Thermo-Bob™ Testing Results / History

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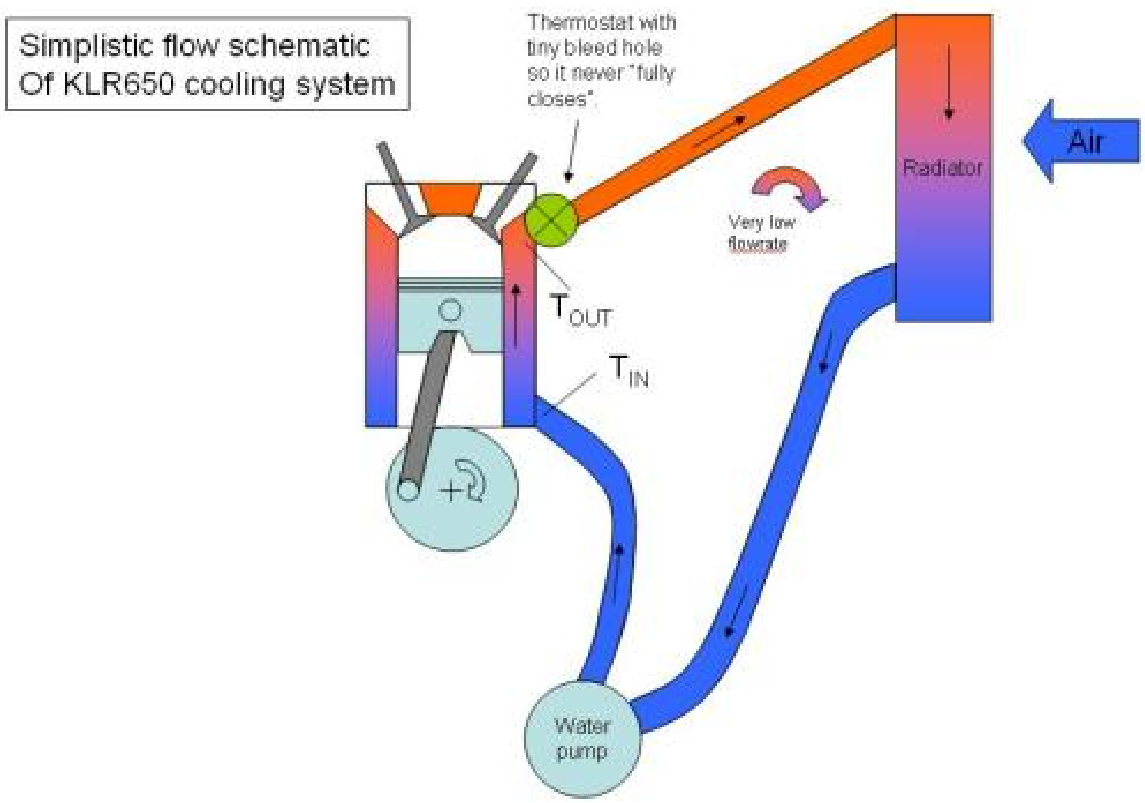
THE BOTTOM LINE:

I believe that the KLR650 coolant is too hot in the summer and too cold in the winter. The cooling system should be designed to run the same temperature all year. I fixed the "too cold" problem by designing and installing a hotter thermostat and added a bypass to the system, as most liquid-cooled engines are designed with one from the factory. Now I have more stable and warmer coolant, plus hotter oil which should result in longer engine life.... and a slight increase in fuel mileage as well.

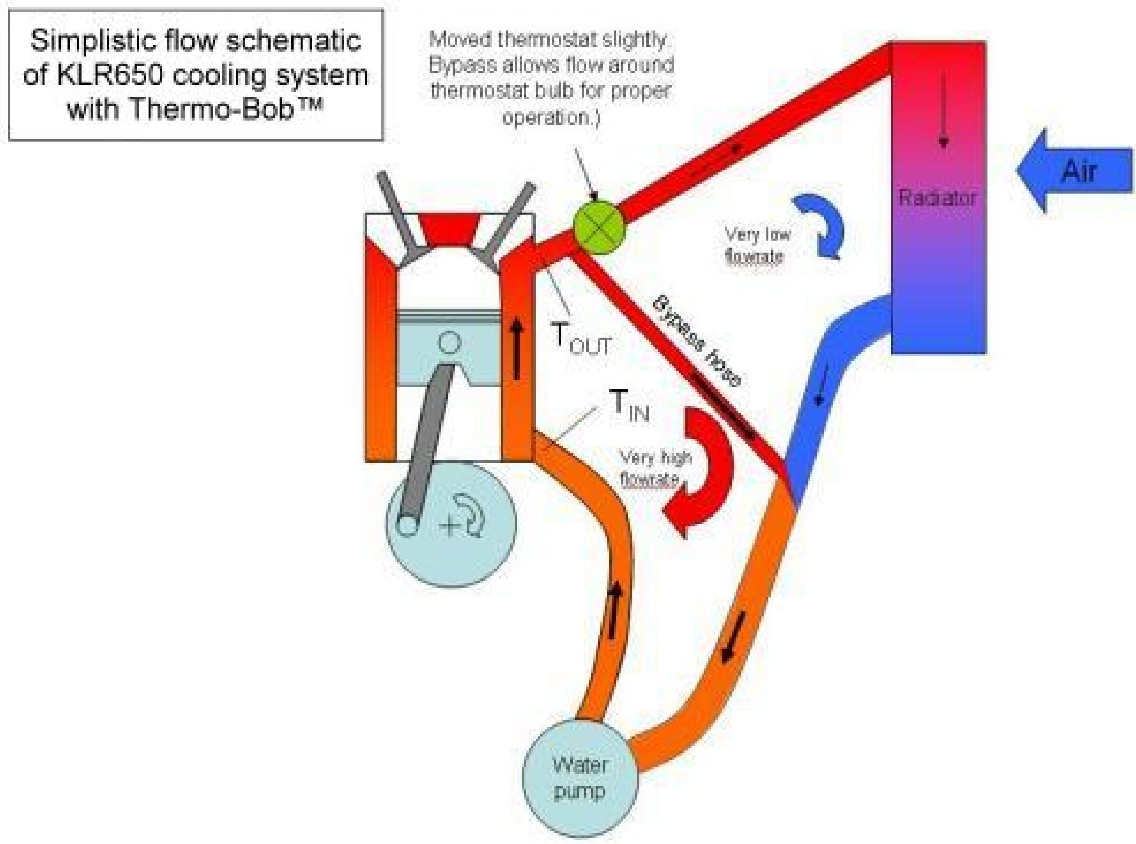
*** SHORT VERSION *** (We'll work quickly, then discuss the details)

Below is a simple diagram of the KLR cooling system.



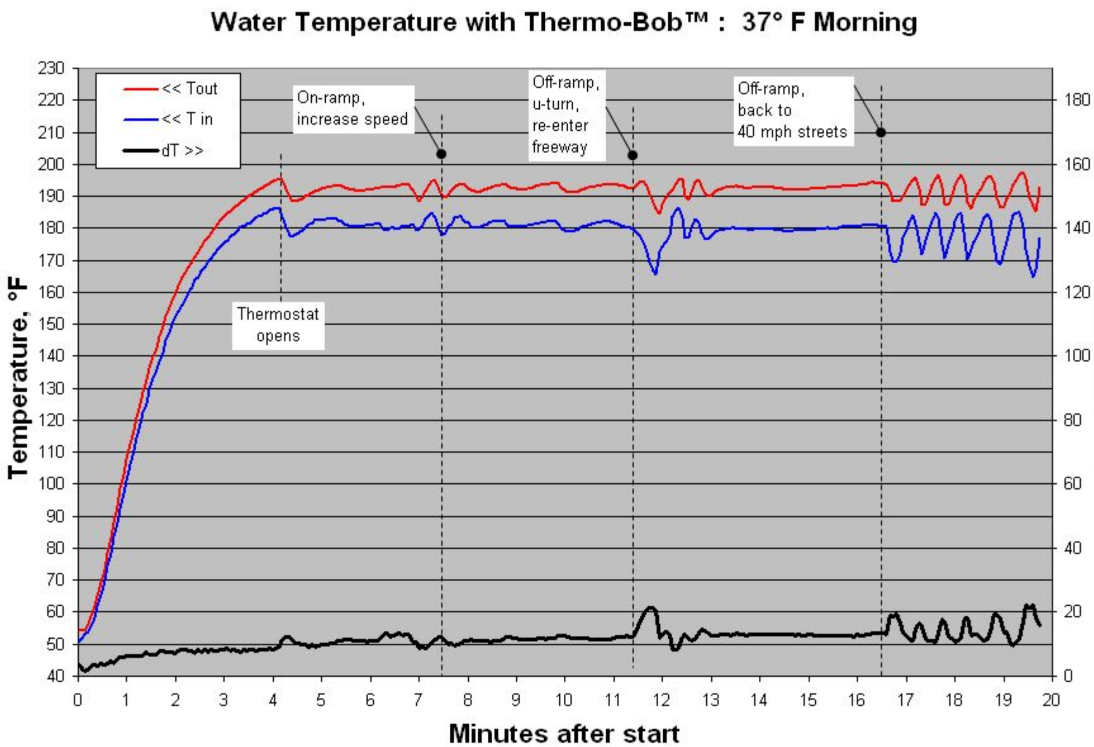
It's pretty simple by design. The factory thermostat tries to maintain a coolant temperature of 158° F exiting the engine. I would argue that 195° is a more appropriate temperature, so the Thermo-Bob uses an automotive 195° thermostat. But there's still a problem with the factory system: The KLR does not have a bypass, so the only way it can control engine temperature in the winter is to restrict coolant flow through the *engine*. (Bypass systems control coolant flow through the *radiator*). Since the KLR cuts coolant flow in the *engine*, it comes in surprisingly cold and has lots of dwell time in the winter to heat to the exit temperature.

