# ThermoGuard Instruments

# Tech Talk

## *Issue No.3*

# Charge Cooling for Diesels

**(what it means and what it does)**

This is the third in what is intended to be a series of short articles discussing various diesel engine technical issues. This article discusses the application of charge cooling to diesels – what it is and what it does.
[This information is presented for the interest of the reader only. The author accepts no responsibility for any adverse outcomes which may result from the reader using all or any of the information presented in practical applications.]

## Intercooled?

"Intercooled" - it's a pretty "cool" looking decal to have along the side of your vehicle but what does it mean? And more importantly, what does it do?

Well, it's a pretty fair bet that it does some cooling. In fact, what is being cooled is the air being ingested by our turbocharged diesel [CI] engine. And this is a very good thing!

The term "Intercooler", when applied to road vehicles (cars, 4WD vehicles and trucks) powered by turbocharged diesel [CI] engines is actually a bit of a mis-use of the term. But before I explain this further, let's get it clear what function the automotive "intercooler" plays in our vehicle's engine and why it's so desirable.

## Why "intercool"?

"Intercoolers" cool the air charge from the turbocharger compressor before it enters the engine, but why is this so wonderful? Probably more important than the decrease in air temperature that's achieved (but that is still useful and important in its own right), is the increase in air charge density that can be achieved by charge cooling.

As we are now aware from the previous articles, air gets hotter when you compress it. And hot air is less dense than cool air, so you have a lower mass of air in a certain volume when it's hot than when it's cool.

Let's go back over a bit of the ground we covered in the last article on Turbo and Superchargers. We discussed that the real aim of all this charge compressing and cooling is to increase the mass of air that is put into the engine's cylinders. Remember that air has mass and the number of oxygen molecules available to combust the fuel is directly related to the mass of air in the engine's cylinders. If we have a fixed volume of air, say 1 Litre, the density of the air is the mass of air contained in that Litre. In the case of air at 15 C and normal atmospheric pressure (about 14.7 psi absolute or about 1.0 bar absolute) the density is 1.225 g/L

As the volume of an engine's cylinders is fixed, the only way to increase the mass of the air charge in them is to increase it's density. So first we compress the air. If our turbocharger increases the air to 2.0 Bar absolute (about 30 psi Abs) and the air temperature is still 15 C, the density would be around 2.45 g/L. BUT (and this is the big BUT), if the temperature is greater than our original 15 C the density will be less than 2.45 g/L.

So, the answer is to cool the air charge. And the cooler we can get that air, the better.

## Terminology – again…

Those of you who have read the previous articles in this series will know that I'm fairly particular (not to say, somewhat pedantic?) about understanding the meaning of technical terms. Which brings us to the term "intercoolers", in particular as it is applied to road vehicles (cars, 4WD vehicles and trucks) powered by turbocharged diesel [CI] engines. Well, they're not – intercoolers, that is – at least in my humble opinion.

Like a lot of technical jargon, the word "intercooler" is a contraction of a longer term. In this case, as far as industry is concerned, it's a contraction of the term "inter-stage cooler", generally as applied to multi-stage compressors. The giant air compressors used to supply plant air to large industrial sites or mines, often raise the air from atmospheric pressure to, say, 800kPa gauge pressure (kPag) (about 120psig) in several stages, often three or more. For example, it might raise the pressure to 300kPag in the first stage, 600kPag in the second stage and 800kPag in the third stage.

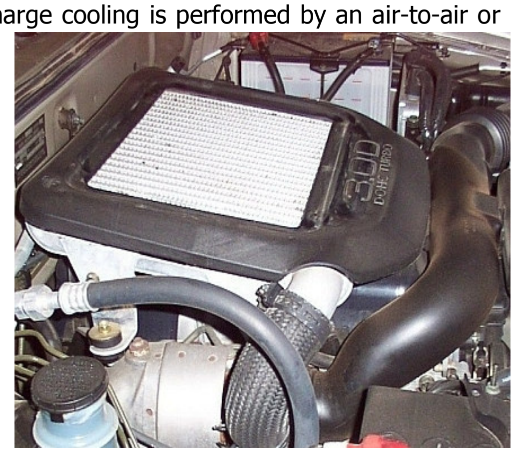
In between each stage, the air will exit the main body of the compressor and pass through a heat exchanger called an "inter-stage cooler" or "intercooler", then pass into the next stage to be compressed some more. The heat exchanger can be either an air-to-air device (like most automotive "intercoolers") or an air-to-water device, like an automotive coolant radiator working in reverse. At the end of the compressor, it is usual to have a final heat exchanger, generally called the "aftercooler", to cool the air before it's piped to the compressed air users.

