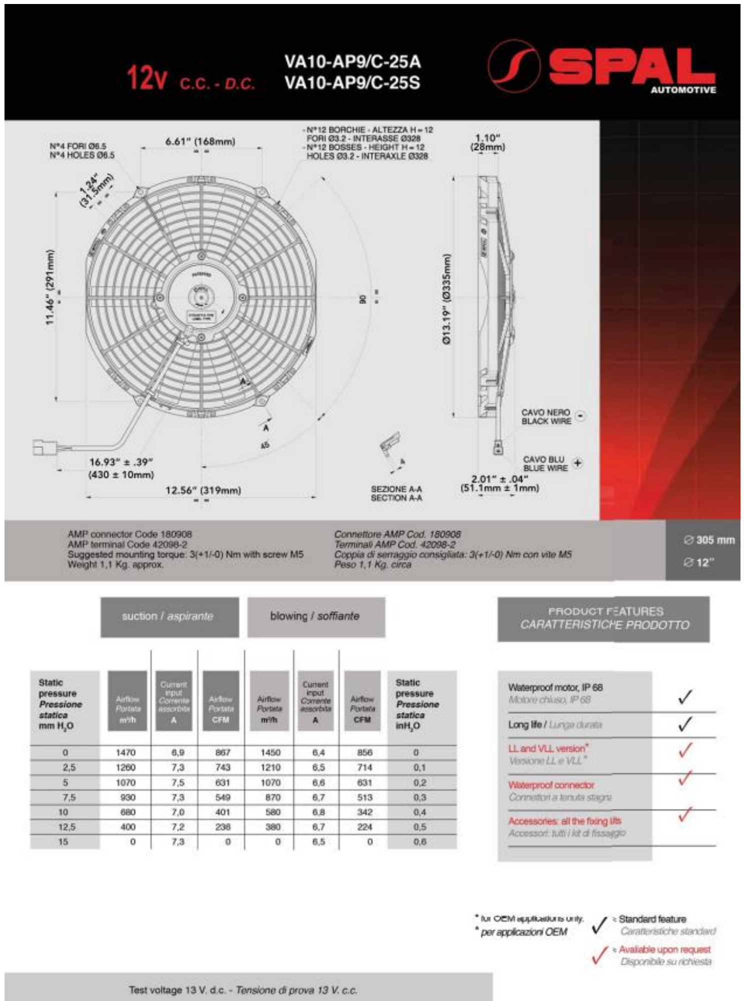
	suction / aspirante			blowing / soffiante			
Static pressure *Pressione statica* mm H_2O	Airflow Portata m³/h	Current input Corrente assorbita A	Airflow Portata CFM	Airflow Portata m³/h	Current input Corrente assorbita A	Airflow Portata CFM	Static pressure *Pressione statica* inH_2O
0	2720	24,5	1605	2790	24,9	1646	0
5	2570	25,9	1516	2610	26,1	1540	0,2
10	2420	27,7	1428	2410	27,2	1422	0,4
15	2270	28,7	1339	2240	28,2	1322	0,6
20	2100	29,0	1239	1950	29,5	1151	0,8
25	1830	30,6	1080	1620	29,5	956	1
30	1570	30,9	926	1230	30,0	726	1,2
35	1030	31,0	608	990	31,1	584	1,4
40	840	32,4	496	680	31,6	401	1,6
45	630	32,3	372	510	32,0	301	1,8
50	410	33,4	242	350	33,1	207	2
55	270	34,8	159	0	35,2	0	2,2
60	0	35,8	0				2,4

Test voltage 13 V. d.c. - *Tensione di prova 13 V. c.c.*

Figure 6. Spal AP90 11” Fan “Brutus”

Brutus weighs over 7 lbs and pulls >25 amps, which is crazy. Using Brutus means that you’ve given up... you screwed up and so you hope that using this giant fan will get you enough airflow to keep the car cool. Don’t use Brutus.

A more reasonable sized fan is something like this fan:



Static pressure *Pressione statica* mm H_2O	suction / *aspirante* Airflow *Portata* m³/h	suction / *aspirante* Current input *Corrente assorbita* A	suction / *aspirante* Airflow *Portata* CFM	blowing / *soffiante* Airflow *Portata* m³/h	blowing / *soffiante* Current input *Corrente assorbita* A	blowing / *soffiante* Airflow *Portata* CFM	Static pressure *Pressione statica* inH_2O
0	1470	6,9	867	1450	6,4	856	0
2,5	1260	7,3	743	1210	6,5	714	0,1
5	1070	7,5	631	1070	6,6	631	0,2
7,5	930	7,3	549	870	6,7	513	0,3
10	680	7,0	401	580	6,8	342	0,4
12,5	400	7,2	236	380	6,7	224	0,5
15	0	7,3	0	0	6,5	0	0,6

Figure 7. Spal 12" AP9 Fan

This fan is much more reasonable, weighing around 2.5 lbs. and pulling only 7 amps. The above picture is the Spal datasheet for the fan. You can see in the lower left a fan curve detailing the airflow rate vs static pressure. Unfortunately, you don't know how big a pressure-drop your radiator is going to create yet, however, once you've built your cooling system can figure out roughly what it is. On the topic of fan curves, compare the following two.

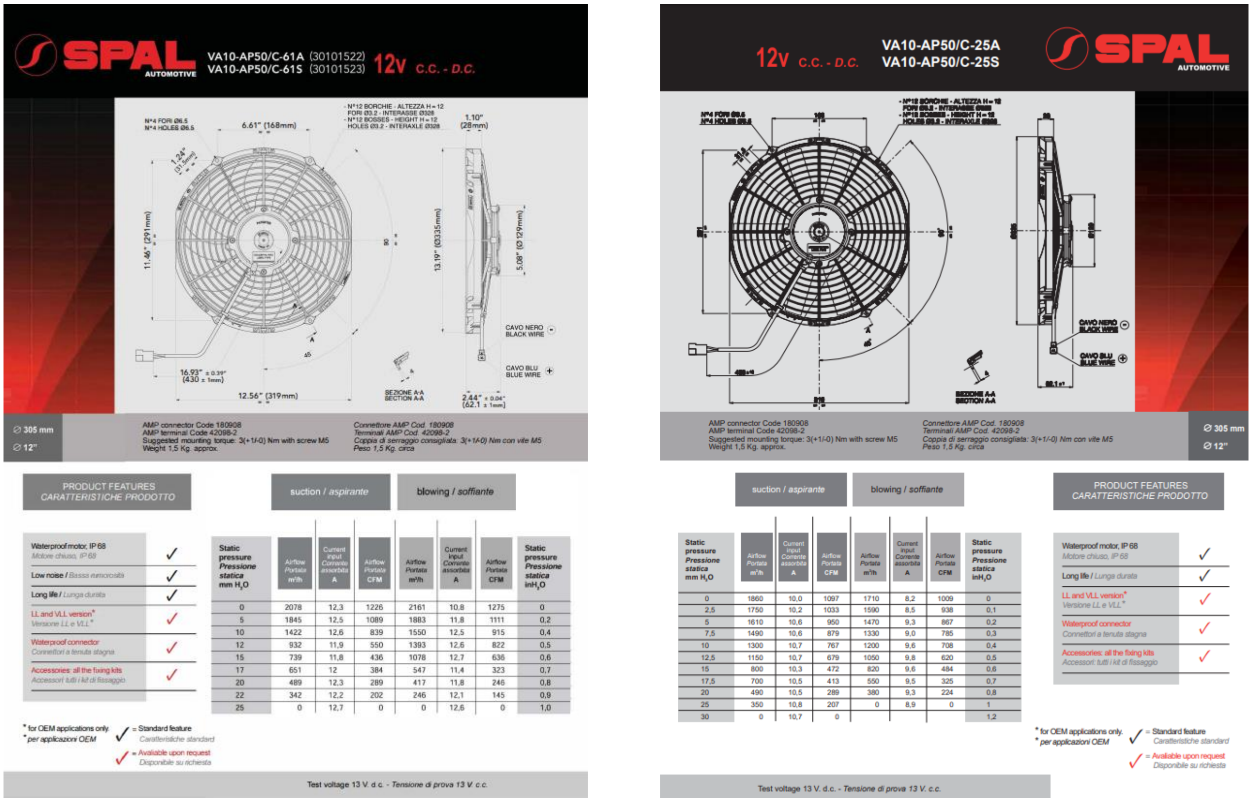


Figure 8. Two Similar SPAL fans

Note that the fan on the left produces a higher flow rate at low static pressure. However, it uses 20% more current to do it and is less effective at higher static pressures. Since you don't yet know what the pressure drop across the radiator is I'd recommend using one more like the one on the right. Comparing the first fan with these two (and these two with Brutus) it seems that the biggest determining factor in weight is the thickness of the fan. So, if you have a small engine or weight is a big factor for your team go with the thinner fan as in figure 5, if you can afford the weight or have a bigger engine, go with something along the lines of figure 6.

Spal is a manufacturer of high performance fans, generally they are some of the most powerful per unit mass fans you can find. As a bonus, they have good datasheets on all their fans. Their website is: https://webstore.spalusa.com/en-us/productlist/0118/products/fans/fans+-+high+performance.aspx

Fan Shroud:

An important addition to the fan and radiator is the shroud that connects the two. The shroud is important both as a mount for the fan and to allow the fan to draw from the entire area of the radiator core. A very basic example is shown in the figure below.

Figure 9. Fan Shroud

This shroud was basically just a loft from the rectangular radiator core to the fan. We then 3D printed the shape out in four parts and glued it together. Ideally, it would be printed in one piece but we didn't have a printer big enough. We then planned on wrapping the part in carbon fiber, unfortunately, we never did and found out that ABS tends to sag and deform under constant stress and high heat. So yeah… wrap it in carbon fiber or fiberglass or get it printed out of something better…

Depending on the placement of your radiator you may need to comply with the line of sight rule that stipulates that there should be no direct line from cooling components to the driver. The shroud above does not provide the protection required by this rule. However, lots of teams run much more comprehensive shrouds/sidepods. A good example of a shroud, the final design not necessarily the methodology, is shown in this paper by the Chalmer's Formula Student Team: http://publications.lib.chalmers.se/records/fulltext/local_164409.pdf

Their final shroud design looked like the figure below.

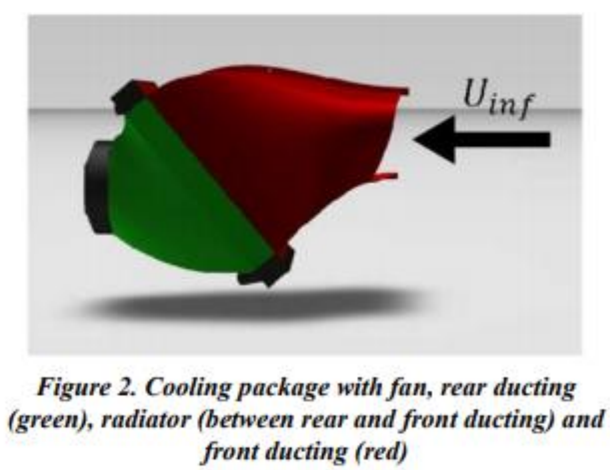


Figure 10. Example Comprehensive Shroud

To be honest, this is a pretty sexy shroud configuration. Apparently, it was also pretty effective as they claimed that it increased their air mass flow rate from 0.19 kg/s to 0.31 kg/s, a 63% improvement. From what I've seen of papers done by other FSAE teams it is more effective to run a smaller inlet area as a front shroud. The front shroud would then create a diffuser effect, slowing the air down and reducing the back pressure created by the radiator.

Generally, FSAE car cooling appears to be limited by the heat-transfer from the radiator to the air. Thus, anything that increases that amount of airflow through the radiator should probably be pursued. Therefore, if packaging allows, shrouds such as the one above should be designed. Starting with a general shape such as the one above, your aero team can use CFD to optimize the shape and ratio of inlet to radiator size to fan size.

Willem Toet, an F1 Aero chief, wrote an excellent, if a bit anecdotal, paper on duct design and their applications in motorsports: https://www.linkedin.com/pulse/air-ducts-down-earth-guide-motorsport-applications-willem-toet. He talks about the proper design of shrouding for radiators and the effects of inlet size and diffuser angle on the ducting. He cautions that, generally, a duct with over a 7° diffuser angle risks separation, though due to the blockage effects of the radiator you can usually get away with more near it. He also recommends focusing on the inlet ducting as they tend to have a much greater effect on the performance than the outlet.

Another function that your shroud can perform is to shield your radiator from line of sight of the driver in order to meet rule T4.5.1.