The next diagram shows the coolant system with a Thermo-Bob kit added.

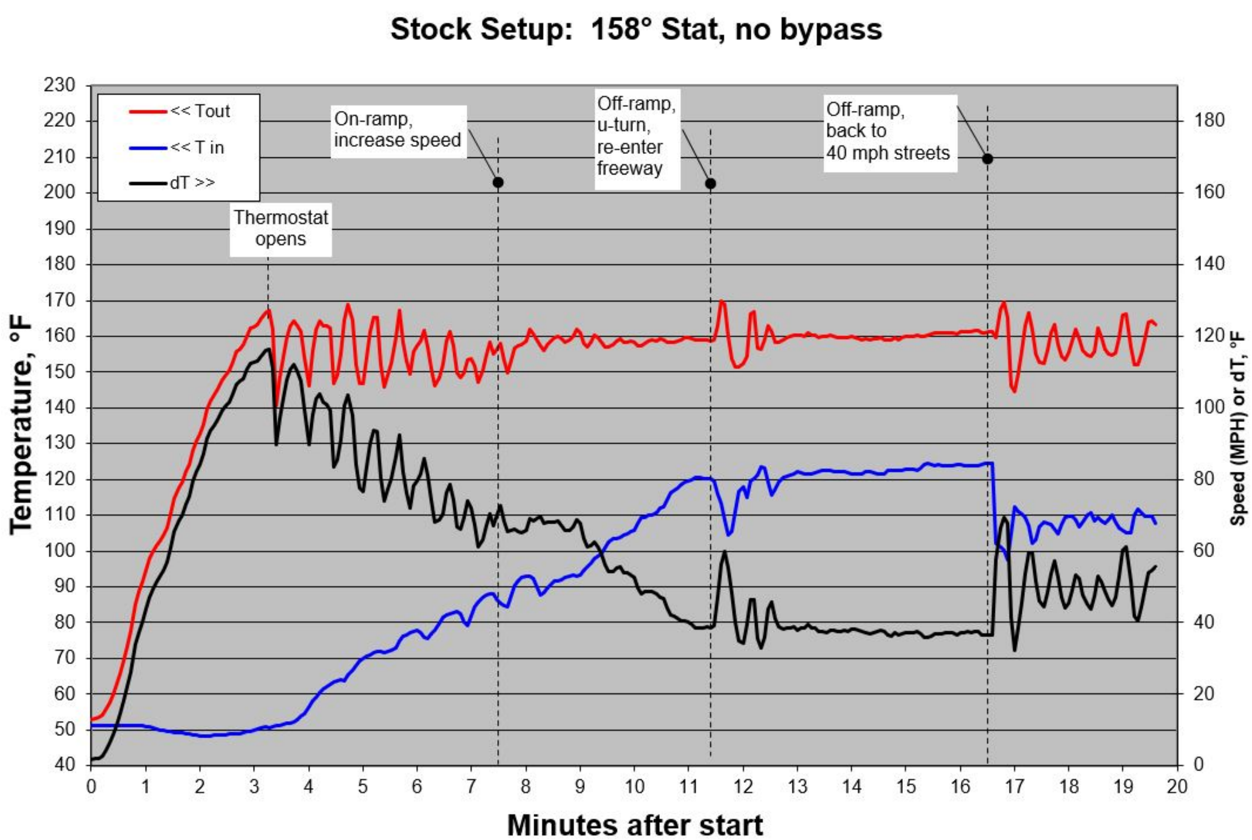


Note how even with the Thermo-Bob's thermostat closed, that the coolant now has an unobstructed path to flow at a high rate all the time, and now the thermostat only mixes in what cold coolant it needs. I've changed the colors of the coolant to reflect what the test results show. Now coolant comes in pretty warm in the first place, only gains a few degrees across the engine, and after leaving the engine and going down the bypass hose, only mixes with a little cold coolant to get a small temperature drop in the coolant before going through the engine another time.

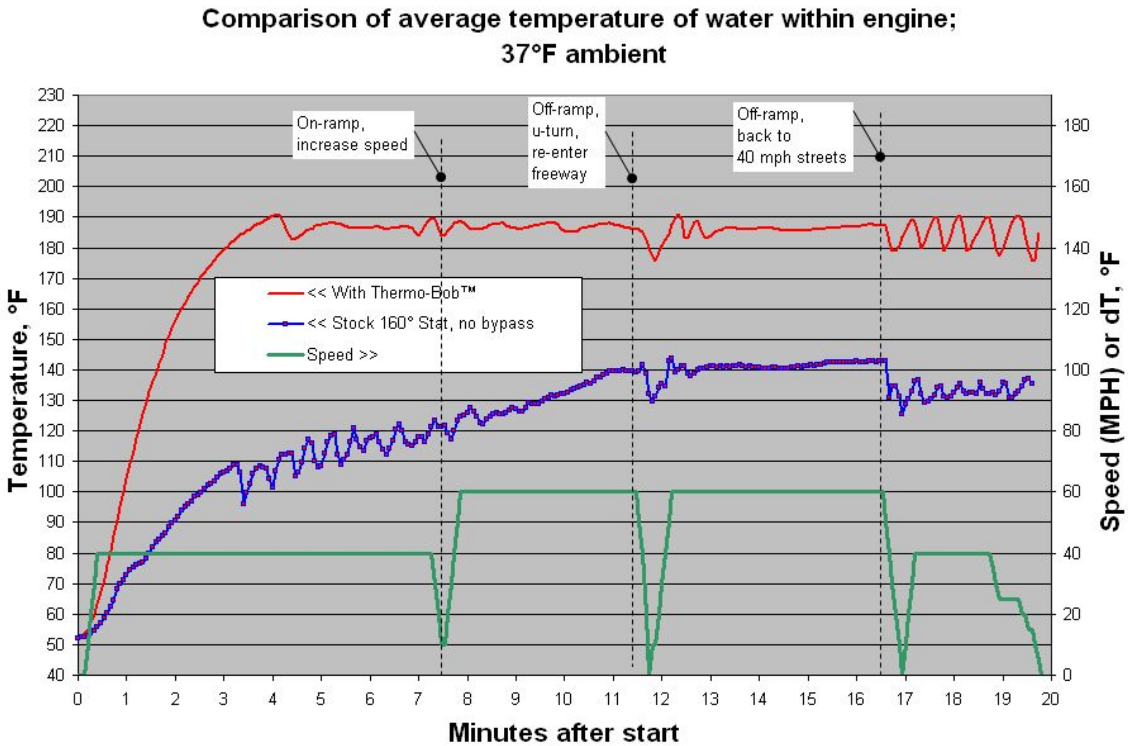
This first graph below shows coolant temperatures with a Thermo-Bob during a 20-minute drive on a 37°F morning. (The bike was stored overnight in a garage, so the test started with ~50 degree coolant.) Note how the engine warmed up quickly and both T_{IN} and T_{OUT} were consistently hot. The goal is to have a small difference between the red and blue lines. The easiest way to show this is to subtract the blue line from the red line and plot it as the black line. Lower is better, and automotive cooling systems are designed with the goal for the black line to be between 0 and 15 degrees. Again, remember to read the black line on the scale on the right side of the graph.



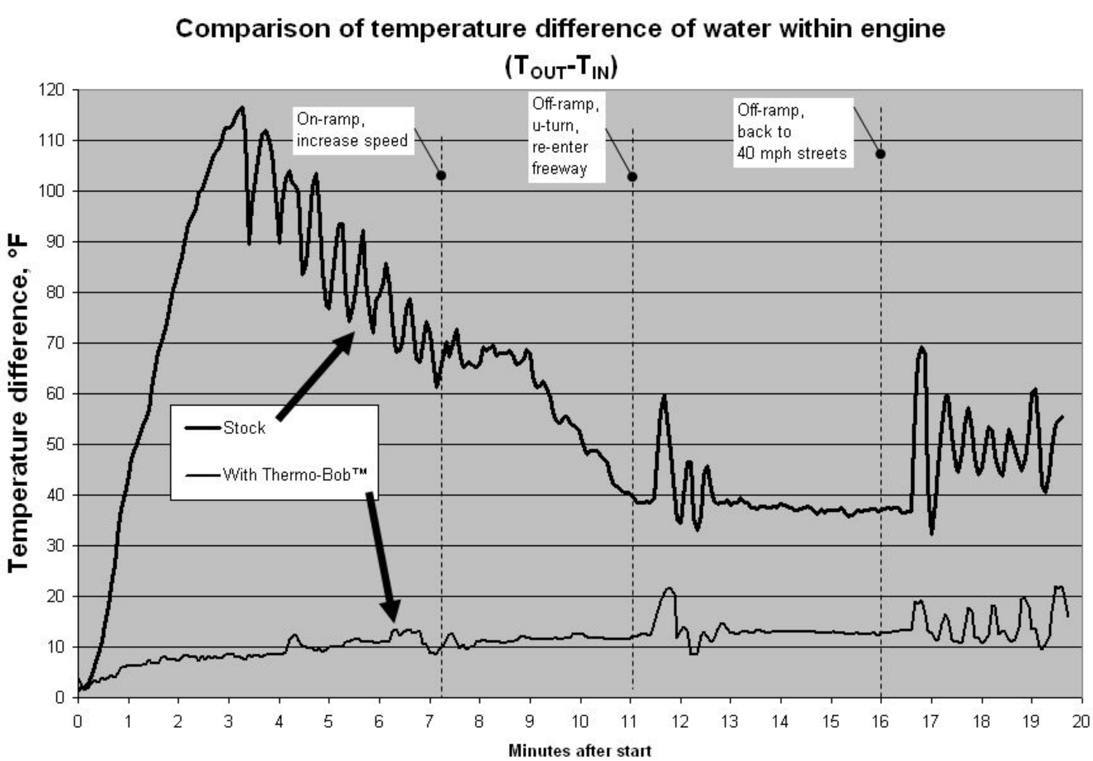
Compare now to this graph below, which is the STOCK KLR on the same drive (37°F morning). T_{OUT} goes through much more pronounced swings at the beginning as it doesn't get a lot of flow across the thermostat's temperature bulb, and T_{IN} is pretty cold for quite a while - after 8 minutes of riding, it was only up to 90°. The bottom of the cylinder is cold, the top is hot. <u>Get a load of where the black line is now - not a good design from a thermal stress standpoint</u>.