Back to the automotive world. Unless you have a very high-tech vehicle with two sequential turbo-chargers and a cooler in between them, I'd say just about all turbo-diesel vehicles which cool the charge air have "aftercoolers", not "intercoolers". But now I am being pedantic. In any case, a better term for such devices is probably "charge cooler" because it describes what the thing is actually there to do. So we'll use that term from now on, shall we? And we'll do this whether the charge cooling is performed by an air-to-air or air-to-water heat exchanger, OK?

## So, what do they look like?

Charge coolers can take several forms and live in various locations in a vehicle. The majority are air-to-air devices and so need a good supply of cool air from outside the vehicle. These usually resemble a small radiator, with thin tubes to contain the charge air and fine fins to disperse the heat to the ambient air.

Many factory air-to-air charge coolers are placed on top of the engine, with a hole in the bonnet (hood) and an air scoop to collect and direct air flow through the cooler core. This is known as a "top mounted" location for obvious reasons.

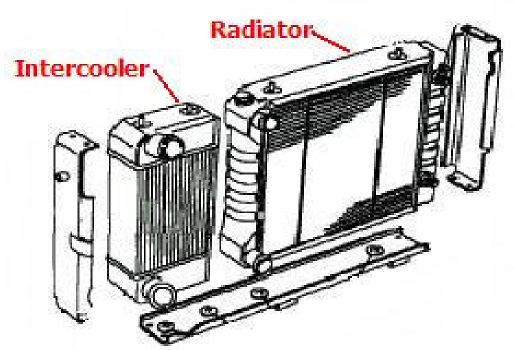



Typical top mounted intercooler

The other common location, and one with some inherent advantages in my opinion, is "front mounted" where the cooler is at the front of the vehicle, behind the grill and either in front of or beside the coolant radiator.

Aftermarket air-to-air charge coolers are usually front mounted as there will not often be room to add a top mounted installation.

Some aftermarket manufacturers are now producing air-to-water devices which can, in theory at least, be mounted just about anywhere. They are often a cylindrical device with large charge air inlet and outlet stubs at each end and smaller coolant hose connections to the outer casing.




Side-by-side front mounted intercooler

These coolers generally have their own closed coolant circuit which in turn needs a small water-to-air radiator to 'cool the coolant', as it were. This then needs to be placed in a good, cool airflow. They also typically require a small electric pump to circulate the coolant. This all adds to the cost and complexity of the installation but the charge cooler itself is usually much smaller than an equivalent air-to-air cooler and they can produce excellent results.

Aftermarket air-to-water intercooler

## *The ugly bit – physics and mathematics*

Many articles and texts on charge coolers at this point launch into long and complicated mathematical explanations regarding heat transfer co-efficients, effective surface areas etc. I prefer to look at the effects of charge cooling rather than the theory of operation.

Last time I brushed over the mathematics relating to these effects but this time we'll have a brief, but hopefully, fairly clear look at it. [*If you're not into mathematics, just skim over this bit and join us again when we start talking about real-world measurements.*]

The pressure, temperature and volume of a fixed mass of gas are related by a rule of physics called the Ideal Gas Equation:

$PV/T$ = Constant,

where P = absolute pressure, V = volume and T = absolute temperature.

All it really says is that if you change any one of these parameters, at least one of the others will change too.

Another way to write this is: $P_1V_1/T_1 = P_2V_2/T_2$,

where, say, $P_1$, $V_1$ & $T_1$ describe our ambient air entering the air cleaner and $P_2$, $V_2$ & $T_2$ describe the air coming out of our turbocharger compressor.

You might think that, as it's called the "ideal" gas equation, it doesn't really apply in the real-world but at the low-ish pressures and temperatures we're talking about, it's pretty accurate. [Though for super-high pressure steam boilers in power stations, for example, the mathematics can get quite a bit trickier.]