Once you've manufactured your shroud and installed it on the car you should ensure that all the seams seal properly. If there are any leaks they will significantly reduce the airflow from the fan through the radiator. One way to do this is if you have a reversible fan you can reverse the flow (plug it in reversed) so that it is pushing through the radiator and then use soapy water at all the seams to find leaks. If you find any leaks the easiest way to solve them is to just keep adding more tape (just try not to make it too heavy or ugly).

Cooling Lines:

These are pretty easy to do. You can choose to use soft lines or hard lines. If you use soft lines keep your bend radii large and avoid kinks at all costs. If you use hard lines there are two important things to keep in mind: commit to them (don't you dare use straight hard lines and soft lines for the bends. This looks terrible and has bad flow characteristics – the judges will not be happy). Also, make sure to create lots of easy to use (and well-sealed) joints so that the system can be taken apart easily. We ended up using circular flanges with silicone gasket rubber in between (you can buy sheets of it on McMaster and then just waterjet it out to fit the face of the joint) joined by 6 bolts. The bolts were kind of annoying, but I have a feeling that using any less would have resulted in leaks. That's probably something that you can experiment with if you want. The flanges are shown below.

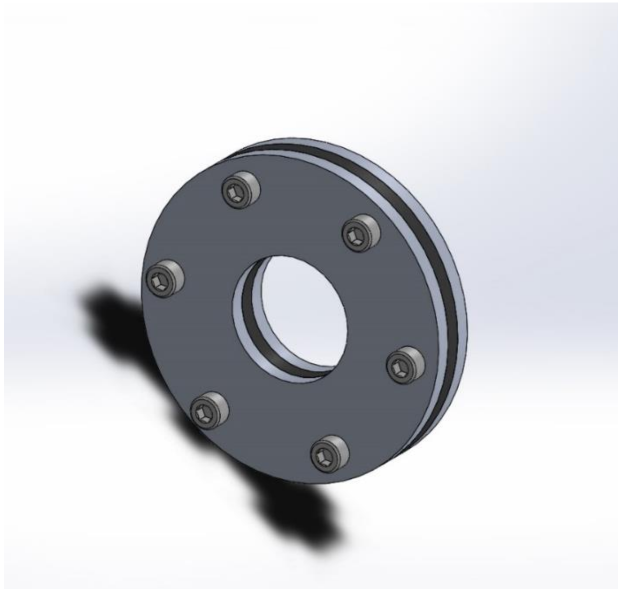


Figure 11. Cooling Lines Joint Example

It's not too hard to get the flanges right. Just make sure they don't leak and are relatively easy to service. The ones picture above were somewhat deficient in the service department so if you think of a better way to do it more power to you. The hardest flanges to seal were the ones mating to the pump as the pump was designed to use an O-ring. In the end, if I remember correctly, we machined O-ring grooves into those specific flanges.

As a rule, you'll want to configure your lines so that the water pump is on the cold side of the system, it's not strictly necessary but my logic is that the cooler water is further away from boiling so is less likely to cavitate. I don't know if that's true, but it makes intuitive sense. I recommend going with a configuration like below.

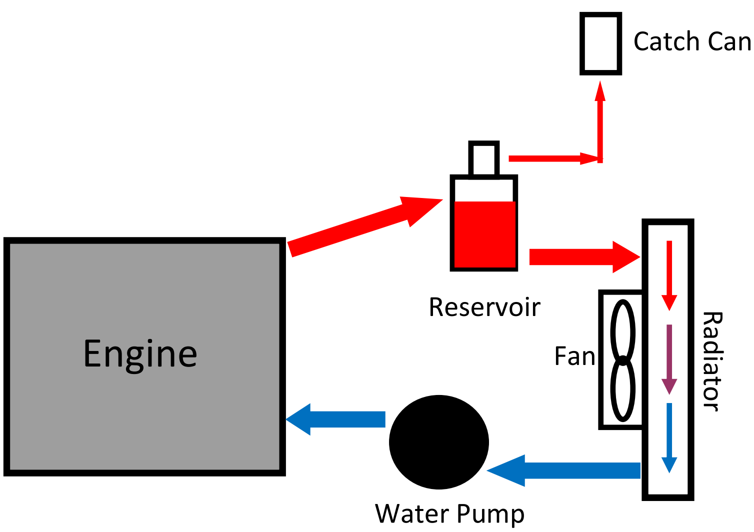


Figure 12 (also 1). Cooling system diagram

Deaerator/ Filler Point/ Overflow Tank/ Reservoir:

The deaerator/ reservoir is the most important part of the liquid half of your cooling system. Why? Because having air in your coolant is very, very bad. There are two reasons for this: bubbles, and bubbles. Okay, Okay… big bubbles and little bubbles.

Big bubbles are bad because they can create disconnects in the water flow, which will cause the water to stop moving and the pump to stall. This happens because air is compressible, the pump will just suck on the air, expanding it until the pressure is equalized instead of causing it to move as it does with an incompressible fluid like water.

Small bubbles are bad because they reduce the heat-transfer from the coolant to the radiator (and from the engine to the coolant). This happens because pretty much all the heat-transfer from the coolant water to the metal of the radiator fins occurs through conduction. Gases are very bad at conduction. Our engine lead shared with me a presentation by another Formula team that said that 4% by volume of air in the coolant leads to a 38% reduction in system performance. Here's a link to that presentation. http://edge.rit.edu/edge/P12221/public/CoolingSystem.pdf. Unfortunately, they didn't bother to cite their sources (it's not a good presentation… don't be like them… but it does have a few useful things). However, you can do some math to see if their claims make sense.

Let's assume the following:

1. All heat-transfer out of the coolant occurs by convection to the metal walls of the radiator
2. Air has a heat-transfer coefficient of 0 in convection (not quite true but compared to water it's negligible)
3. The air is evenly dispersed throughout the coolant.

Convection heat-transfer is linearly dependent on surface area of the contact patch. Since you have 4% of the volume of coolant taken up by air and it is evenly dispersed throughout, it follows that some portion of the contact surface of the coolant is taken up by air. To find that amount, you take the 3/2 root of 4% (Volume is dimension cubed while area is dimension squared; thus, 3/2) to find the % of the surface area taken up by air.

$$\sqrt[3/2]{0.04} = 0.117 \tag{1}$$

Since you assumed that air conducts no heat you get a 12% drop in heat-transfer. However, even if you consider the fact that the air would also reduce the energy carrying capacity of the fluid, a 38% drop seems a little bit much. However, 12% is still a significant reduction in performance.

Fortunately, there is an easy way to get rid of our bubble problems. A reservoir:

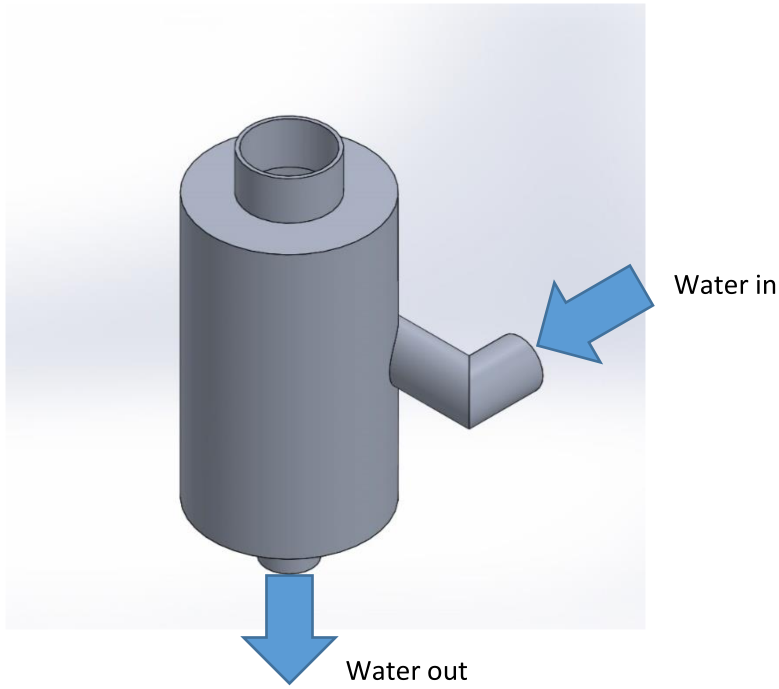


Figure 13. Deaerator/Reservoir (ISO)

The reservoir solves the problem of the big bubbles by providing a space for them to collect without blocking fluid flow. This works because when water goes down, air wants to go up. To make sure that the reservoir is effective at this you must make sure it is the highest point in the whole system. I'll say it again, **it must be the highest point in the system.** Additionally, you should ensure that air anywhere in the system can follow a purely upward path to the reservoir. Essentially, that means that all tubes leading to the reservoir should point up to it. When you fill the system with water you will have air in it. You will need to bleed the system, it's a foregone conclusion. Luckily, if your reservoir is high enough, if it generates enough head pressure this will happen mostly for you. You may need to jostle car/tubes a bit to dislodge some bubbles but for the most part they should flow towards the reservoir. If you have a particularly stubborn air bubble at the pump that is preventing fluid flow, you can usually get rid of it by increasing the elevation of a large body of water in your system, if you have soft lines you could lift the reservoir, with hard lines you may need to tilt the car to raise the height of the reservoir.

In order to fully accomplish the above task, the reservoir needs to be a certain size. Exactly how big that is, I don't know. It just needs to be big enough to accommodate all the air in the system while still having enough water in it to not starve the pump. We used one with the dimensions below, and it seemed to work.

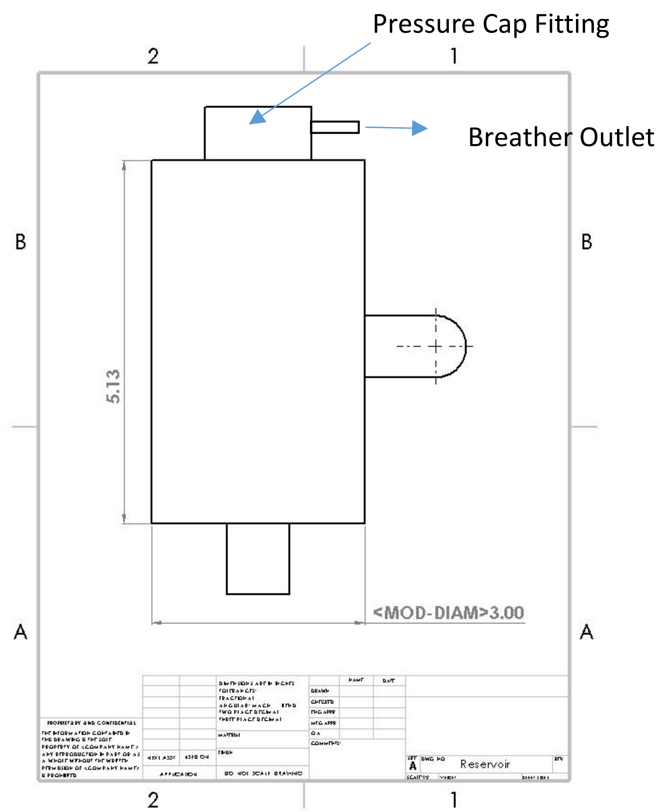


Figure 14. Reservoir Drawing

Bear in mind, you can change the size and orientation of the parts of the reservoir as needed. It doesn't have to be exactly like this. You just need to have an area for extra water and for air to collect that doesn't impede flow. Since the reservoir is the highest point in the system you'll want to be filling from there. Thus, the top of the reservoir should be a pressure cap such as this one: https://www.summitracing.com/parts/snn-10392/overview/. The pressure listed with the cap is the maximum system pressure allowed before it vents. By increasing this pressure, it raises the boiling point of the water in the system. Use something reasonable (for a race car) like 20-25 psi.

The reservoir solves the other problem, air inclusion/small bubbles, by … well… I don't really know but I suspect it's the same way that it solves the big bubbles. In other words, water moves down, and air moves up. I have also read somewhere that the swirling of the water in the reservoir (due to the positioning of the inlet off the centerline) also helps remove air. Intuitively that sounds reasonable, but I can't confirm that it actually works that way. Maybe that's something that you guys could test yourselves.

Water Pump:

Other than the radiator itself, the most important part of the system is the water pump. It may seem pretty simple, indeed if you had to you could go with the mechanical pump on the engine, but there are certain things you want to take into account. The important factors are weight, cost, power usage, flow rate, and control.

Picking A Pump:

First, however, you need to pick the electric water pump to go with. The critical thing is to get enough flow rate. How much flowrate is enough? I don't know. Fortunately, it's something that can be tested or just reasoned out. Since testing comes later, for now you should use some good old-fashioned engineering judgement (remember, educated guessing) to get the required flow rate and thus, a pump.