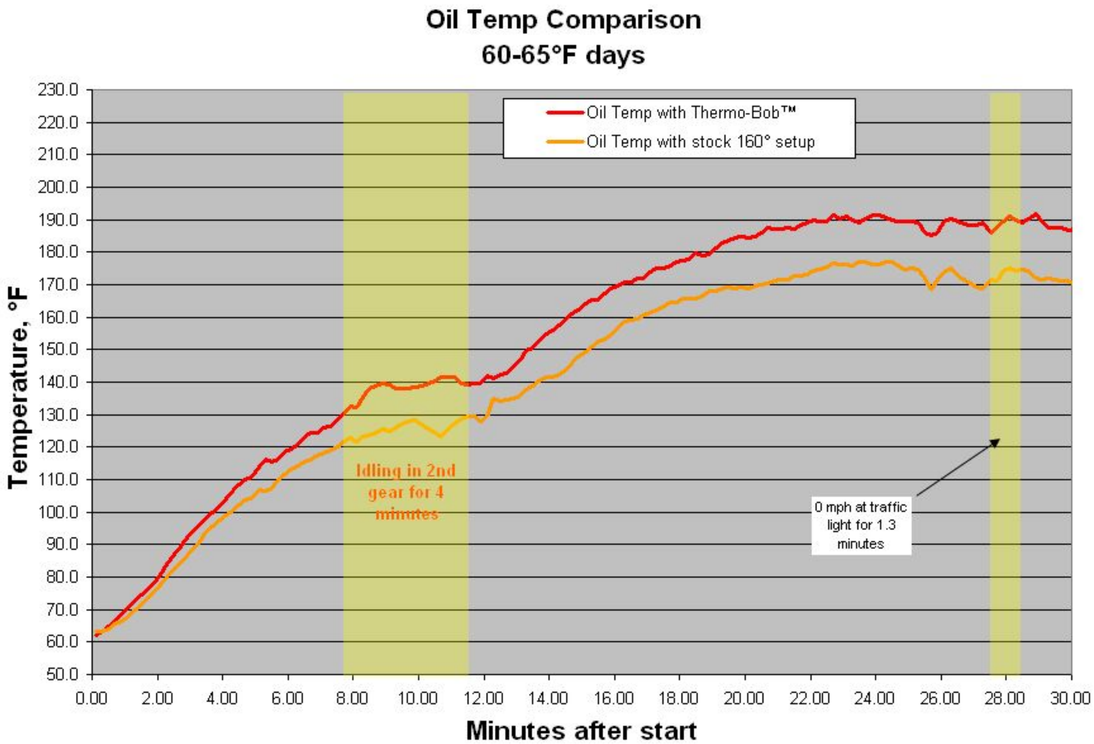
Below, this might be the best way to look at the results; the figure shows the <u>*average temperature of the coolant around the cylinder*</u> during the two tests. On a colder day the blue line would be lower and lower - but the red line would not budge. I think this is significant. Note how the modified system just sits there at 185° average.



Below is a comparison of the two "black lines"… wow.



An added benefit for the KLR is that it helps the oil warm faster as well. The plot below shows the oil temperature during two similar tests on 60-65°F days. We'd like to see 190-210 degree oil, and you can see that it takes a long time to heat the oil in the first place, but the Thermo-Bob heats it faster and to a better temperature. Colder days or shorter rides only make the stock system look worse.



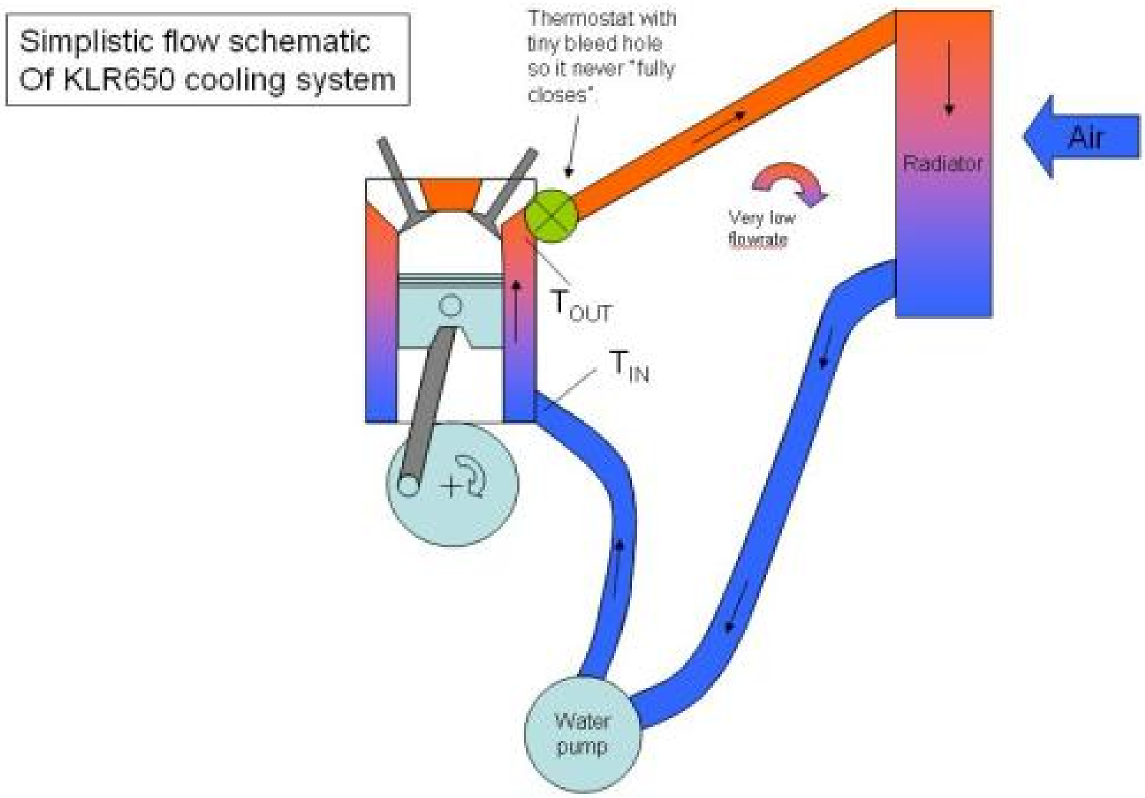
*** THE DETAILS ***

We're going to run through this again with more detail, so we can understand system operation plus answer questions such as:

How were the temperatures obtained and recorded?

- What was the driving cycle?
- What does the thermostat look like and how does it work?
- Why is there a hole in the factory thermostat?
- Why does the factory system see such large temp swings?
- Why do you want a large flowrate all the time?

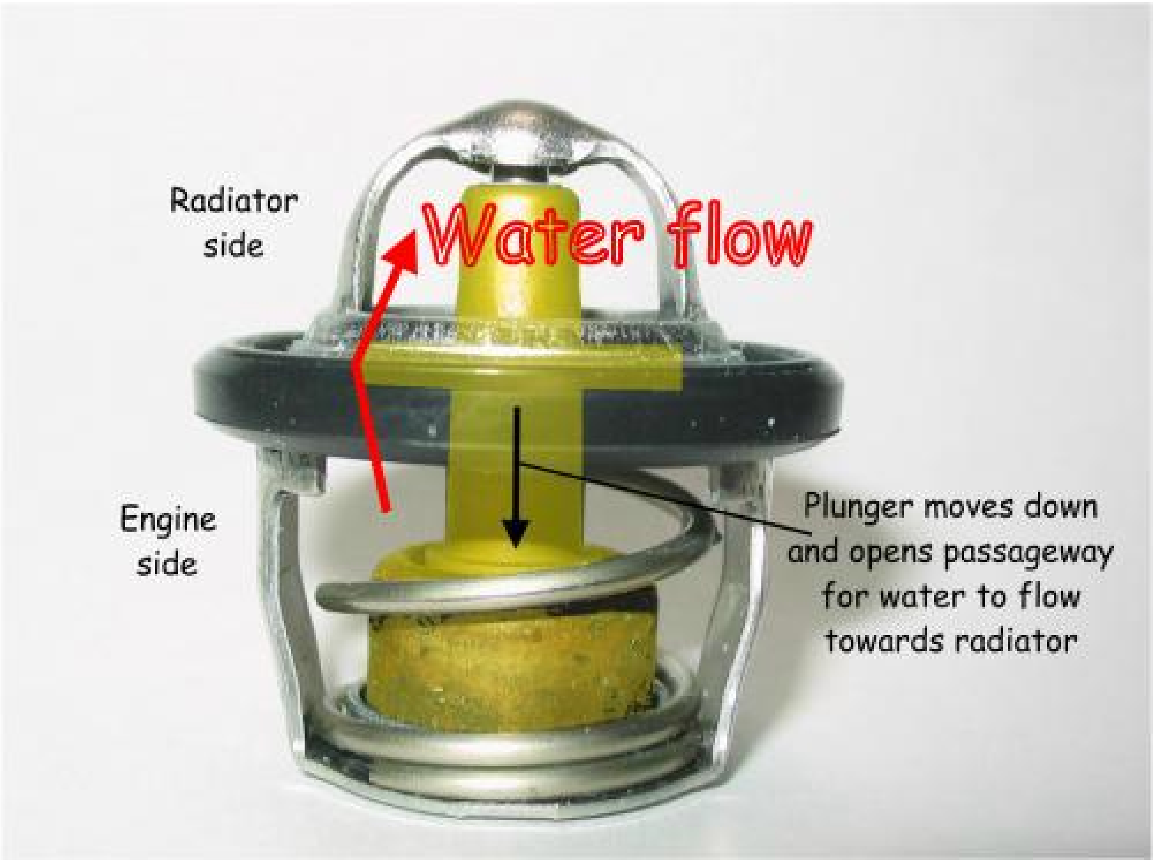
OK, here we go into all the minute details of how those statements are made, and I'll tell you what you already have figured out by now - I'm a mechanical engineer. For some reason I want to know how things work and enjoy understanding how a system works as a whole. My background is peppered with lots of automobile powertrain testing and modification – and when I bought a KLR650 (my first liquid-cooled bike), I found myself sitting on the floor next to the bike staring at where the radiator hoses connected, locating the water pump and thermostat, trying to figure out where coolant entered and exited the engine, and of course – thinking of ways to make it better. So let's start out with a basic schematic of the KLR cooling system on the next page.



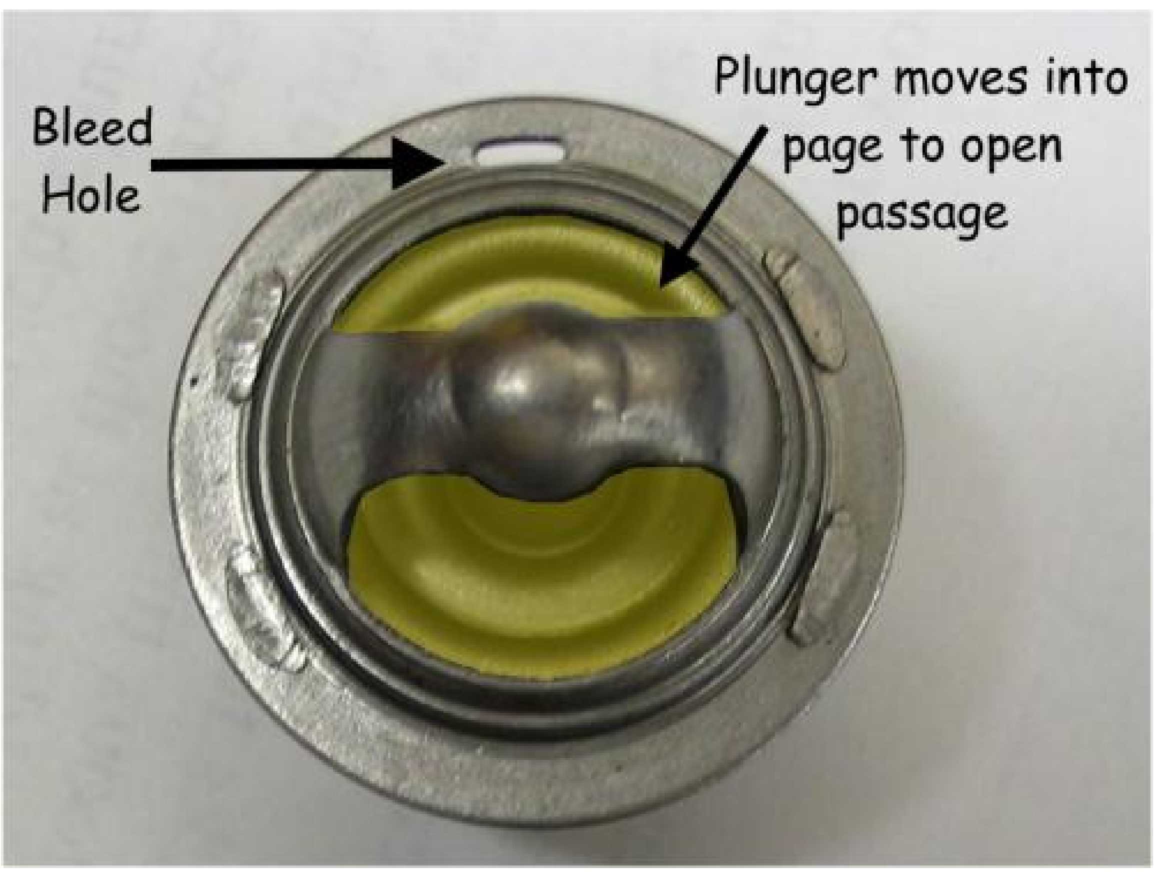
Start at the bottom of the radiator. Coolant gets sucked down into the water pump and is then pushed up to enter the engine at the bottom of the cylinder liner. This is labeled "T_{IN}" because we are going to install a thermocouple there to monitor temperatures where the coolant goes IN. The coolant continues up around the cylinder liner and up into the cylinder head, getting hotter as it removes heat from the engine while flowing around the liner, intake ports, exhaust ports and combustion chamber roof. At the highest point in the head, (my diagram is not totally accurate, it's just a cartoon) there is a thermostat to control temperature, and we'll add a second thermocouple here (T_{OUT}) to measure coolant temperature as it goes OUT of the engine. After the thermostat, the heated coolant is pushed up the radiator hose into the top of the radiator, where airflow across the radiator (due to road speed or the electric fan being on) cools the coolant for another trip around the engine.

So far, so good. It looks simple; heat is *added* to the coolant by the engine, heat is *removed* from the coolant by the radiator. But a system like this will be at the mercy of the ambient air temperature if there is no thermostat – you would have a bike that would run cold on a cold day and hot on a hot day. To establish a "minimum" temperature no matter how cold the air is outside, a thermostat has been added to the system by our friends at Kawasaki. The thermostat is essentially a valve that opens and closes at a certain temperature. On the KLR, the thermostat tries to maintain the coolant temp at 158°at the top of the cylinder head. There are no other temperature ranges available, even if you wish it was lower or higher.

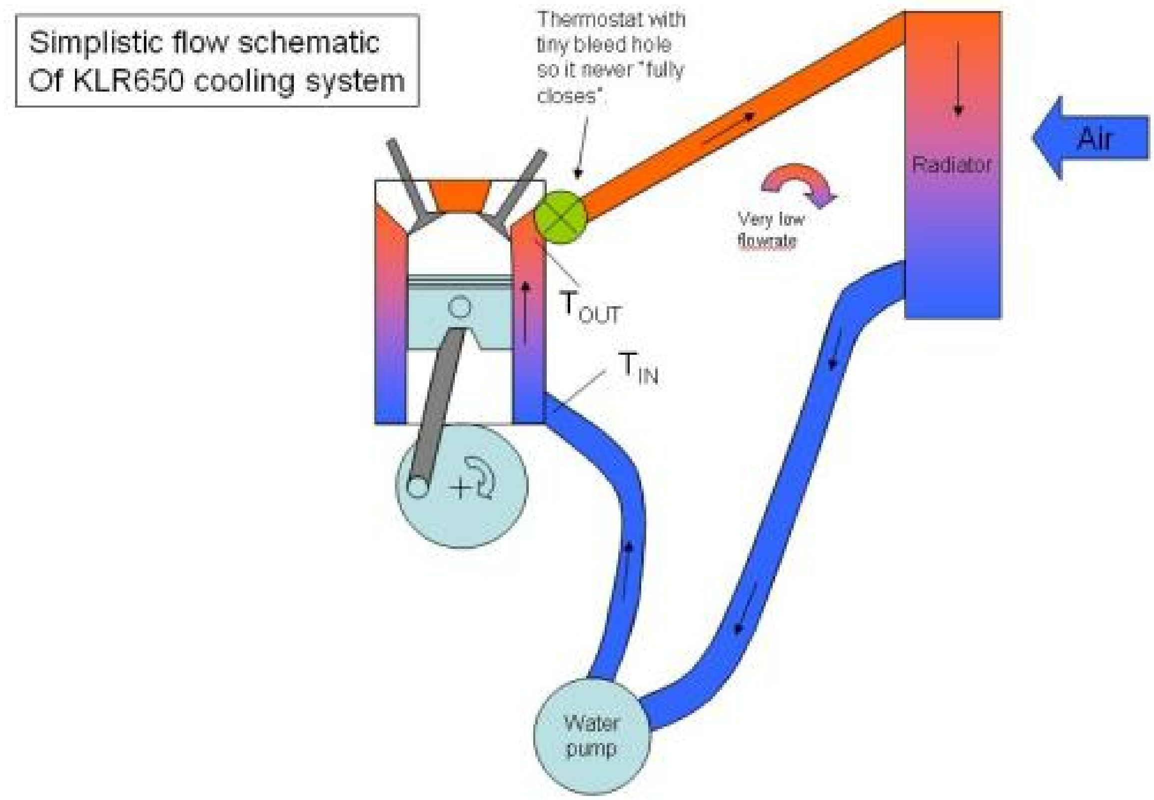
Let's start with a side-view (below) of the KLR thermostat to help visualize how it works. The gold part senses temperature, and when hot enough, moves down against the spring. I've ghosted-in a plunger so you can see how it closes off flow until it moves.



Below is a top view of the 'Radiator side' of the thermostat. To help you appreciate the size, the thermostat is barely larger than a quarter. The plunger has been highlighted in gold to make it a little easier to visualize. Also note that there is a bleed hole that lets coolant sneak around the thermostat, even if it is totally closed.



OK, let's break this down and look at system operation in a little more detail. I'll repeat a figure you've seen before to make it easier to follow along in this discussion.



Let us assume that the entire coolant system is empty. If we fill the system by pouring in coolant at the top of the radiator, you will see the first reason that the bleed hole has been punched into the thermostat… it allows you to fill the system to the top in one easy maneuver as there is a leak path around the closed thermostat. Face it – as you are pouring in 38 fluid oz of coolant into a dry system, 38 fluid oz of air must leave the cooling system to make room for it. Thus, as coolant is filling the system from the bottom, air will not be trapped against the closed thermostat. Instead, air will leak through the bleed hole and allow coolant to fill the entire cooling system in a single pour.