Luckily, you can establish and upper and lower bound for your hypothetical pump fairly easily. We know how much energy you need to transfer to the radiator and you can establish what your maximum temperature delta would be. With those two pieces of information you can establish the absolute minimum flow rate needed. The energy transfer needed is going to be approximately 30% of the maximum power produced by the engine. If you are using a 4-cylinder engine, a really good engine is producing around 100 HP. With a 1-cylinder engine such as the YFZ450R, a top engine will produce 50 HP, so you should use those as benchmarks. The hottest air temperature you might see is 100° F at FSAE Lincoln and the maximum coolant temperature you ever want to have is 212° F (lower is of course better).

So, using the heat transport equation:

$$W = c * \dot{m} * \Delta T \tag{2}$$

Thus, converting into metric, you get the resulting equations:

4-Cyl:

$$74.6 * 0.3 = 4.186 * \dot{m} * (100 - 37.8) \tag{3}$$

1-Cyl:

$$37.3 * 0.3 = 4.186 * \dot{m} * (100 - 37.8) \tag{4}$$

Solving for the 4-cylinder you get a mass flow rate of 0.285 kg/s, converting to a more commonly used unit you get 5.1 l/min. For the 1-cylinder you get a flow rate of 2.6 l/min. Since, it's actually impossible to get the water temperature down to the ambient air temperature and because there is a significant pressure drop across the cooling system (meaning that the actual flow rate will be significantly less than the maximum) you should use a factor of safety on the flow rates of 4. For 20.4 l/min and 10.2 l/min.

For the maximum flow rates, you should use the maximum flow rate of the original mechanical pumps on the respective engines. The maximum flow rate, with radiator and restriction, that UT found for the CBR600f4i engine was 43 l/min (pg. 20, https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf). Since there was still significant pressure drop in that system you should use a factor of safety of 1.5 giving you a target max flow rate of 65 l/min. For the YFZ, I wasn't able to find any hard flow rate data; however, I believe the max flow rate was somewhere around 40 l/min.

Now that you have target flow rates, you can pick a pump. There are several sources for water pumps. You can, for instance, choose to use an automotive booster pump, from a turbo car with air-to-water intercooler, such as this one: https://www.ebay.com/. However, the best pumps I was able to find were from Davies Craig, an Australian company used by FSAE teams like Monash. http://daviescraig.com.au/electric-water-pumps.

Assuming you choose to go with Davies Craig pumps, there is an easy choice for a 1-cylinder engine. The EBP40 booster pump, http://daviescraig.com.au/product/ebp40-electric-booster-pump-kit-12v-9040. With no restriction it flows 40 l/min, similar to what the YFZ pump does stock. The situation becomes a little more difficult for the 4-cylinder teams. You could go with the same EBP40 pump; indeed, it falls within the flow rate range defined above. In fact, Davies Craig claims that a smaller pump than that, the EBP23, would be suitable for motorcycle engines 500 – 1000cc. However, I like to be on the safe side with this, and so would recommend going with a larger pump, the EWP80, http://daviescraig.com.au/product/ewp80-electric-water-pump. In 2016, we actually used the EWP80 with a YFZ450R engine, although that was because Davies Craig wasn't selling the EBP40 at the time, so we had to go upsized. Apparently, Monash is also quite conservative with their water pump as they too use the EWP80 pump for a 4-cylinder engine.

Advantages (And Disadvantages):

I have to admit, I am extremely biased here, and will now proceed to explain to you why I think that you should use an electric water pump. In fairness, I should first tell you the disadvantage of using an electric water pump. That disadvantage would be the cost. That cost is that the EBP40 pump costs $225 (and the EWP80 costs $250) plus the, admittedly much smaller, cost of the electronics to control it. Obviously, since the mechanical pump already comes with the engine, it's free. Alright, with that out of the way, let's get down to business.

The first advantage for the electric water pump is weight. Although a mechanical water pump is already integrated into the engine, it can be removed; thus, we can count its weight. With the YFZ450R engine we were able to remove the pump cover and the pump impeller, the total weight of those parts was close to 1.5 lb. I expect that a 4-cyl engine the parts would weigh a bit more, maybe 2 lbs. This assumes, that you take out the impeller, the shaft that drives it, and the bearing for it and cover that hole up with an aluminum plate. The EBP40 pump weighs only 1 lb. and the parts needed to make it work don't add significant weight so you're looking at a weight save of approximately ½ lb. for the 1-cyl engine and similar for the 4-cyl.

The second advantage for the electric water pump is power usage. This may seem counterintuitive, but trust me, you'll save the most important power… horsepower. The general consensus is that mechanical water pumps create more mechanical losses (sapping power from the engine crank) than electric pumps. I haven't been able to find any hard numbers on it but have seen estimates that at maximum rpm, the mechanical pumps can take up to 1.5hp to operate. The electric water pump takes much less power, at max flow rate and max pressure the EWP80 takes 7.5A at 13 volts. That converts to about 100W, at ~50% alternator efficiency (http://www.delcoremy.com/documents/high-efficiency-white-paper.aspx), that gives us approximately 0.3 HP taken from the engine. That's a saving of up to 1.2 HP (probably not that much but still good power).

The third, potential, advantage is flow rate. Depending on the pump you choose you could end up with significantly more flow rate with the electric pump than the original mechanical pump.

The fourth, and definitely the most important advantage, is the amount of control that the electric pump offers you. With a mechanical pump the flow rate is a direct function of engine RPM as shown in the figure below (data: https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf pg. 46).

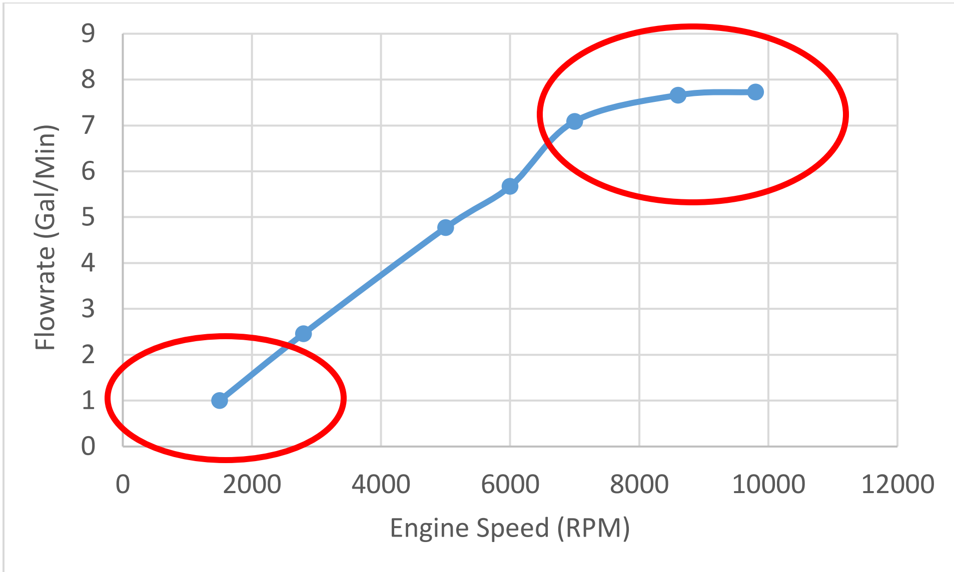


Figure 15. Flowrate vs Engine Speed

As shown in figure 15, the flow rate increases roughly linearly with engine speed until around 7000 RPM at which point it begins to level off. I have highlighted the areas where this presents issues. One is at low engine speeds, as the flow rate goes to near zero. This could mean that the car could overheat while idling or at low speeds. The biggest issue with this is when the engine turns off: the water stops moving. This introduces something called "heat-soak." Heat-soak is a very bad thing. Heat-soak is when the water in the engine stops moving and the heat in the areas of the engine hotter than the water, like the piston and exhaust valves (especially the exhaust valves), soaks into the water. This can cause the water in the engine to heat up, sometimes even to the point of creating local boiling, which can damage the engine and make you have to wait for it to cool down in order to start up again. However, with an electric water pump (and fan) you can continue to run the cooling system after the engine turns off (such as during driver change in endurance). This was invaluable at Lincoln 2016 as many cars (5-10) failed to restart after sitting for driver change due to heat soak but our car was fine.

That right there was the biggest reason we loved having an electric water pump.

The other issue with the mechanical water pump is what happens at full engine speed. As shown in figure 15, the water flow rate starts to level off after around 7000 RPM, this is okay, not great as the engine is producing the most power at high speeds, so you'd ideally want the most flow rate, but okay. Unfortunately, that plot doesn't show what happens at higher rpms: cavitation. Cavitation (just like heat-soak) is a bad thing. It is when gas bubbles form at the edges of an impeller (or propeller) reducing flow rate and introducing gas into the fluid (https://www.britannica.com/science/cavitation). Both of which are bad and reduce heat-transfer. Happily, you can ensure that an electric water pump never spins too fast and thus, pretty much never have to worry about cavitation.

Controllers:

Now that you've decided to use an electric water pump (told you I was gonna be pushy about it), you need to create a way to control it and the fan. Luckily, most ECUs present us with an easy solution: PWM tables. The PE3 ECU that we used had two tables that could take in two inputs each and output PWM on one channel. PWM stands for pulse width modulation, meaning a square wave signal that you can change the duty cycle, the width of the pulses, of, as shown in figure 16 below.

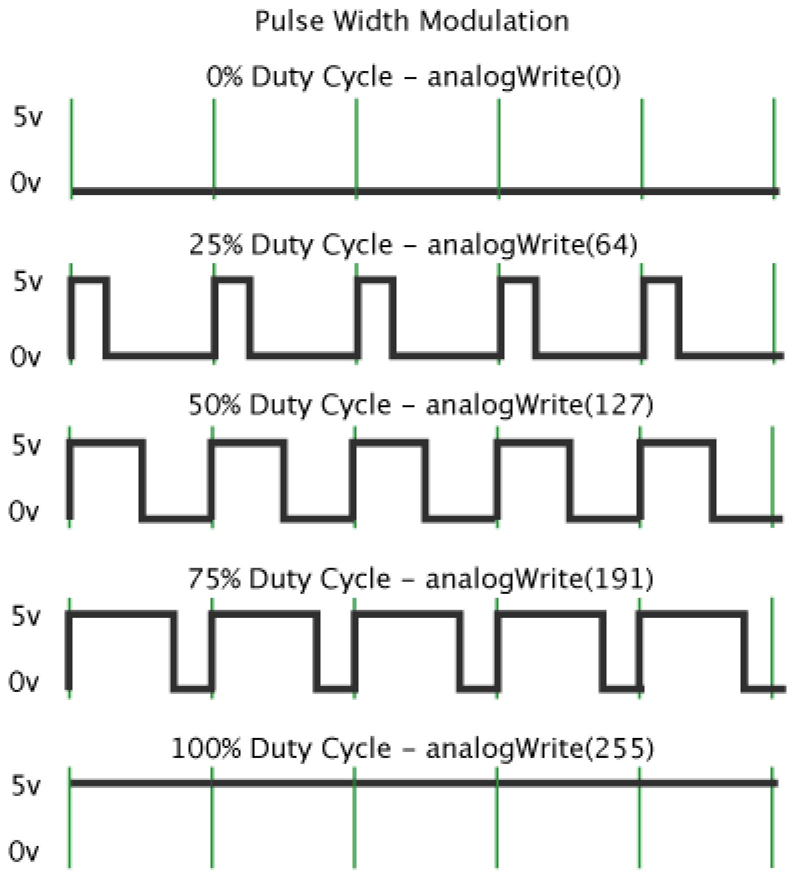


Figure 16. PWM (https://www.arduino.cc/en/Tutorial/PWM)

The nice thing about this is that you can control the average voltage a system receives using PWM. If you set up the input of a transistor (probably a big MOSFET or some kind of H-bridge) you can vary the output voltage of the transistor, controlling the speed of the pump or fan attached to it. An example of such a PWM table is shown below. Your fan one might look like this, using air and water temp as the inputs, and PWM duty cycles as your output (in bold).

		Air Temperature				
	deg F	0	30	60	90	120
Water Temperature	0	**0**	**0**	**0**	**0**	**0**
	60	**10**	**15**	**20**	**25**	**30**
	120	**40**	**45**	**50**	**55**	**60**
	180	**80**	**80**	**85**	**85**	**90**
	240	**100**	**100**	**100**	**100**	**100**

Figure 17. PWM Output table example

If you end up using liquid oil cooling, then you may want to use engine oil temperature and water temperature as your inputs since the heat transfer out of the oil would be dependent on water temperature so the colder you can get it, if your oil is overheating, the better.