Now imagine putting on the radiator cap and closing off the system and going for a ride on a cold morning. We'll assume that the system has a stock 158° thermostat, and the engine is being started on a cold morning after sitting overnight. All of the coolant throughout the cooling system is cold, thus the thermostat is closed.

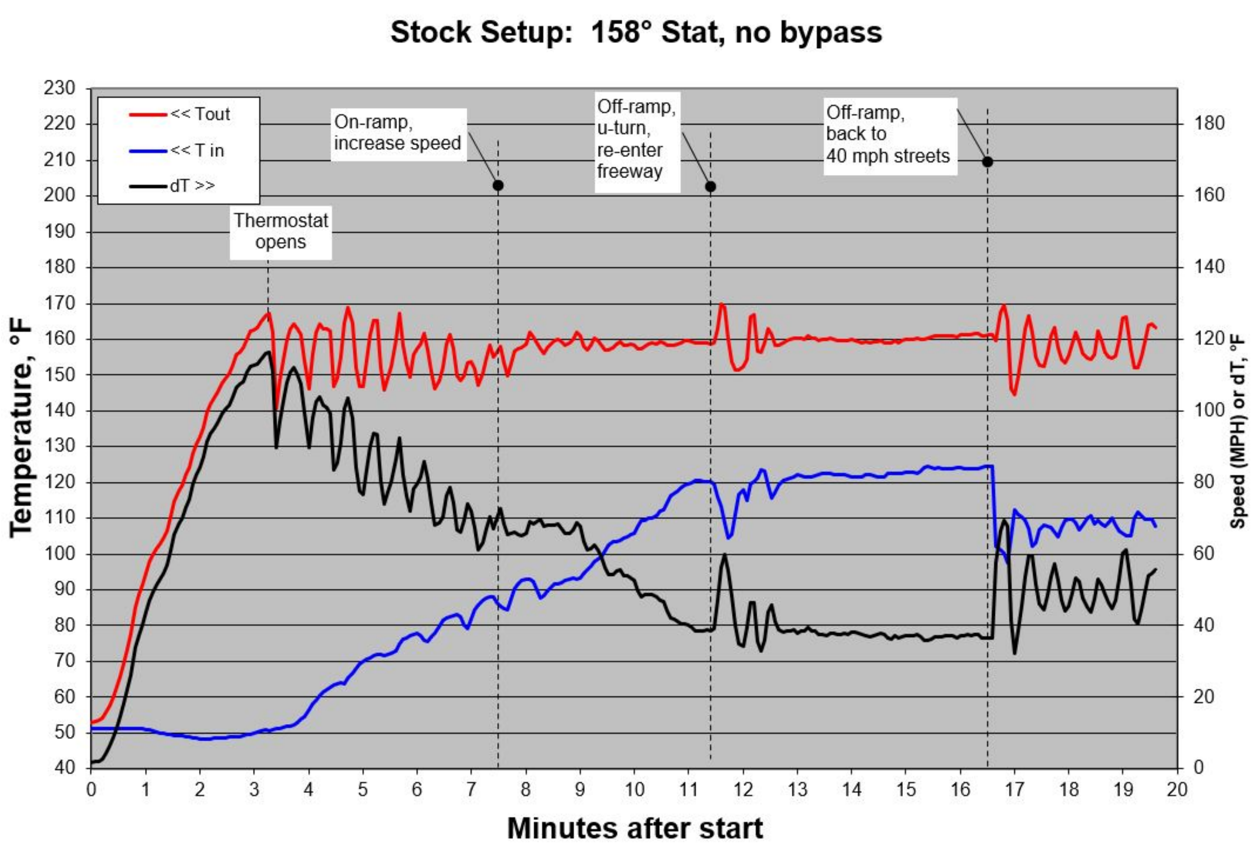
When you start the engine, the water pump tries to circulate coolant at a pretty good rate but the thermostat is closed. So the only reason there is *any* coolant flow at all is because of the tiny bleed hole… so coolant flow is about 2% of what it could be.

The cold coolant in the engine begins to heat as you ride away, and you might see the second reason that the bleed hole has been punched into the thermostat … this hole guarantees coolant flow right around the temperature sensing portion of the thermostat. If there were no bleed hole at all, coolant might be hotter in some part of the engine (say over near the exhaust ports) than 158°, yet the thermostat would still be closed because the coolant near it may be 145°. The bleed hole has been placed in the very part that they want to see coolant flow over for reasonably quick response. <u>The bigger the bleed hole, the better the response will be – but on the other hand, a bigger bleed hole will delay warm-up because more of your coolant is being chilled by the</u>

radiator, which you wish wasn't being utilized yet. This is a legitimate problem on non-bypass systems... you're juggling thermal response with warm-up time, and to make one better the other must get worse.

After a few miles of operation, the coolant at the top of the engine is hot enough that the thermostat starts to open. Remember, however, that the coolant flowrate has been so slow that the coolant entering the bottom of the engine is at ambient temperature because of such a long dwell time that it had in the radiator. With the thermostat open for the first time, the coolant flowrate increases and the engine gets 'splashed' with a gulp of cold coolant. This coolant makes its way to the thermostat in no time as it doesn't gain a lot of temperature in the fast trip. Suddenly the coolant coming to the thermostat is well below thermostat temperature, so the thermostat starts to shut and this cycle begins again. Some people don't think the coolant flowrate can change this quickly, but the data proves otherwise. Check out the red line between minutes 3 and 6 in the plot below. Hot. Cold. Hot. Cold. Hot. Cold. And get a load of how cold the water is coming *into* the engine (blue line). 50 degrees F for the first 4 minutes. Then 60 degrees. Then 70 degrees. Then 80 degrees. Nine minutes into the ride, it's still down at 90 degrees. Sheesh!

If the day is cold, this cycle will continue all day – and if ridden real smoothly, you'll eventually hit some steady-state point where the thermostat is just barely open and temperatures stabilize (say, 50° coming in and 158° going out). If it's a hot day (say 90°) the KLR radiator won't be able to dump as much heat out of the coolant as the engine is adding, so temperatures will continue to climb past the 158° thermostat rating and the thermostat will be open all the time. Since the heat removed from a radiator is proportional to the difference in the temperatures of the coolant in it and the air around it, temps will continue to climb until the radiator is finally able to dump as much heat as the engine is adding to the coolant. Stock KLR's seem to stabilize around 110° to 115° over ambient, meaning on a 90° day that coolant exiting the engine stabilizes around 200° to 205°F... and that's if you're not tailgating, climbing a hill, carrying a passenger, or riding fast. Those things would raise temps even higher.



Now let's talk about what we *want* the results to look like. We would like the bike to warm up quickly, in the fewest miles possible. This allows us to remove the enrichener as quickly as possible (improves mileage and reduces dilution of engine oil with fuel) and to allow the piston-to-wall clearances to tighten up quickly, minimizing the amount of raw fuel and blow-by diluting the oil as well. And since water is a by-product of combustion, some of it does get by the rings into the oil. Faster engine warm-ups promote faster oil warm-ups, helping get the oil up to temperatures where that water can be boiled off.

OK, so we want the bike to warm up quickly. What temperature do we want it to stabilize at? Well, since water boils at 212°F at sea level, most engine designers like to see oil temps between 190° and 220°F in the sump. Additionally, the hotter you run the coolant, more of the heat of combustion goes into pushing down on the piston rather than being sucked out by cold cylinder walls (i.e., better mileage). So most designers settle in around 200°F these days as a good temperature to stabilize at. Some drag racers still like a 160° thermostat in their V8's because the incoming air in the intake manifold is heated by the coolant, and they're trying to keep inlet air cold. That is not a problem on the KLR we must worry about.

But wait – the KLR still has a 158° thermostat. That's "1950's" cold. Maybe Kawasaki doesn't like these bikes to run hot for some reason. But that can't be it- their undersized radiators have them running 210°, 220°, even 230° all summer for owners in the South! So what's up with the cold thermostat? My guess – due to the lack of a bypass, the cycling was being juggled with too-cold coolant, and they struck a compromise. The Thermo-Bob eliminates both compromises.

OK. So we've established that we'd like to see a quick warm up of both coolant and oil, and once at thermostat temperature, we'd like to see the bike at that temperature all the time.

RESULTS

Time for some results. I mounted three thermocouples on my KLR; one at T_{IN}, one at T_{OUT} and one in the engine oil and have taken data for more than a year, over 10,000 miles of riding. I have a Fluke data recording device that can take data as frequently as every second if it is needed. The bike has been run in ambient conditions as low as 23°F and as high as 116°F. So we have lots of data here. That 23°F number is reasonably cold, and the testing shows that even in the 70's, the 195° thermostat and bypass were a good addition. It even becomes a better addition when it gets colder outside.