Oil Cooler:

This part of the system is both simple and complicated. It's especially simple if you're using an engine like the CBR600 that already comes with an integrated oil cooler. However, if you're not then there are two ways to go about it: using air or liquid to cool the oil. Each method has advantages and disadvantages to it.

However, first you need to know how much energy do you need to take out of the oil? In 2016 I analyzed the rate of change of the temperature in the engine oil (YFZ450R, without an oil cooler) and found that it was increasing by approximately 0.122 °C. With approximately 1.7 kg of oil in the engine I was able to calculate the amount of excess heat-transfer into the oil using the equation below.

$$W = c * m * \Delta\dot{T} \quad (5)$$

Using 2.08*10^3 W/kg for oil and the numbers above I got a heat-transfer rate of 432 W or a bit over ½ HP. Since this was for a N/A engine, and a turbo is going to add significantly more heat into the system I'd use a safety factor of 2 for your design. This gives you 860 W or a bit over 1.0 HP.

Using that number and the equation above (just with the dot on the m now) you can solve for your minimum flow rate. The maximum oil temperature we ever wanted to see (actually it was too high but we did see it) was 280 °F (138 °C), and if you assume you are cooling it down to the same temperature as the coolant that gives us 200 °F (~90 °C) for our minimum temperature for a delta of 48 °C.

$$860 = 2.08 * 10\text{^}3 * \dot{m} * (138 - 90) \quad (6)$$

Or, m_dot = 0.0086 kg/s which equals 0.1667 gallons per minute.

System configuration and other components:

Before you set about designing the actual cooling part of the oil cooling system you should figure out how the whole system goes together first.

Disclaimer: These designs assume that you're using the original wet sump system that came with your engine (I don't think there are any that come stock with a dry sump). If you already have the external tanks and pumps of a dry sump system this becomes much easier: just put the cooler inline in your system.

The simplest system diagram (the system we used in RGP005) is shown below:

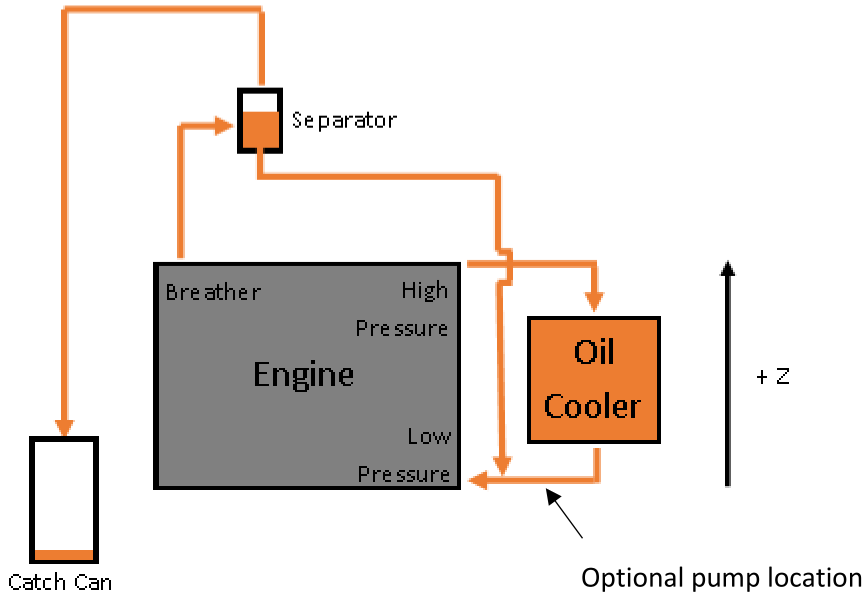


Figure 18. Oil Cooler System w/o Turbo or Pump

This is the simplest version of the oil cooler system, the version that should work for a N/A engine without too much pressure loss across the oil cooler. In order to keep the pressure-drop small (maximizing oil flow rate) the lines to the oil cooler should be as short as possible and it should be kept as low as possible as well. The oil separator should, on the other hand, be placed as high as possible so that oil will drain from it (as it is purely driven by gravity). If your engine doesn't already come with oil inlets and outlets in the block (and likely it doesn't) you will need to tap two spots. One in the case near where the oil is stored (so probably the bottom of the crankcase). That spot will be at lower pressure and will be where the oil will come back to the engine. The other spot will be somewhere after the secondary oil pump (if your engine has one) that is at a higher pressure in order to force oil through the cooler. Happily, the YFZ450R we were using did have a secondary mechanical scavenge pump that circulated oil but didn't act as a main supply. In 2018 (and I assume 2016 but I don't remember) we tapped that pump to provide oil for the turbo and oil cooler.

To be honest, I don't think this is the correct way to go as we were not getting anywhere near the oil flow rate needed to properly cool the engine. I will advocate very heavily to use an extra electric oil pump to ensure that you're getting enough flow through the system. If you do decide to use an auxiliary electric oil pump then place it after the oil cooler so that it pulls from the cooler and pushes into the crankcase. The disadvantage of using an extra pump is, of course, cost and weight.

Unfortunately, finding a pump that can work (reliably) with hot oil is a little more difficult than finding one for water. Fortunately, we are not the first person to use oil scavenging and there are applications out there that require similar pumps to us. I've been able to find two different pumps that look like they would work for our situation. One of them is the one that RGP007 is using, it's relatively inexpensive (I say relatively because it's still $275) but relatively heavy (2.7 lbs). That pump is part number 03-1040 from RBracing at this website: https://www.rbracing-rsr.com/oilsystems.htm. Scroll down to near the bottom and you'll find a link to purchase the pump. It has a flow rate of 1 GPM, so we have a good factor of safety over our minimum flowrate. The other pump is an aircraft part from Weldon Pumps.

https://www.weldonpumps.com/weldon-unfeathering-pumps. This pump is 1 lb lighter but much more expensive, you'll have to contact them to get exact tech specs and ordering info, but I've been able to find a pump in that series for around $1000. http://www.aircraftspruce.com/catalog/eppages/8120gweldonpump.php?clickkey=8751. Hopefully you can find it cheaper, but if you've got the money and want to save the weight go for it.

Even if you don't go with that style of oil system you still can use the separator. In its design, the separator is like a miniature version of the water reservoir (without the pressure cap). An example is shown below.

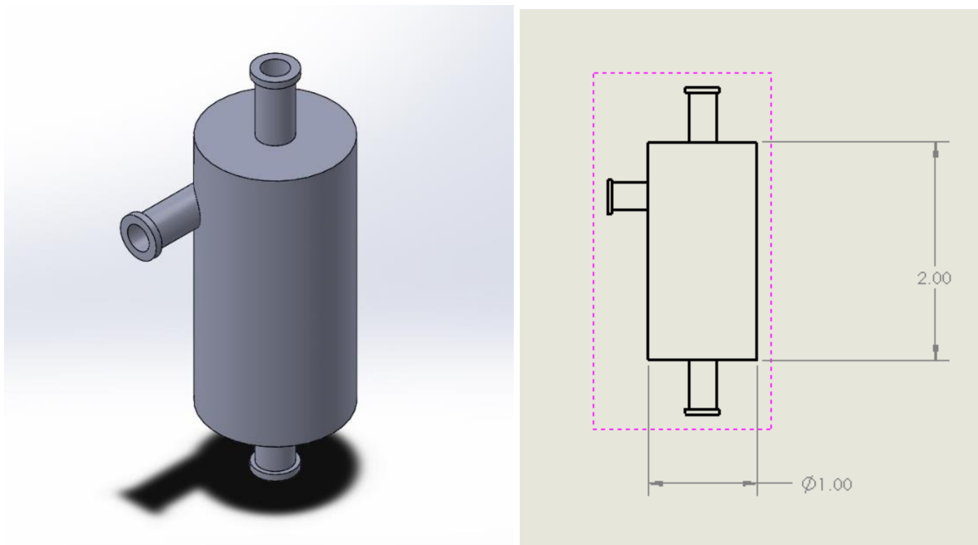


Figure 19. Air/Oil Separator Example CAD

Like the water reservoir, oil will come in at the top and drain out of the bottom while hopefully the air will vent out the top. This part doesn't need to be very big or sturdy so you should strive to make it super light. Ours was made out of, I think, 1/16th in wall aluminum tube and plate which worked fine.

Adding a turbocharger to the system ups the complexity of the oil system due to the need to feed the Turbo, as shown in the figure below.

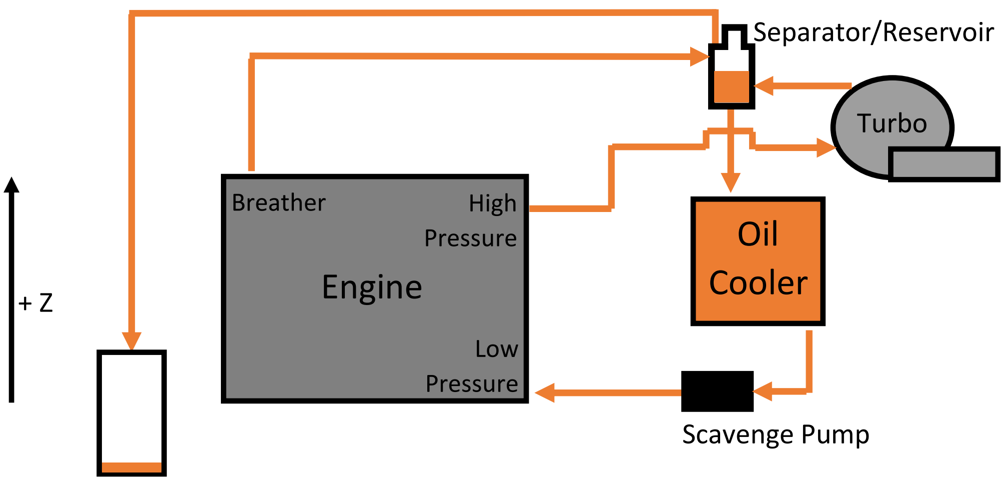


Figure 20. Oil Cooler System w/ Turbo and pump on cooler

In this system the turbo is fed by the high pressure from the engine and then drains into separator. In order, to minimize oil blow-by in the turbo we need to make sure that the system after the turbo is at a negative gauge pressure. This is accomplished by the scavenge pump which pulls fluid from the separator through the oil cooler and back in the engine. Unfortunately, if you were to use a separator similar to the one in the previous system (open to the atmosphere) the scavenge pump would be useless for the turbo. Thus, you need to design a new air/oil separator like the one shown below.

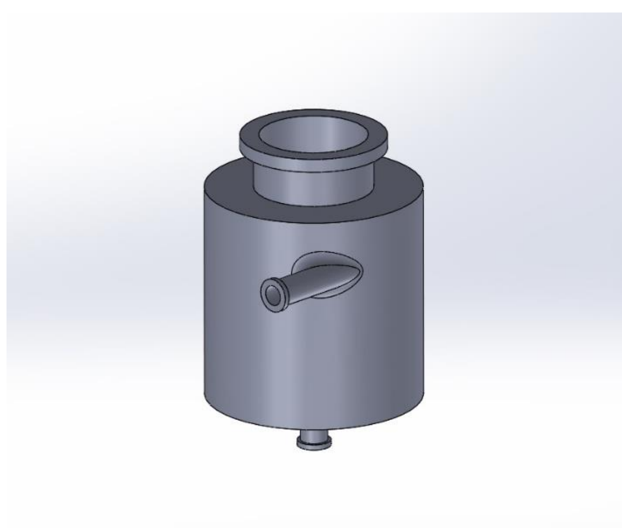


Figure 21. Oil Reservoir/Separator Example CAD

Since this system requires a negative pressure after the turbo you need some kind of way to seal the separator while making sure the pressure never gets over atmospheric and that the system can still breathe. It's a bit sketchy, but you should be able to use radiators caps just like the water reservoir to accomplish this. You'll want to modify a radiator cap to ensure that the pressure never goes above atmospheric while still sealing the system if the pressure goes negative (since the seals in radiator caps are forced upwards and open by positive pressure, negative pressure should make the seal even stronger). You can accomplish this by removing (cutting off) the spring that holds the seal down as shown in the figure below. Additionally, this separator, since the pump is going to be drawing from it (and to fit the cap) needs to be a bit bigger and sturdier than the other one.

Figure 22. Radiator Cap

Remove the spring circled in the picture above. That way the cap will only seal against negative pressure.

Once you've figured out what kind of system you have you'll need to pick a cooler. Also, if you've got the time and the spare sensors you may want to put temperature sensors in before and after the oil cooler, so you can see if it is effective.

Air Cooling:

Air cooling is the easier solution to implement because there are already some nearly plug and play solutions out there. One of them is to use the oil cooler from a small ATV such as this one from a Yamaha 450 (Yamaha 450 Oil Cooler). If you place the oil cooler in front of the main radiator inside the shroud (butted up against the radiator) then you don't even need to provide its own airflow/shroud. The radiator itself looks like the below picture.

Figure 23. Oil Radiator

The upside of going with a radiator like this is that it only costs $20, so it's pretty cheap. The downside is the weight and the uncertainty of whether or not it will work. That radiator weighed 1.5 lbs. (ignoring the extra oil inside it). The other downside is due to the fact that the radiator needs to be mounted fairly far away from the engine in order to get enough airflow. This means that there is likely to be a higher pressure drop in the system, meaning that you are likely to either have to use a pump or just accept having a lower oil flow rate. Unfortunately, the rate of heat transfer is strongly dependent on both the flow rate of oil and the flow rate of air so if you do accept a low flow rate it might just not work. Sadly, I don't have any of the dimensions on the radiator myself to do an analysis of the heat transfer coefficient from the oil side, but you should be able to use the equations developed in the water cooling section to estimate the heat transfer rate.

Water Cooling:

Water cooling is the harder solution to implement because there aren't any plug and play solutions available for small motorcycle engines. Fortunately, it's not "that" difficult to make work. If you wanted to, you could go with a really fancy (and more efficient) heat exchanger design. However, since you're gonna have to make this piece yourself I'm going to suggest going with something simpler. In other words, a simple finned piece since that should be easy to analyze and to manufacture. Speaking of manufacturing, 3D printing metal is fantastic, isn't it?

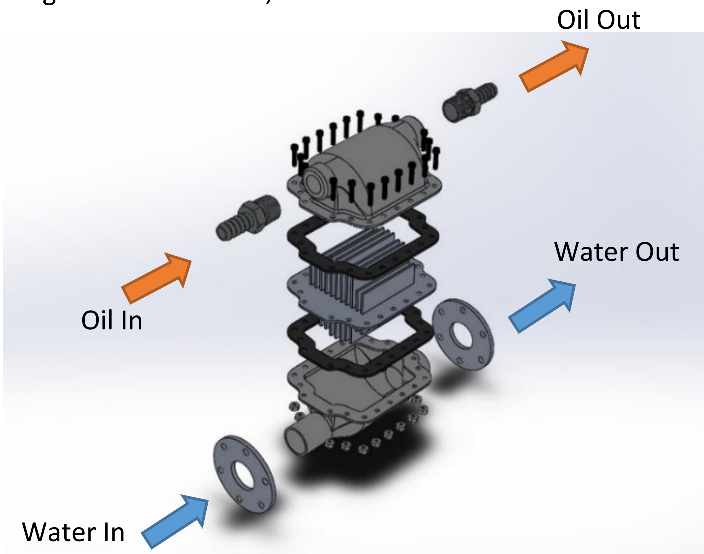


Figure 24. Liquid Oil Cooler (Exploded)

What you're looking at here is a finned heat exchanger. Oil flows through on one side and transfers heat to the metal fins which transfer heat to the water on the other side. All of the parts are designed to be 3D printed in metal (The fins are a bit iffy but should work). Okay, now to figure out just how much surface area (and other things) you need to cool the oil. Which brings you to the "fun" part: heat-transfer. Unfortunately, that's easier said than done. It's actually a lot easier to design the heat exchanger first and then figure out if it works. So, that's what I'm gonna do in the following example.

I will be using the equation below to model the system shown in figure 24.

$$\dot{Q} = UA_s * \Delta T \tag{7}$$

U is the heat transport parameter for a heat exchanger and is defined by the equation below.

$$\frac{1}{U} = \frac{1}{h_1} + \frac{R_{wall}}{A_{wall}} + \frac{1}{h_2} \tag{8}$$

Or in other words, U is a function of the convective heat-transfer coefficients between the wall of the heat exchanger and the two fluids and the resistance of the wall. If I assume that the resistance of the wall is minimal, then that goes away.

So, fair warning… I'm going to be making a lot of assumptions. Because heat-transfer is hard, okay?

What equation 8 means is that I need to find the convective heat-transfer coefficients for each of the fluids. In order to do that I need these assumptions:

1. Assume each fin of the heat exchanger acts like it is in free stream laminar flow.
2. Assume that the heat-transfer through the other components of the heat exchanger is minimal
3. Assume that the oil flowrate is the full 1 GPM of the pump
4. Assume that the water flowrate is 40 LPM.

The only dangerous assumption for us here is #1 that the heat exchanger fins act in isolation. Since they are pretty close together, it's completely possible that they act more like a tube. However, we'll see that, at least for the oil, the flow will be laminar no matter if it's in free stream or in a tube.

Alright, since this is acting as a fin in freestream our heat-transfer coefficient is defined as:

$$h = \frac{k}{L} * Nu \qquad (9)$$

Where k = 0.144, and L = 2 in (0.0508 m). Nu is the Nusselt number which is defined by the following equation for laminar flow.

$$Nu = 0.664 * Re^{\frac{1}{2}} * Pr^{\frac{1}{3}} \qquad (10)$$

Pr is the Prandtl number which can be found in tables for different materials at different temperatures. For oil at approximately 100C the Prandtl number is around 300, for water it is around 2. Re is the Reynolds number for the full length of the fin which is defined by the following equation.

$$Re = \frac{V*L}{\upsilon} \qquad (11)$$

The Reynolds number is a ratio describing the effect of viscosity vs inertia within the fluid. V is fluid velocity, L is length, and υ is the kinematic viscosity. Reynolds number can also tell us whether or not the flow is laminar by comparing it to the critical number for the type of flow. I'm getting my thermal and physical data on oil from the table here:

$$Re = \frac{0.048\frac{m}{s}*0.0508\ m}{0.2*10^{-4}\frac{m^2}{s}} = 122 \qquad (12)$$

So, my Reynolds number is 122. The critical number (the Reynolds number at which flow transitions from laminar to turbulent) for free stream flow is 5*10^5; our number is far below this threshold. The critical number for pipe flow is 2300; happily, our number is also below this threshold, so I can be confident that the flow is fully laminar. The water Reynolds number is 81800 meaning that if this flow behaves more like pipe flow then it could be turbulent which would change our Nusselt number calculation. However, in the end, the water coefficient is so much larger than the oil it doesn't really matter, oil will dominate the heat-transfer rate.

Alright, I can then plug my Reynolds numbers and Prandtl numbers into equation 10 to get the Nusselt numbers. For oil I get Nu = 40.6. For water I get 239.3.

Then I can plug my Nusselt numbers into equation 9 to get the heat-transfer coefficients. For oil I get 115 W/m^2 * K and for water I get 3170. Since the oil heat-transfer coefficient is so much smaller I'll use that for our U value.

Since the oil temperature will be dropping (and water temperature rising) over the distance of the heat exchanger I'll have to use something called the log-mean temperature difference to calculate the average ΔT.

$$LMTD = \frac{(T_{H,in}-T_{C,in})-(T_{H,out}-T_{C,out})}{\ln\frac{(T_{H,in}-T_{C,in})}{(T_{H,out}-T_{C,out})}} \tag{13}$$

Fortunately, I can assume that, since the flow rate of the water is so much higher than that of the oil that the difference between $T_{C,in}$ and $T_{C,out}$ (T of the cold side at the inlet and outlet) is negligible. Thus, I can assume that each is 90 °C which will cancel out the T_C terms on the top of the fraction. Additionally, I'll go with 138 °C as the starting oil temperature. Unfortunately, I don't know what the ending oil temperature will be. This means that I will need to guess a first ending oil temperature and then iterate the solution until the temperature and heat-transfer rate match up. If I assume that our heat-transfer rate will be 860W then I can calculate what the resulting ending oil temperature would be by solving equation 5 for the ending temperature. If I do that, I get a $T_{H,out}$ of 129.8 °C. Using that number, I can solve the first iteration of the heat exchanger equation (#7). Additionally, I also need the heat-transfer surface area (for the oil side of the heat exchanger) (measured from the CAD shown in figure 24): 44 in^2 or 0.0284 m^2.

$$\dot{Q} = 115 * 0.0284 * \frac{(138-129.8)}{\ln\frac{138-90}{129.8-90}} = 143\,W \tag{14}$$

Hmm… okay, that could have gone better… 143W is about 1/6th of where I want to be (I could iterate a few more times but since this isn't the final version of the heat-exchanger it isn't worth it). So, looking at equation 7, what can I do to improve our heat-transfer. Well, I can increase U, I can increase surface area, or I can increase delta T. What's the best way to do it, though? Since one of the advantages of this system is that it is lighter than air cooling, I'm gonna do my best to not increase the weight of the system here.

The easiest thing to do first is to increase the ΔT. I'll do this the same way the OEMs fix their problems… with a bit of software. So, instead of making 200 °F the target maximum water temperature, I can design my fan and water pump software to make sure the temperature maxes out at something lower, like 180 °F; (it's a win-win, because that way we'll get a bit more engine power too). So that brings the cold side temperature down from 90 C to 82 C increasing my heat-transfer by approximately 20%.

Next, I can try and increase area. The first thing to do is to increase the fin density, as they are pretty sparse right now. Okay, I was able to better than double the fin density (while halving their thickness so that the weight and cost would stay the same) to bring the surface area up to approximately 93 sq. in for a 111% increase. I also realized that I had gotten to the point where I had introduced a significant area reduction in the cross section which means the flow would be moving faster. The cross-sectional area (of the liquid) went from 0.0013 m^2 to 0.00084 m^2 speeding up my flow and increasing my Reynolds number by 60% - don't worry it's still laminar. That would increase my Nusselt number by 26% - increasing my heat-transfer by the same amount. Okay, so far I have increased the total heat-transfer by 2.11*1.2*1.26 = 3.2 times … half way there…

Next thing to do is to either increase the length of the system, increase the radius (and thus the number of fins we can include) or increase the oil flowrate. In order to double the heat-transfer we'd need to increase the length or the flowrate by 4 times as if you expand the heat exchanger formula out all the way they both end up at the ½ power. However, we would only need to double the radius of the heat exchanger (assuming that by doing so, we would also be able to increase the fin area by 4 times) in order to double the heat-transfer. Unfortunately, by doubling the radius we would also be quadrupling the volume, and thus the weight, and cost of the system… so yeah, we're not going to do that.

The best option now seems to be to increase the flowrate. To do this I can specify using a bigger pump, part number 03-1034 from RBRacing, which has a flowrate of 2.0 GPM, costs $50 more and weighs 0.4 lbs. more than the previous pump. By using this pump I would double my flowrate, doubling the Reynolds number, and increasing the heat transfer by a factor of sqrt(2). If you're not running a turbo you should be able to stop here, otherwise, read on.

Alright, now I've increased the heat-transfer by 3.2*1.44 = 4.5 times… not bad for only $50 and 0.4 lbs. Still not quite enough though. Unfortunately, the only viable option I have left is to double the length of the heat exchanger. By doing so I should be able to increase the heat transfer by a factor of approximately sqrt(2). Which brings me to a total increase of 6.4 times.

Thus, the final Reynolds number is 615. The final Nusselt number is 110. Interestingly, the final heat transfer coefficient is only slightly more than the one I started with (by doubling length we reduced the efficiency of the heat exchanger) 156 W/m^2 K. The final surface area is 4.2 times the original at 0.119 m^2. Additionally, the oil outlet temperature is now around 134 °C (due to doubling the flow rate). All of this gets me the following equation for heat transfer.

$$\dot{Q} = 156 * 0.119 * \frac{(138-134)}{\ln\frac{138-80}{134-80}} = 1039\ W \tag{14}$$

Nice! So, after a couple of iterations to get the ending temperature right… I get a heat transfer rate of approximately 1000 W, a bit more than needed but that's not a bad thing considering all of the assumptions I made. Unfortunately, now comes the painful part: cost and weight.

Liquid Oil Cooler BOM:

Part No	Description	Qty	Wt Ea (lb)	Total Wt	Cost Ea ($)	Total Cost
XXXX	Oil Cooler - Oil Side	1	0.18	0.18	350	350
XXXX	Oil Cooler - Water Side	1	0.18	0.18	350	350
XXXX	Oil Cooler Gasket	2	0.02	0.04	--	--
XXXX	Oil Cooler Exchanger	1	0.62	0.62	1075	1075
91251A110	4-40 x 0.5	24	0.0017	0.0408	0.087	2.088
90631A005	4-40 Nylocks	24	0.0017	0.0408	0.0279	0.6696
53505K680	Oil Tube Flange	2	0.057	0.114	16.15	32.3
XXXX	Water Pipe Flange	2	0.04	0.08	--	--

Total	1.30	1810

Alright, so it's not cheap. That's printing aluminum for you… But hey, if you've got the money… you can save a bit of weight and guarantee that the cooler will work. Also, you can definitely get this printed for cheaper if you put the work in. I quoted this on 3D hubs which is decent for small jobs. However, big print shops like Stratasys (https://www.stratasysdirect.com/) will have a lot of big jobs going so you can contact them and see if they will fit your part into one of those, saving you some money. It's been awhile since I had to contact them, so I don't remember the email, but they should be willing to help. Otherwise, 3D hubs' website is https://www.3dhubs.com/. You upload your parts and they'll give you a quote. Generally, the quote is based on part height and weight so try and upload your parts in the shortest orientation.