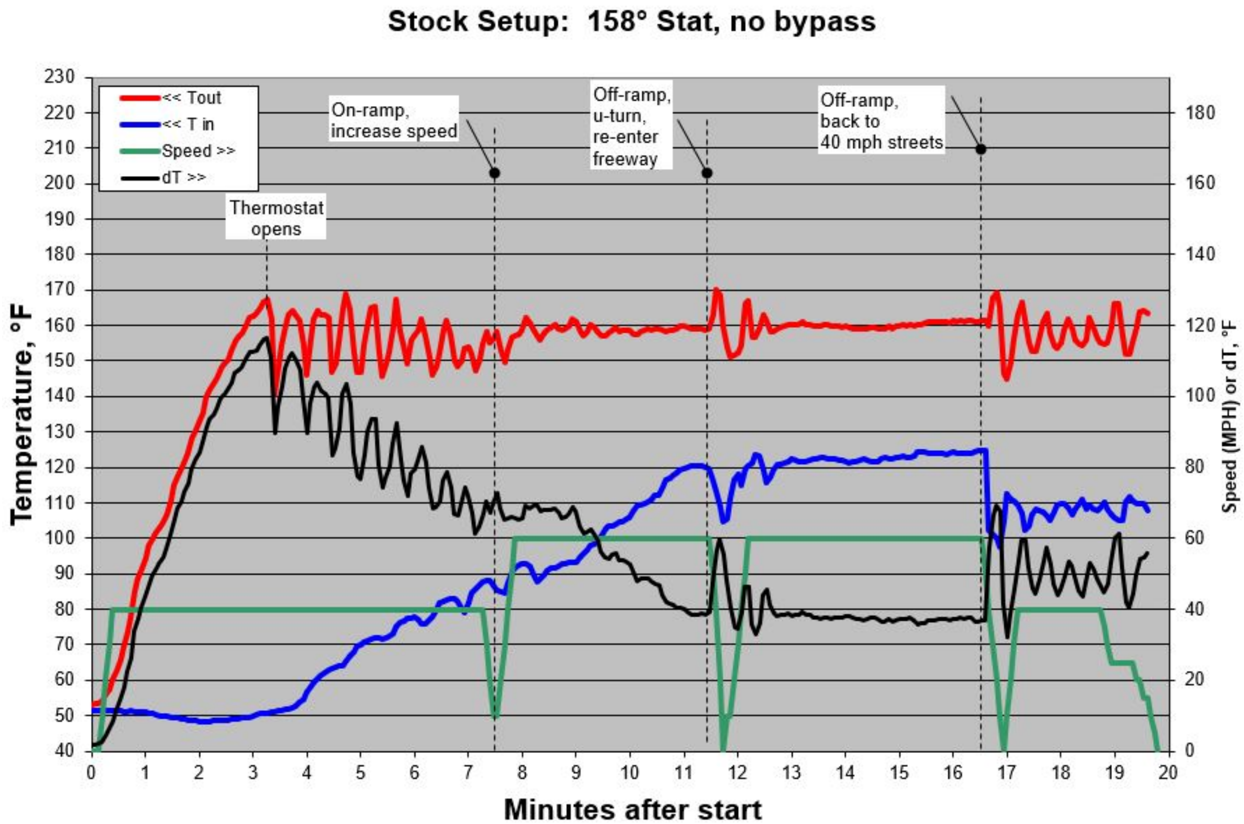
TEST CYCLE

For the tests we're discussing in this article, I put together a driving cycle that could be repeated very consistently, thus allowing changes to the cooling system to be directly evaluated.

For these two tests:

- I pushed the bike out to a major feeder street so it could be ridden immediately after engine start.
- Since the traffic lights are timed on the major street, the first 7 ½ minutes of riding were at a pretty steady 40 mph, and I never stopped.
- I then entered a freeway on-ramp, and rode 60 mph for 4 minutes, pulled a u-turn (took ~ 1 min) and rode another 4 minutes at 60 mph.
- I then rode for a few minutes at 40 mph, slowed to zero, and the engine was shut down.

Yeah, yeah, details. But rigor is needed during testing to provide results that can be compared to each other. Below is the data from the 'stock' bike on a 37°F morning, and there is a lot to talk about, as I have all the data in one plot. We'll take it slowly to digest it all, one piece at a time.



As you can see above, this was a 20-minute test from cold start. Data was taken every 4 seconds. The green line represents speed and is read off the right-side scale. You can see the driving cycle that was just described.

There is a significant amount of data here, so we'll take this slowly. The red line represents T_{OUT}, blue is T_{IN}, and black is the difference between these two readings, called "dT" or "delta T". The black line is read on the right scale, not the left. It is an especially useful parameter because it gives us a direct indication of coolant flowrate, on top of telling us how different the "top" and "bottom" temperatures of the engine are.

First 7.5 Minutes (mostly 40 mph riding):

Let's look at T_{OUT}, the red line. Note how it rose quickly (good) and went to about 165° before opening the first time. Once the thermostat opened, you can see that it then cycled over and over as we discussed earlier – the thermostat is opening, gets a gulp of cold coolant, shuts and starts the cycle again.

You really can't have a complete conversation about T_{OUT} unless you also watch T_{IN} (the blue line). This is what I meant by ***system*** operation - one thing affects the other. Note how T_{IN} started at 52° (garage temp), and once outside in the 37° air, actually *dropped* in temperature for the first 2 minutes of riding! This is because the coolant flowrate in the radiator is almost zero, so the coolant has lots of dwell time in the radiator which is being exposed to 37° air. Four minutes into the ride, the thermostat opened for the very first time. Note how T_{IN} suddenly started to rise – this is the 'big splash' we discussed. These happen pretty quickly... the valleys are spaced about 25 seconds apart.

Now it's pretty easy to understand the black line, dT – and see how the coolant flowrate must be really small, because the coolant is well over 100 degrees colder coming in than it is leaving the engine. Each time the thermostat opens, the coolant flowrate increases, and the dT plummets (coolant is in the engine for less time, so it picks up less temperature) and the cycle starts again. By the time we are 8 minutes into the ride, dT has "rattled down" to about 70 degrees. Ouch, still a lot!

The engine oil (separate tests) heats slowly. Compared to coolant, there's a lot of oil (80^+ oz.) and after the first 8 minutes of riding on a 60 degree day, oil has climbed to only 120°F. We have a long way to go here. How many people have an 8 minute ride to work and shut it down every day? Now it might be easier to see why people recommend that "short-driving-cycle" bikes should change their oil more frequently due to contaminants that never get boiled off.

<u>Minutes 7.5 – 16.5 (mostly 60 mph riding):</u>

The heat generated from making more power to push the bike down the road at 60 mph has increased dramatically so the thermostat opens a little more and T_{OUT} stabilizes at 158-160°F. Coolant entering the engine (blue line) stabilizes at 123°F. You can see some thermostat cycling when I got off the throttle to do a u-turn.

<u>Minutes 16.5 – 20 (0 to 40 mph stuff):</u>

Coolant exiting the engine continues to cycle around 158°F. With less heat going into the coolant but still good airflow through the radiator, coolant entering the engine cools to around 108°F. Not exactly what I'd shoot for in a design in terms of hot oil either ... on this particular test I didn't have thermocouples in the oil, but could hold my hand continuously on the clutch cover after the 20 minute ride. The engine cases were that cold.

<u>RECAP OF THE STOCK KLR COOLING SYSTEM:</u>

1) **T_{OUT} swings wildly as the thermostat gets contradicting data - too hot then too cold.**

2) **The black line shows that the temperature difference between the bottom and top of the cylinder is significant.**

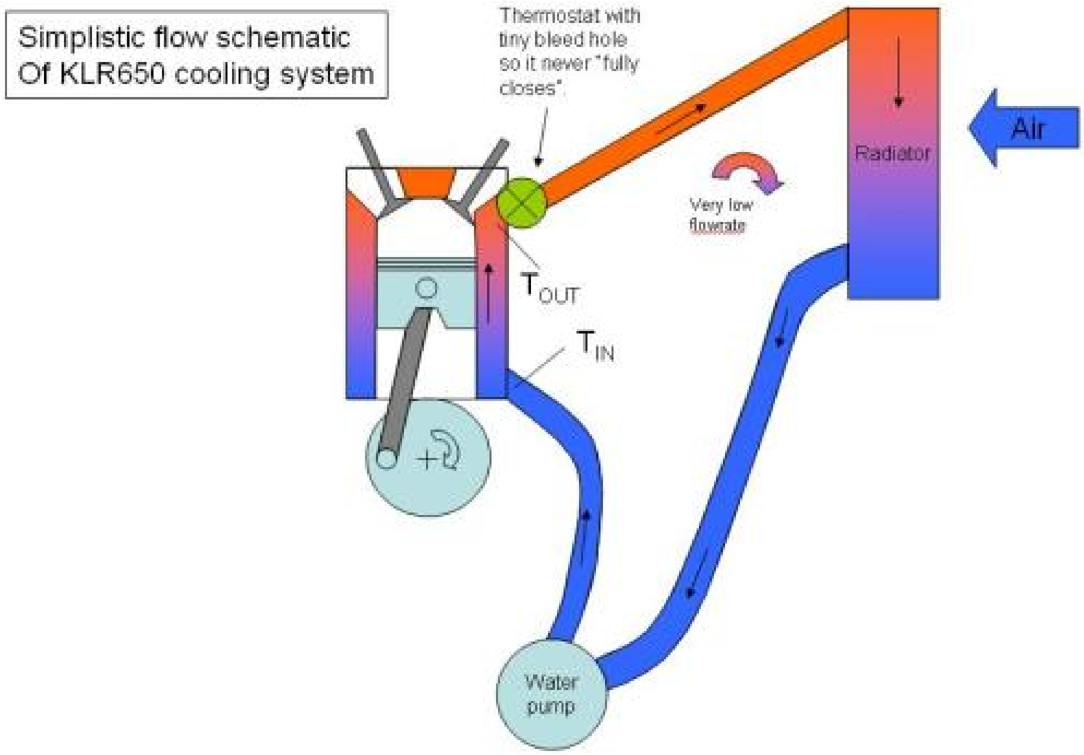
3) **Oil warms slowly. On a 65° day, it barely makes it into the 170's after a full half-hour of riding – too cold in my opinion.**