Here's a link to the CAD parts that I designed. You can use them as is or you can modify them as you need. For instance, if you don't have a turbo then you won't need as big a cooler. For instance, you could not increase the length of the cooler to cut the weight in half and the price down by probably 2/3rd. (reduce the main body length in CAD from 3.5 in to 2 in, and if you want, change the fin geometry around a bit). If you do so, your heat transfer rate will drop to around 700 W.

Here's the link to my CAD:
https://drive.google.com/file/d/1Prf5PlA4pUuhXgqGM1qZ4Te51ieWEgqO/view?usp=sharing

Some other notes on manufacturing, the gasket should be CNC cut (waterjet or whatever you want to do) out of a high-temperature oil resistant material such as Viton, https://www.mcmaster.com/#rubber/=1chfolo. The water pipe flanges as shown are designed to be used with hard lines you can change up those flanges to be whatever works with your system. Same with the oil flanges, if you want you could have them printed into the metal. Additionally, if you want to save money, you can make the oil and water side metal pieces out of welded tube and plate, they just won't necessarily be quite as light or have as good flow characteristics.

If you choose to use the liquid cooling approach you will need to hook up the oil cooler to the coolant water lines on the cold side. You should aim to keep the oil lines as short as possible to minimize the pressure drop in the lines.

Wrapping It All Up:

There's just one thing to add to the system before you're done: temperature sensors. Obviously, having at least one is critical, preferably right before the radiator. However, it's better if you add a second one to the system right after the radiator. This way, you can tell what the temperature drop is across the radiator. If the temp drop is near zero then you know something is wrong, perhaps the fan isn't working.

So, that's pretty much it. Use and learn from the above and you should be able to design an effective cooling system. Generally, the tech judges don't ask much about cooling. Potentially, they will ask why you chose to use an electric water pump. Also, occasionally, the aerodynamics judges will ask about the radiator shrouds and how you optimized them. Unfortunately, that's a pretty difficult question as it's difficult to do internal CFD on a radiator and get accurate info. Fortunately, some of that information is in the paper I linked in the shroud section. If you chose to go with liquid cooling for the oil, that's pretty unique and might get you a few points for innovation.

The Right Way to do it:

Alright, now comes the interesting part: Figuring out how to actually do it right. So, what do you need to do?

One note, it's critical that you perform these tests with ambient conditions that are representative of what you'll see at competition. If you are going to Michigan and Lincoln, and you expect Lincoln to have an air temperature around 90 °F then you should perform your tests in that sort of temperature (or use some heaters to heat up a room). This will ensure that your system performs well enough in extreme conditions. If you've got the time and money you could perform the tests twice, once at Lincoln ambient and once at Michigan (or use some engineering to approximate the difference) and design a separate cooling systems for each competition to save weight at the colder one (Michigan unless the weather decides to be really weird).

You need to more efficiently size the radiator, fan, and water pump as well as determine what the most effective radiator core arrangement and fin density is. The most effective way to do this is to test the components listed above separate from running the car. In so doing, you can create a series of relationships between the heat-transfer out of the system and the main parameters: water flow rate and air flow rate. The other things you need to know to size the fan and water pump are the pressure drops across the entire coolant loop and across the air side of the radiator.

So, listing what you should learn:

1. Pressure drop across the engine/cooling lines/radiator
2. Water flow-rate vs PWM setting
3. Pressure drop across the radiator (airflow)
4. Air flow-rate vs PWM setting
5. How much heat the engine actually puts out.
6. Relationship between heat-transfer out and water flow rate
7. Relationship between heat-transfer out and air flow rate
8. Effect of different styles of radiator core.

Test Setup:

So, in order to do that what do you need? You need something that will move hot coolant through the radiator, measure the water flow rate, the air flow rate, and the temperature before and after the radiator. If you've designed your system along the lines of what was described earlier in this document, this is a fairly simple task.

Pressure Drop across the engine/cooling lines/radiator & Water flow-rate vs PWM setting:

This experiment is the easiest to perform of the three tests you'll be doing. All you'll need to do with this one is to measure the flow rate across the system at a set voltage and compare it to the manufacturer's supplied flow rate vs pressure curves. The items needed are listed below:

1. Complete cooling system (a la Figure 2.)
2. Ultrasonic flowmeter (Something like this one: Amazon flowmeter, this one is the cheapest one you can get… it works… it's not super easy to use or very robust however)
3. Power Supply (w/ adjustable voltage)

So, the only really annoying thing to get for this test is the flowmeter. Unfortunately, it's also a pain to set up properly. Luckily (although not for me), I have some experience with it. There are two things you need to know to setup that flowmeter properly.

1. It must be set up on a long straight piece of hard tube. – So if you're running hardlines this is pretty easy just put it on the longest and straightest tube you have. If you're running softlines however, you'll have to do some modification. Get a long straight hard tube (metal, pvc, anything will do) and insert it into your system somewhere and then mount the flowmeter sensors to there. Don't try and do it on the soft tube – trust me – we did, and it just didn't work right.
2. The screw terminals on the flowmeter electronics suck, the wires will fall out. Just be prepared to deal with it.

Alright, other than that this is pretty easy to setup. Put the flowmeter somewhere on cooling tubes – done. Next, hook the power supply up to run the pump and set it to the voltage that Davies Craig tested the pump at. For the EWP80 that's outlined here: http://daviescraig.com.au/media/694/1427092566.EWPSelectionGuideTechSpecs2009.pdf. TL; DR, it's 13.5 V. Keep that PDF, btw, you'll need it in a bit.

Pressure Drop across the air side of the Radiator & Air flow-rate vs PWM setting:

This measurement isn't too hard to take but will require some custom fabricated pieces for it. What you want to do is measure the air flow rate across the radiator at a set voltage input and compare that to the airflow vs pressure chart provided to you by the fan manufacturer. The items you'll need are listed below.

1. Radiator (Can be detached from liquid side if desired)
2. Fan
3. Radiator Shrouds in the style described in Figure 10 above
4. 2 x hot wire anemometers (something like: Amazon Anemometer, I know it's expensive hopefully the school will let you borrow some)
5. Probe holders and adaptors
6. Power Supply (w/ adjustable voltage)

So, most of that you should already have. The custom components you'll need to make are the probe holders. These will go at the inlet and outlet of the shroud system and hold the anemometer probes in the locations shown below.

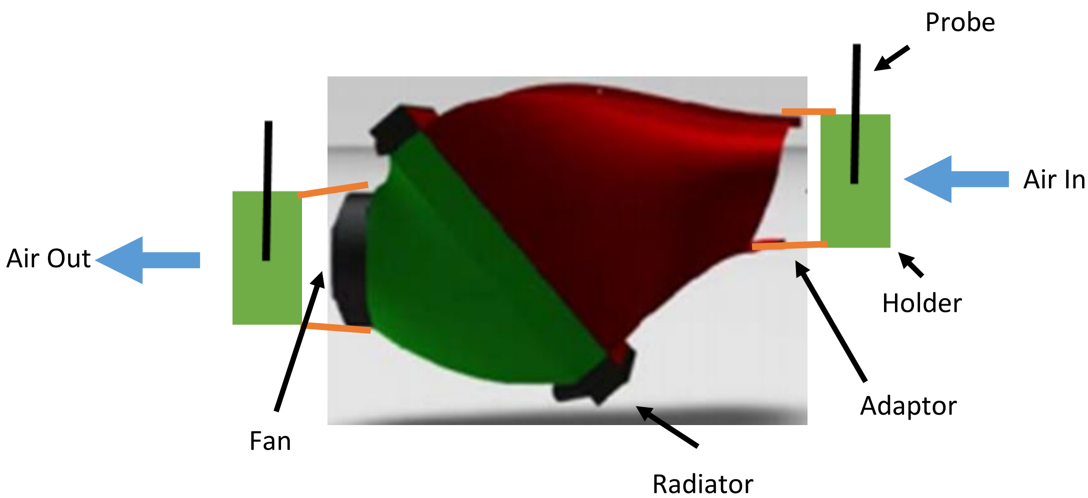


Figure 24. Air Pressure Drop Test Setup

An example of the probe holder is shown in CAD below.

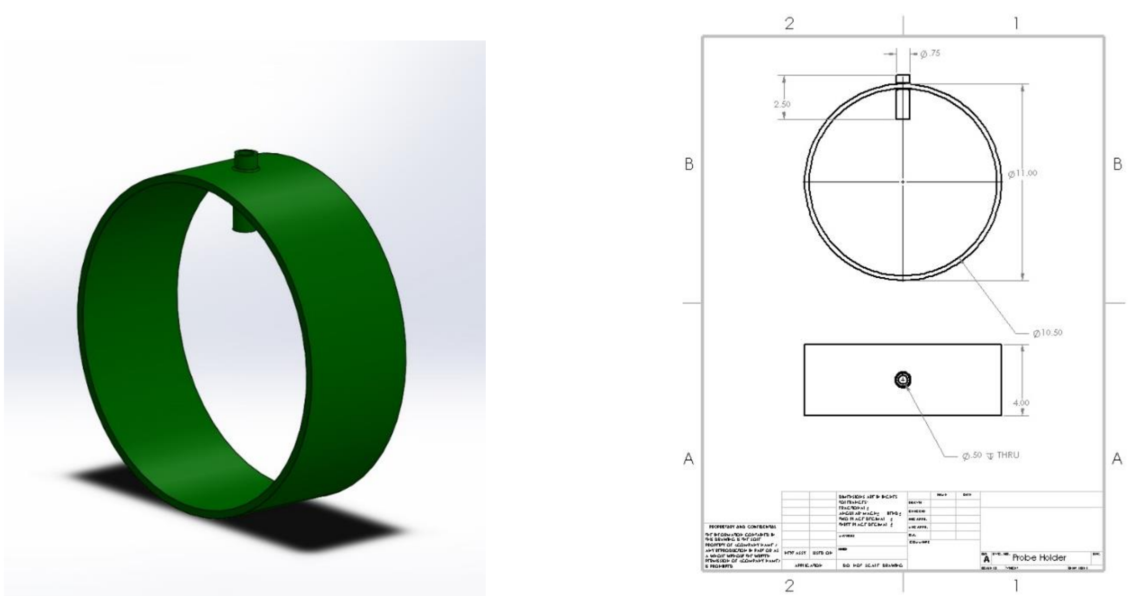


Figure 25. Probe Holder CAD example

The size of the adaptors should match the inlet (or outlet) that they are attached to; so, if you have an 11” diameter fan than the probe holder for that side should be an 11” diameter circle. They don’t need to be super long, only 3-4” or so, as you don’t need to be super precise so making sure the flow is fully developed isn’t that important. The part that actually holds the probe should (obviously) be slightly larger in diameter than the head of the probe so that the body drops in and stops halfway through (so it should be smaller in diameter than the largest section of the probe body). These parts can be 3D printed out of any simple FDM machine or you can go fancier if you want.

The adaptors can be as simple as something like construction paper wrapped around the inlet and taped together. All that really matters is that they seal as well as you can make them (lots of tape).

You should hook the power supply up to the fan so that the input voltage exactly matches the voltage that the manufacture tested the fan at. So, for the fan in figure 7, you can find that information at the bottom left of the datasheet: 13 V.

Make sure that all the seams in the system are sealed as well as possible (this is something you should do when installing the shrouds on the car too, regardless of this test). If you have a reversible fan you can reverse the flow so that it is pushing through the radiator and then use soapy water at all the seams to find leaks. And that's pretty much it for the setup.

How Much Heat the Engine Actually Puts Out:

This is probably the hardest test to set up since it requires running the engine. Unfortunately, the flow meter is, as far as I can manage at least, too fragile to get data while the car is actually driving around so you'll want to set it up on a dyno. Either a chassis dyno or an engine dyno will work just fine.