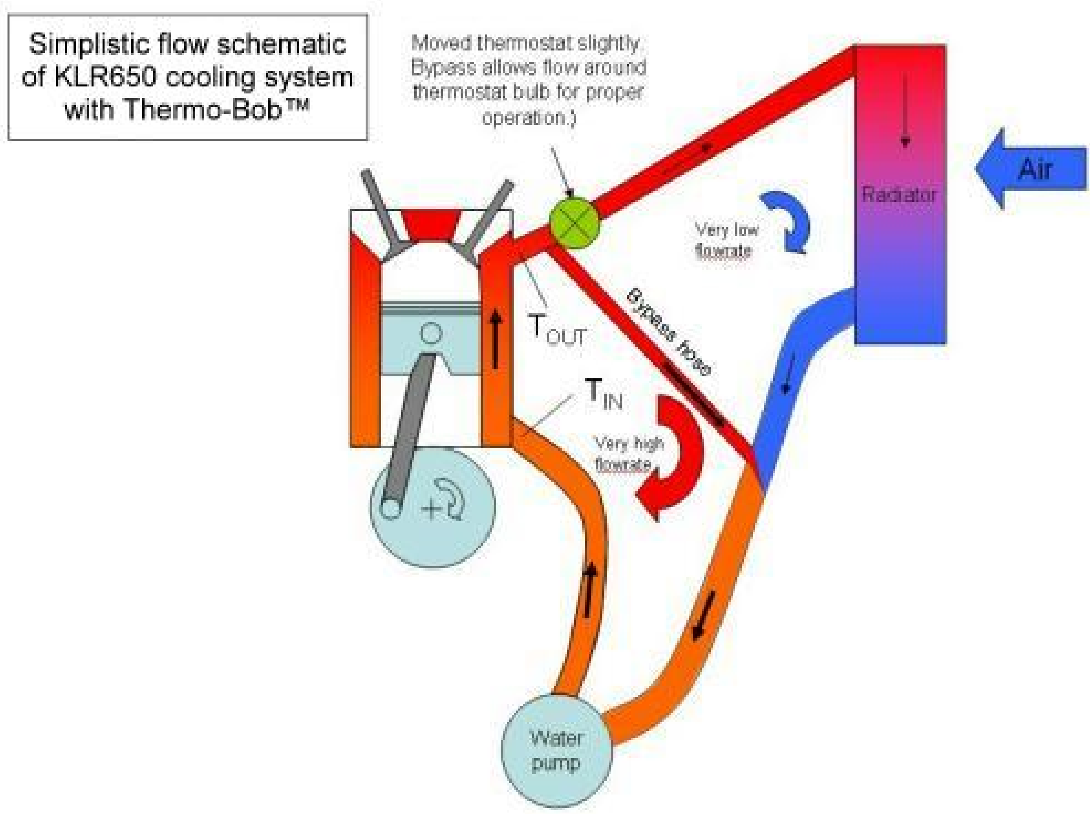
The key in typical cooling system design is that high coolant flowrates make temperatures stable. It keeps hotspots from forming and purges all critical areas in the cylinder head much better than a low flowrate. It also minimizes thermal stresses in the engine as the temperatures are all pretty similar. Multi-cylinder car engines have wear problems with cylinder taper at the first cylinders to get coolant (coldest) vs. the last cylinders to get coolant (warmest). Designers go to great lengths to minimize dT across an engine when it is running.

Well, what can we do about some of these problems? The KLR cooling system is about as simple as they come. We would like to reduce the temp swings where the thermostat cycles open and shut, but far more importantly, we would like the dT to drop to something around 10 degrees instead of the current 115°F dT measured. We would also like warmer oil, and we would like warmer steady-state coolant for some mileage.

Well of course, we need a bypass. It's so integral to a thermostat-type system that it amazes me the KLR didn't have one. But I guess it's a dollar saved and a few less parts, so there's one less leak possibility. But I'm willing to take that risk.

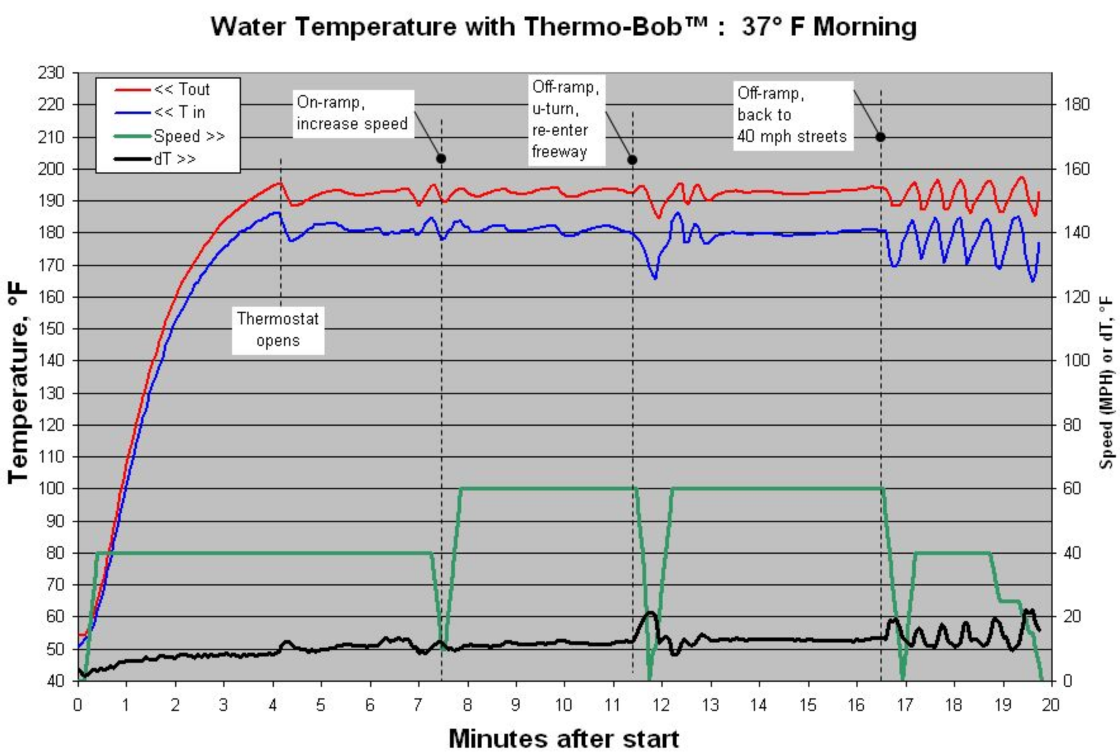
I'm going to repeat the stock KLR cooling system here again so you don't have to scroll up to the top, and right below it will show the cooling system with a Thermo-Bob added.





Do you see the difference in the system layout? We've moved the thermostat slightly and generated a way for coolant to bypass the radiator entirely. Now, even with the Thermo-Bob's thermostat totally shut, coolant can circulate at a reasonable rate all the time as the bike is warming up. Coolant leaves the water pump and travels up through the engine. This warmed coolant travels through the bypass line and goes directly back into the water pump for another pass by the cylinder. The temperature-sensing bulb of the thermostat is being bathed in fifty times the coolant flow of the stock system, so it will respond quicker and show smaller temp cycles. We can now eliminate the bleed hole so it will warm up even faster! (The only downside will occur when filling the system for the first time, we will have some trapped air to deal with.) Once the bike is warm and the thermostat is wide open, the bypass will not detract from the system too much because its small size is more restrictive than the radiator so the majority of the coolant will still go through the radiator.

Since the thermostat had to be mounted outside of the engine for a bypass to be fitted, a housing has to be fabricated. Well, that's what the Thermo-Bob is. Below is what the coolant temperatures are on the same driving cycle.



Wow, I think we solved all those problems in one shot. Note:

1) T_{OUT} climbs to 195° and then sits there all the time.

2) T_{IN} is nice and warm right from the beginning - HUGE IMPROVEMENT.

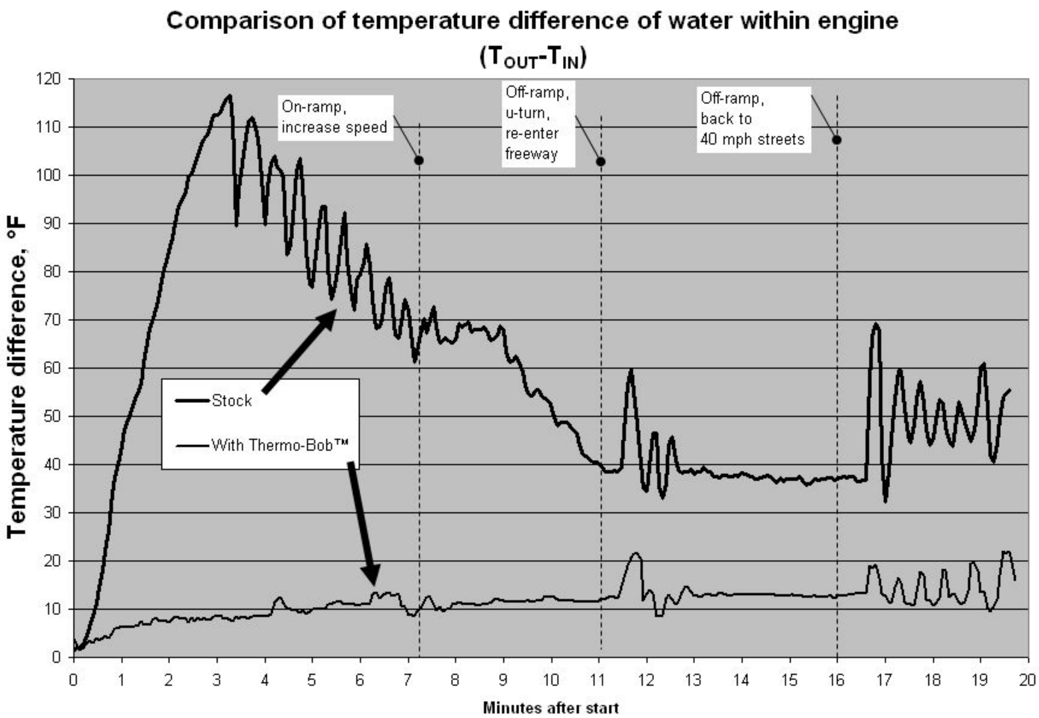
3) dT is up to only 8° by the time the thermostat opens, and then sits at 10-15°.

4) Oil is warmer (on the 60-65 degree day, oil made it to about 192°F as you'll see in a minute).