You'll want to set up the system similar to the test for the pressure drop across the engine system with the flowmeter set up on a hard line. You'll need to make sure you have a fan set up properly on the radiator, so you have airflow. Additionally, you'll want to make sure to put two temperature sensors in the coolant lines: one before and one after the engine. It'll probably be easiest to hook the water pump and fan up to the controllers that you will be using later although you may need to adjust the settings in the table a bit later. That's pretty much it for this setup; it sounds simple, but the dyno makes it difficult.

Heat-transfer Relationships:

Alright, what you're doing with this one is the most important and most difficult test to accomplish if perhaps not the most difficult one to setup. What we're going to do is to get a large constant temperature source of hot water (like a big tub) and run that water through different radiators at varying air and water flow rates to see what the effects on the heat transfer are.

Here's the items you'll need:

1. Cooling system consisting of water pump, radiator, fan
2. Additional radiators with similar core area (For instance 1 saldana, 1 C&R, 1 double pass)
3. Two temperature sensors attached to some sort of logging system (before and after radiator in the cooling system)
4. Large reservoir of hot water with a flange to attach a tube to at the bottom (the bigger the less you have to refill it)
5. Ultrasonic flowmeter from test 1
6. Two hot-wire anemometers from test 2
7. Probe Holders and adaptors from test 2
8. 2 x power supplies (or 1 power supply and a constant voltage source like a very large battery)

So, you'll want to set up the test rig something like the following:

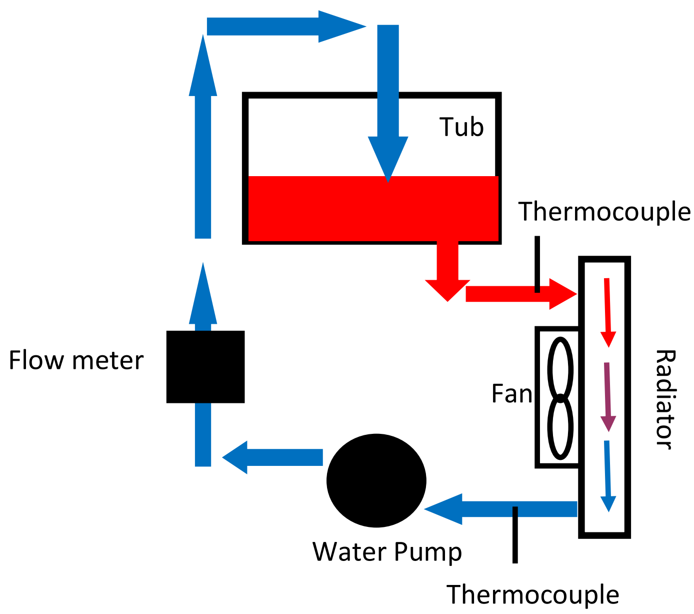


Figure 26. Heat Exchanger Test Rig

An important point, the Radiator and fan in this system should resemble the system in Figure 24 with two hot-wire anemometers. You'll probably have to do some modifications to make the fan shroud fit the different radiators.

Additionally, you're going to want to pull from the bottom of the tub in order to prime the pump as these ones aren't self-priming. Fill the tub up with as much water as hot as you can get it. If you can you might want to find the hot-water-heater for the building and get the water directly from there. Set the power supplies up on the fan and water pump so that you can control their speed with the voltage input. Like I said, not a super complicated setup.

Data Collection and Analysis:

Now we get to the harder part, actually collecting and using the data.

Pressure Drop across the engine/cooling lines/radiator & Water flow-rate vs PWM setting:

Alright so for the first test, to determine the pressure drop across the cooling system, what you're gonna do is run the water pump at the test voltage (13.5 V) and measure the flow-rate across the coolant line system using the flow meter. So, set the power supply to 13.5 V and let the flow stabilize for a minute or so, then take flow rate measurements several times, say every 10 seconds for the next two minutes just write down the number that the flow meter says.

Once you've got those data points get the average flow rate and compare it to the flow-rate vs pressure chart corresponding to your pump. For the EWP80 it's the one below:

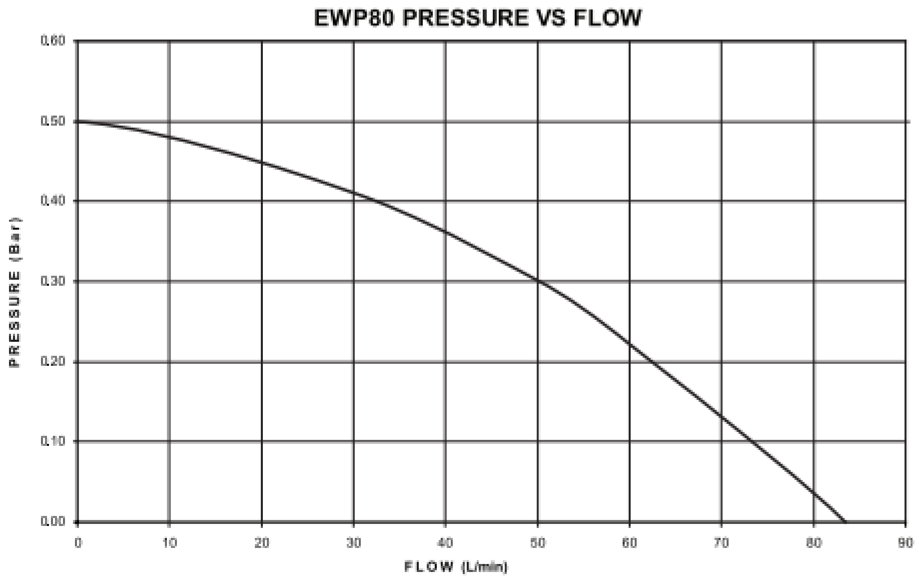


Figure 27. Flow-rate vs pressure drop (Davies Craig PDF)

Find the pressure that matches your flow-rate and that's the back pressure in your system. Write it down as it'll be good to be able to tell the judges if they ask and it will help you pick a pump should you choose to resize. Remember, different pumps are affected by back pressure differently if, for instance, the EWP80 pump has a flowrate of 60 LPM in your system you can't expect the EBP40 to flow 30 LPM. The ratio may not be the same because the smaller pump will be more affected by pressure.

The second test with this system is to try and figure out what the flow rate will be at different PWM settings. We'll simulate the different PWM settings using the power supply. Set the power supply to match the voltage that your car normally sees while driving, probably around 14 V and measure the flow rate at that voltage. Then, remembering that PWM is a way to approximate a lower input voltage, adjust the supply voltage down for the next PWM setting i.e. 90% PWM would be 90% of 14V (12.6 V) and so on. You'll use this data in conjunction with the heat transfer relationships to set up our control tables.

Pressure Drop across the air side of the Radiator & Air flow-rate vs PWM setting:

This will sound really familiar if you already read the test outlined above. The first thing is to determine the pressure drop across the system. To do that you're going to run the fan (in the whole radiator setup) at the test voltage used by SPAL (13 V) and then compare it to the fan curve the manufacturer gave you in their technical documentation. So, turn the fan on, let the flow rate stabilize for a minute or so, and then measure the speed using the two anemometers. Record this data a bunch of times, say, every 10 seconds for two minutes and then average each set of data to get the average velocities. You can assume that the velocity at the center of the duct is a representative average velocity for the whole area. This is not quite correct, but, because both ducts are quite short the flow shouldn't be very developed and thus it should have a fairly uniform velocity profile. You can then use the cross-sectional area of the two probe holders to calculate the air flow rate at the front and rear of the system. Then average those two together to get the flowrate through the radiator. Why should you use two anemometers? Well, because there will be leaks no matter how careful you are and I'm assuming that an average of the air going out and the air coming in will be representative of the airflow in the middle of the system. That should be a pretty good assumption. So, once you've got your flowrate compare it to the fan curve given us. If you've used the 12" SPAL AP9 fan from figure 7 then the fan curve's actually a table like this one:

Static pressure *Pressione statica* mm H_2O	Airflow *Portata* m^3/h	Current input *Corrente assorbita* A	Airflow *Portata* CFM
0	1470	6,9	867
2,5	1260	7,3	743
5	1070	7,5	631
7,5	930	7,3	549
10	680	7,0	401
12,5	400	7,2	236
15	0	7,3	0

Figure 28. SPAL AP9 12" Fan Curve

With that you can find where your flowrate lies in the table above. Remember that number, you should use it next time you pick your fan to maximize flowrate at your particular pressure.

Next, you'll figure out what the flowrate is at different PWM (voltage) settings. So same as the test above, find the flowrate at the voltages corresponding to different PWM settings. You'll use those to create our control tables.

How Much Heat the Engine Actually Puts Out:

So, for this test you're going to put the engine on a dyno and run it at different speeds (at full throttle) and see what the energy output of the engine is. To do this you need to run the engine at each RPM point for a little while until the temperatures stabilize and then measure the water flow rate and the temperature before and after the engine in the coolant loop a couple of times over the course of a couple minutes. Average these values and then solve for energy flow rate using equation 2 (m_dot = V_dot*rho).

$$W = c * \dot{m} * \Delta T \quad (2)$$

You'll want to get this at a range of different RPM values. The data you get out will probably look something like this:

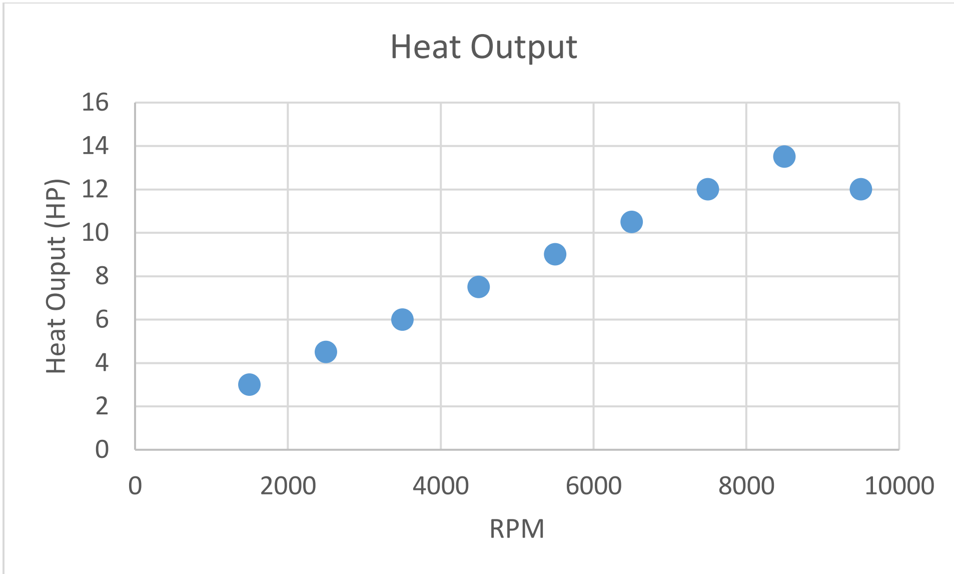


Figure 29. Example Heat Output vs RPM

Yeah, it probably will look a lot like the engine's power curve, but who knows, maybe not. Once you've got that data you should look at your engine logs from testing and competition to see what your average operating RPM range is, so you'll know what the average heat output of your engine will be. Once you get this value you can use it to size your radiator (with a bit of a factor of safety).

Also, it would be valuable to figure out the relationship between engine power output and the heat output. Is it a straight 30% like the rule of thumb? Or is it more complicated? You'll want to know this if you're engine gets more (or less) powerful for the next year to size your system.

Heat-transfer Relationships:

Alright, this will be the most important and also probably the most difficult set of tests to perform. First thing we're going to do is to figure out which radiator we want to do all the other tests on. We're going to do this by testing each radiator at the maximum pump and fan settings to see which one gives us the most heat transfer per unit mass (of radiator). So, fill up your tub with hot water and turn the power supplies up to 14V. Let the flow stabilize for a bit… 20-30 seconds should be enough and then measure and record the water flow rate, air flow rate, and temperature before and after the radiator. Then, repeat for the other radiators.

I'd be very interested to see here if the double-pass radiator does perform significantly better than the normal radiators as observed in this paper: https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf. If it does, it would definitely be worth it to use them in the future.

Once you've got data for all the radiators you can calculate the heat transfer using equation 2. Divide the value you get here by the mass of the radiator (hopefully the core areas for all the radiators are equivalent so you don't have other factors here) to get the heat transfer per unit mass. We'll use whichever radiator performs best at this test for the rest of the tests.

So, the next thing to test is to find out the relationship between the heat transfer rate and the water flow rate. Alright, you're going to want to look at a nice linear progression of water flow rates for this one, so you should use the data from the test for water flow-rate vs PWM setting to determine what settings you should use for the following test. Say, for example, your maximum flowrate is 60 LPM then your data table might look something like this:

Flow Rate (LPM)	PWM Setting	Air Speed (m^3/s)	Temp in	Temp out	Δ T	Heat Transfer (W)
60	100%	.12	XXX	XXX	XX	XXXX
55	XX%	.12	XXX	XXX	XX	XXXX
50	XX%	.12	XXX	XXX	XX	XXXX
45	XX%	.12	XXX	XXX	XX	XXXX
40	XX%	.12	XXX	XXX	XX	XXXX
35	XX%	.12	XXX	XXX	XX	XXXX
30	XX%	.12	XXX	XXX	XX	XXXX
25	XX%	.12	XXX	XXX	XX	XXXX
20	XX%	.12	XXX	XXX	XX	XXXX
15	XX%	.12	XXX	XXX	XX	XXXX
10	XX%	.12	XXX	XXX	XX	XXXX
5	XX%	.12	XXX	XXX	XX	XXXX

Figure 30. Example Heat Output vs Flow rate table

What you're trying to figure out here is what the shape of the heat transfer curve is. This can tell us if the radiator is air transport limited or water transport limited. That is if there is a point in the operating range where one of the two mediums cannot transfer anymore energy but the other still has some headroom. Let's say that your heat transfer curve looks something like this:

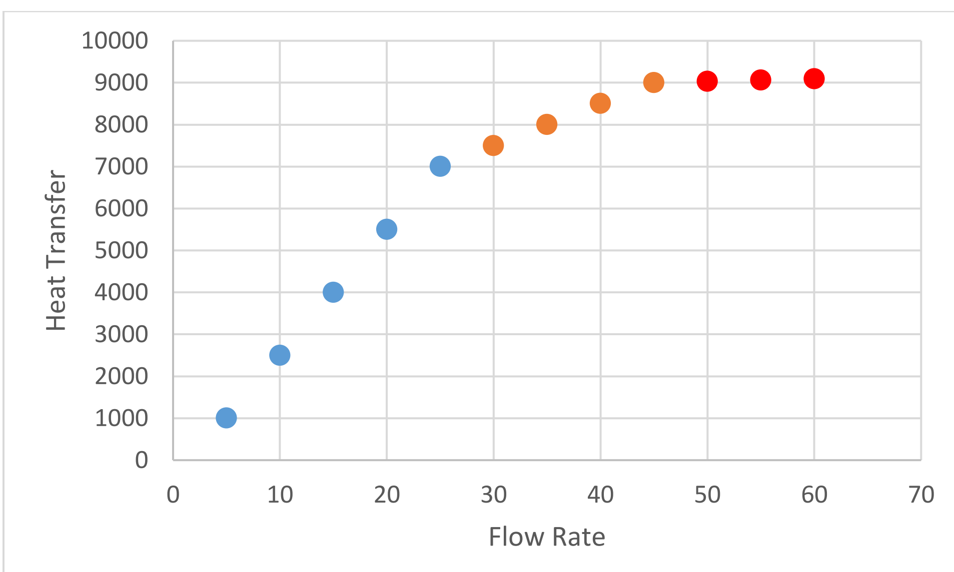


Figure 31. Example Heat Output vs Flow Rate Chart

I used three separate colors on this chart to illustrate three possibly phenomena that you might see in your data. The blue region is where the water flow rate is very low, this would be a region where it might be possible that the flow rate of the water is so low that the coolant literally cannot carry enough energy (remember equation 2, the heat transport equation is dependent on mass flow rate). The orange region is where your mass flow rate is high enough, but the heat transfer out of the system is limited by the forced convection on the water side (this is slowly increasing because as demonstrated in the liquid oil cooler section convection heat transfer is proportional to the sqrt of flow velocity). The red region (where the curve is flat) is where the heat transfer is limited by the convection from the radiator to the air. No matter what you do to the water flowrate you won't be able to increase the heat transfer out in this region. That's the region you'll want to avoid operating in as its just wasting energy to run the pump that fast. Note, the orange and blue regions may end up being combined in your data. Also, if your fan is powerful enough you may not see the air-side limited region (unlikely as it would take a monster fan to do this.)

Alright, next you're going to do what you just did for the water side with the air flow rate. So, set the power supply for the water pump at 14V and prepare your PWM settings for the fan power supply. Your data table will look something like this:

Air Speed (m^3/s)	PWM Setting	Water Flow Rate	Temp in	Temp out	Δ T	Heat Transfer (W)
.12	100%	60	XXX	XXX	XX	9100
.11	XX%	60	XXX	XXX	XX	8200
.10	XX%	60	XXX	XXX	XX	7300
.9	XX%	60	XXX	XXX	XX	6400
.8	XX%	60	XXX	XXX	XX	5500
.7	XX%	60	XXX	XXX	XX	4600
.6	XX%	60	XXX	XXX	XX	3700
.5	XX%	60	XXX	XXX	XX	2800
.4	XX%	60	XXX	XXX	XX	1900
.3	XX%	60	XXX	XXX	XX	1000
.2	XX%	60	XXX	XXX	XX	500
.1	XX%	60	XXX	XXX	XX	200

And your chart will look something like this:

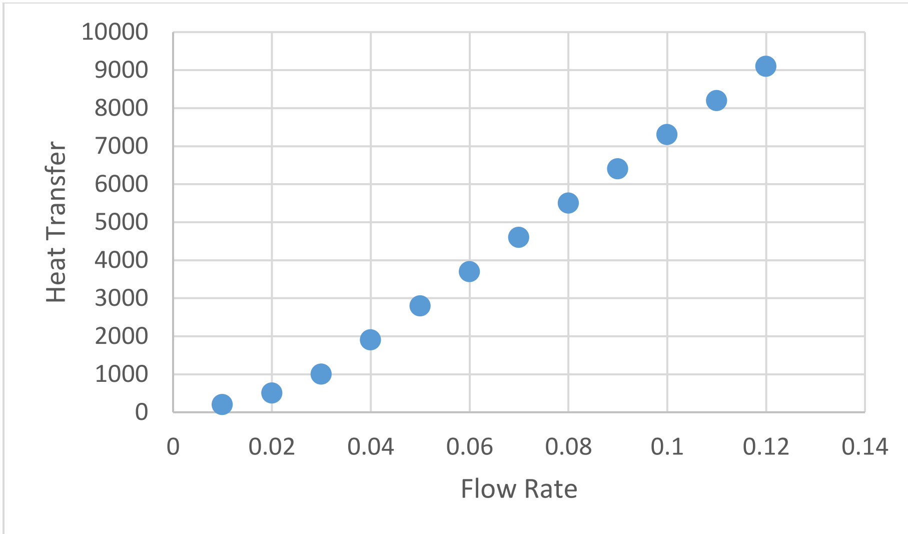


Figure 32. Heat Transfer vs Air flow-rate

I suspect that with air flow you're get something that looks pretty much linear, but I could be completely wrong on that one.

Using the Data:

So, now that you've got the data from the previous tests, what should you do with it? Well, for now, all you can do is create your control tables with the new data you have. However, if you decide that you want to resize your radiator, fan, or water pump then go for it. What you're going to want to do with the control tables is to set the water pump and fan settings to match the average engine heat output over the endurance course (with something like a 10% FOS on the heat transfer) at whatever your target engine temperature is. Based on figure 1, I'd recommend shooting for somewhere between 70 and 80 °C to maximize engine power. Then, since what we have here is a rudimentary proportional controller you're going to want to make the ramp around your target temperature fairly shallow, let's say that at +- 10 °C shoot for +- 20% heat transfer rate. Then underneath that you can ramp fairly quickly down to the slightly over the heat transfer rate the engine puts out at idle until you get down to whatever you want your minimum engine operating temperature to be. Below that you could probably turn the fan off in order to allow the engine to warm up quickly and keep the water flow rate at about the same as it was for the idle setting. Above the + 10 °C operating temperature is the area you never want the engine to be in so set your fan and water pump to the maximum in order to cool the engine off ASAP.

When you go to resize your cooling system components you'll want to do so with all of them together so that none of them are particularly oversized. My recommendation, is that you look at your engine heat output data and size a radiator, fan and water pump combo that can transfer the maximum amount of heat the engine puts out but no larger. This ensures that no matter what you'll be able to cool your engine down but doesn't waste too much weight. Of course, if you want to risk it and this is pretty justifiable, honestly, you could size your system to transfer less energy than the maximum (but more than the average in endurance) to save weight – just be careful that you account for any ambient temperature swings – if it ends up >100 at Lincoln again and you designed on the limit for 85 then you could be screwed. If you do this, it's not too hard to fix though… if the air temperature is too high then just use a bigger fan to compensate.

Index of Useful Websites/Papers:

U Toronto paper studying cooling system design – double pass vs single pass – Some design and test methodology
https://www.mie.utoronto.ca/mie/undergrad/thesis-catalog/289.pdf

Saldana Radiator Website
http://www.saldanaracingproducts.com/customradiator.html

Spal (Fan Manufacturer) Website
https://webstore.spalusa.com/en-us/productlist/0118/products/fans/fans+-+high+performance.aspx

Chalmers FS team study on radiator shroud design and its influence on cooling, drag, and their undertray
http://publications.lib.chalmers.se/records/fulltext/local_164409.pdf

Willem Toet Lecture on duct design for motorsports applications
https://www.linkedin.com/pulse/air-ducts-down-earth-guide-motorsport-applications-willem-toet

Rochester Institute of Technology presentation on cooling system design – effect of air inclusion on cooling performance
http://edge.rit.edu/edge/P12221/public/CoolingSystem.pdf

25 PSI Pressure cap – Summit Racing webstore
https://www.summitracing.com/parts/snn-10392/overview/

Ebay auxiliary water pump
https://www.ebay.com/itm/Universal-Auxiliary-Water-Pump-Coolant-Pump-for-Volkswagen-Corolla-Mercedes-Benz/122944579157?_trkparms=aid%3D222007%26algo%3DSIM.MBE%26ao%3D1%26asc%3D44039%26meid%3D2a7ebd57e4a444349f3b724ae863478b%26pid%3D100005%26rk%3D4%26rkt%3D6%26sd%3D323045344021%26itm%3D122944579157&_trksid=p2047675.c100005.m1851

Davies Craig water pumps
http://daviescraig.com.au/electric-water-pumps

Davies Craig EBP40 Water Pump:
http://daviescraig.com.au/product/ebp40-electric-booster-pump-kit-12v-9040

Davies Craig EWP80 Water Pump:
http://daviescraig.com.au/product/ewp80-electric-water-pump

Paper on alternator efficiency
http://www.delcoremy.com/documents/high-efficiency-white-paper.aspx

Description of Cavitation:
https://www.britannica.com/science/cavitation
PWM description and tutorial
https://www.arduino.cc/en/Tutorial/PWM

RBRacing electric oil pumps
https://www.rbracing-rsr.com/oilsystems.htm

Weldon aerospace oil pumps – contact and technical info
https://www.weldonpumps.com/weldon-unfeathering-pumps

Weldon pump distributor/price
http://www.aircraftspruce.com/catalog/eppages/8120gweldonpump.php?clickkey=8751

Yamaha ATV oil cooler
https://www.ebay.com/itm/Yamaha-Rhino-450-4x4-UTV-OEM-Oil-Cooler-09-2009-1222/152085171226?hash=item2368fb8c1a:g:lsUAAOSwfQRXMRB1&vxp=mtr

Stratasys – 3D print shop
https://www.stratasysdirect.com/

3Dhubs – 3D print service shop
https://www.3dhubs.com/

Liquid Oil Cooler CAD:
https://drive.google.com/file/d/1Prf5PlA4pUuhXgqGM1qZ4Te51ieWEgqO/view?usp=sharing

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https://www.mcmaster.com/#rubber/=1chfolo.

Cheap Ultrasonic flowmeter on Amazon:
https://www.amazon.com/TUF-2000M-TM-1-Ultrasonic-Flowmeter-DN50-700mm-40-90%E2%84%83/dp/B00DEFLOHQ/ref=sr_1_5?ie=UTF8&qid=1523852949&sr=8-5&keywords=ultrasonic+flow+meter&dpID=511fOqbJg9L&preST=_SX342_QL70_&dpSrc=srch

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http://daviescraig.com.au/media/694/1427092566.EWPSelectionGuideTechSpecs2009.pdf

Hot wire anemometer from Amazon:
https://www.amazon.com/TPI-565C1-Anemometer-Hot-Wire-Temperature/dp/B0095X8YZG/ref=sr_1_4?ie=UTF8&qid=1523813500&sr=8-4&keywords=hot+wire+anemometer&dpID=4105A2OuEwL&preST=_SX342_QL70_&dpSrc=srch