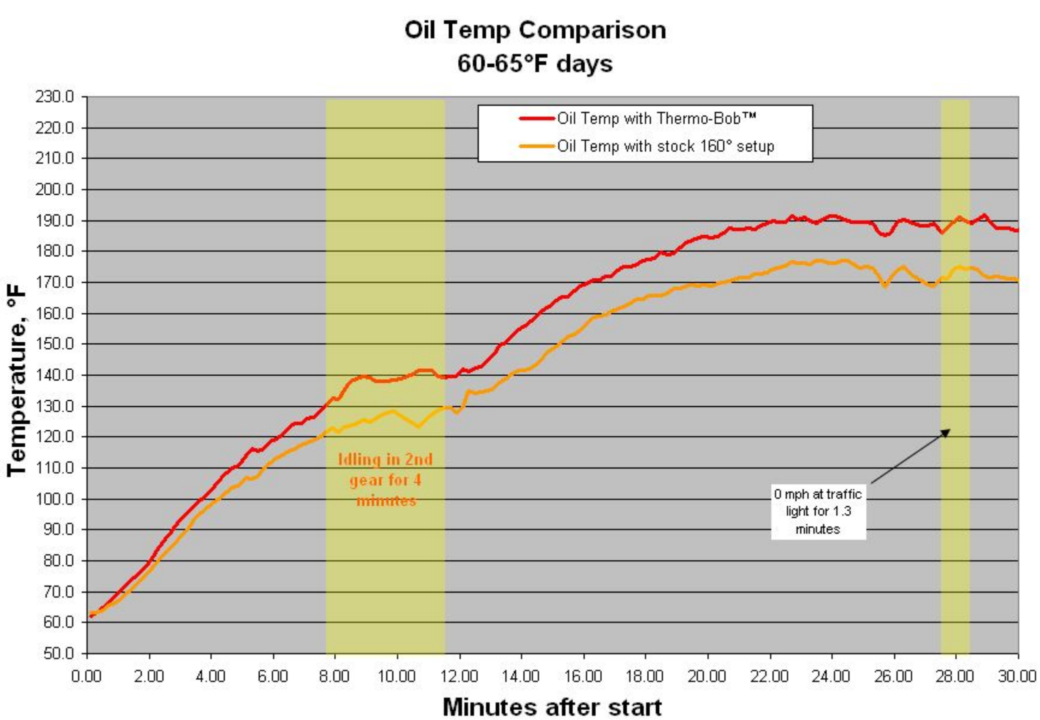
<u>Comments:</u>

T_{OUT} cycles with the thermostat, but not as wildly as before. This is because the non-bypass system got gulps of 50°F coolant off the bottom of the radiator. WITH the Thermo-Bob, we have flow even with the thermostat closed, all of it through the bypass, then when the thermostat does open, we're mixing a smaller 'gulp' of cold radiator coolant with a larger portion of nice toasty 195° bypass coolant that was already flowing.

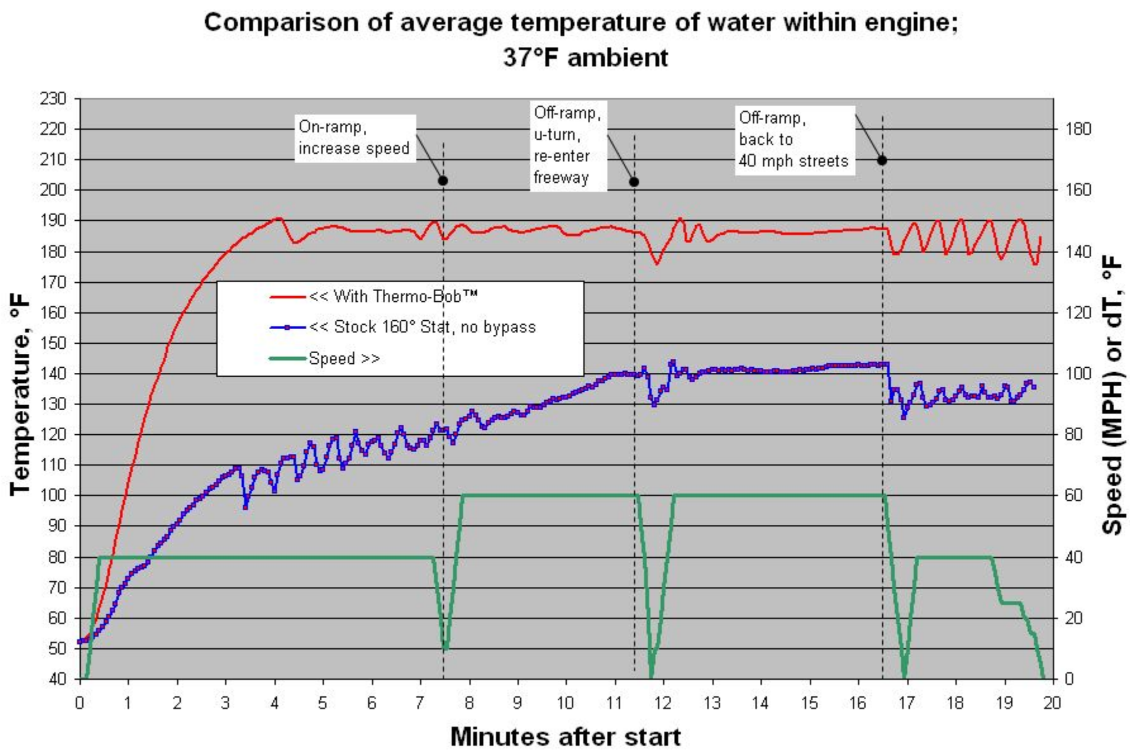
T_{IN} is much warmer, holding the bottom of the cylinder liner at much closer temps to the rest of the liner and cylinder head. I've never heard of a bad result from this, only good results. This also helps warm the oil more, as this heats the engine cases a slight bit more and also gives more heat into the oil running back down from the top end on it's way back to the sump. The plot below shows a comparison of the black lines, remember – lower is better.



Below is a comparison of oil temps between two tests conducted at 60-65°F. The oil temp with the Thermo-Bob immediately outperformed the stock setup, and the gap between the two constantly grew during the ride. Peak oil temperatures on those 60-65°F days were 192°F with the Thermo-Bob, and 178°F with the stock setup.



As for a coolant temp comparison, should we only compare the temperature of the drops of coolant leaving the engine to each other? That provides ***some*** information, but since the temperature is different throughout the engine, I have plotted the average coolant temperature in the engine (avg of T_{IN} and T_{OUT}) of the two tests. This is shown below and it a bit eye-opening.



In the plot on the previous page, the red line is with the Thermo-Bob, and the blue line is stock (158° thermostat with no bypass). Keep in mind that if this test were done on a colder day, the blue line would be lower and lower, but the red line would not budge.

Cylinder taper and wear

For years I've seen a correlation with cylinder wear and cold coolant temps. I'm not going to try to explain why it occurs as I don't fully understand the wear mechanism, but want to show a few sources of information as examples of what I've read. This first entry was from a person with a water-cooled straight six engine in his truck and a significant oil control problem on the #1 cylinder (which is the coldest)...

"I dropped in to see Jerry Wright who I regard as an expert, he's built engines that won in their class at Daytona! He's a Mechanic's Mechanic. He tells me the story of a customer who brought in a car with 40 some thousand miles on it that was worn out. The #1 cylinder wall taper was worse than some 300,000 mile motors. Jerry said had asked the owner.... "what had happened to the thermostat?? The owner replied "I take them out of all my rigs, darned things cause nothing but trouble". Jerry looks upwards and shakes his head.

With this story told, Jerry recalls my efforts to pass emissions at 60,000 miles or so.. "didn't you find it running cold ?" I thought back.... "Yes!" I remembered the gauge reading low and how I thought it was just a gauge problem or something. When I did take the thermostat out, I found it stuck open, I put a new one in and the gauge read as expected.

Considering that number one cylinder gets a shot of cold water out of the pump, it may be affected by the lack of a thermostat more than the others.

The lesson for DIYers... your engine needs the proper operating temp. Get that engine up to operating temp fast and keep it there!

A final note, talked with Dale Green, (a well known NW engine builder), added some valuable insight into what happened to this engine. First he said we were probably right about the cold water taking out cylinder number one. This problem is often seen in 350 small block marine applications where temp control is NOT adequately maintained. Number one cylinder shows tremendous wear, others are OK."

This other entry is from MarkNet, which is a great KLR650 reference.

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1) Consider the lower life of raw water (sea water through the engine cooling system) versus heat exchanged (cooling system with corrosion inhibitor such as antifreeze which passes heat to sea water through a heat exchange system). The raw water system has to run at lower temperature or minerals from the seawater will plate onto the inside of the engine cooling passages. Because the raw water systems don't run at 180 or 195 degree F, the engines last a fraction of the time.

2) I've seen rebuilt engines worn out completely (12 to 15 thou of cylinder taper) in one winter where the manifold cross over passage (which heats the automatic choke) was plugged.

So I'm not trying to quantify it, but all I'm saying is the wear rate is higher on a stock KLR rather than one with a Thermo-Bob in my opinion. Future wear rate will be decreased, that's all, which extends life.

Here's my "big picture" wrap-up: On vehicles with rocker arm valve trains, the valve train is always the first to wear out due to the side loading of the valves and the small bearing areas of a valve stem when side-loaded. Bucket/shim valve trains on the other hand, have phenomenal life because the side loading is limited to the shim/bucket which is five times as large, has 5 times the area - you never see them wear out "first".

And here's the reality check. Our KLR's have this superior top end... and why do people rebuild these bikes? Oil consumption / ring wear / cylinder taper seems to be what goes first on the 650. The Thermo-Bob, in my opinion, make a nice improvement directly to this problem. As of January 2021, I have over 180,000 miles on my Thermo-Bob equipped KLR without a rebuild. I would argue this is one of the main reasons it has gone so far without issue.