Now, we'll modify the Ideal Gas Equation a bit to suit our purposes. [Any theoretical physicists out there, please just come along with us for a while, OK?]

As mentioned earlier, the equation applies to a fixed mass of gas. In our case let's say this is the mass of air drawn in through the air cleaner of our engine in one second, while we're driving at full throttle and heavy load. The volume of our air is related to the mass of our air by the equation:

$V = m/d$, where m = mass (grams) and d = density (grams/Litre),

and so, if we replace "V" in our equation, we get: $P_1m_1/T_1d_1 = P_2m_2/T_2d_2$.

As the mass of air leaving our turbocharger is the same as the mass of air entering it, $m_1 = m_2$ and our equation becomes:

$P_1/T_1d_1 = P_2/T_2d_2$

We can rearrange this to:

$d_2 / d_1$ = post-turbocharger density/pre-turbocharger density = $P_2/P_1 \times T_1 /T_2$.

Before we go on, we do need to clarify our pressure and temperature measurements. We discussed the concept of absolute pressure in the first article of the series, that is, pressure above an absolute vacuum. So, to convert from gauge pressure (or boost pressure) to absolute pressure, we need to add 14.7psi or 1.0Bar.

A similar thing applies to temperature. Zero degrees Celsius is obviously not as cold as anything can even get. In fact, that temperature is -273.15°C or Absolute Zero. To convert from Celsius temperature to absolute temperature, we need to add 273.15 to the Celsius temperature. The units of absolute temperature are Kelvin (K), so 0°C is the same as +273.15K and 25°C is 298.15K etc.

Absolute pressure and absolute temperature are the units we need to make use of our gas equations.

## *Some real-world measurements.*

Readers of the last article may recall my use of some figures recorded from actual measurements on my vehicle on a pleasant Autumn morning in 2005, when we were towing our 2 tonne+ caravan up a mountain range:

$P_1$ = 1.00Bar Abs, $T_1$ = 23°C = ~296K and

$P_2$ = 1.98Bar Abs, $T_2$ = 184°C = ~457K.

Our re-arranged equation gives us:

$d_2 / d_1$ = post-turbocharger density/pre-turbocharger density = 1.98/1.00 x 296/457 = 1.283

This means our turbocharger has increased the density of the air charge to ~28% above the ambient air. It is a long way short of the 98% increase we might have expected by looking only at the boost pressure to ambient pressure ratio (1.98/1.00 = 1.98).

Now let us have a look at the figures for the air entering the engine, after having passed through the vehicle's standard intercooler.

$P_3$ = 1.98 Bar Abs[1], $T_3$ = 91°C = ~364K. The intercooler has dropped the air temperature by a massive 93°C ! Even better news is the air charge density we have recovered:

$d_3 / d_2$ = post-intercooler density/pre-intercooler density = 1.98/1.98 x 457/364 = 1.256

So we have now increased our air charge density by another ~26% by cooling it through the intercooler.

Now the total increase in density is:

$d_3 / d_1$ = post-intercooler density/pre-turbocharger density = 1.98/1.00 x 296/364 = 1.61

or ~61% higher than the ambient air density. Now we're talking some serious improvement in performance, as long as we increase the fuel supply along with this increased air charge.

# A final effect

I mentioned earlier that many articles about charge cooling spend a lot of time on the theory of heat transfer across a heat exchanger. Another reason this is not so important for real-world automotive charge coolers is that these equations only accurately describe the steady-state. That is, a situation where the air charge temperature and mass flow are constant, as is the ambient temperature and airflow through the cooler. This is rarely the case. The flow rates and temperatures are generally changing all the time as the vehicle speed and load changes.

A more relevant issue to be understood about charge coolers is, in my opinion, the "heat sink" effect. Many people will be aware of the large finned aluminium heat sinks attached to the backs of powerful stereo amplifiers. These are there to absorb the peaks of heat generated by the amplifier electronics during loud, powerful pieces of music and then to disperse this heat to the atmosphere. Most charge coolers often work in a similar fashion, rather than as a steady-state "radiator" of heat.

The heat sink effect is illustrated by the two following charts of actual temperature and boost pressure measurements on my vehicle.

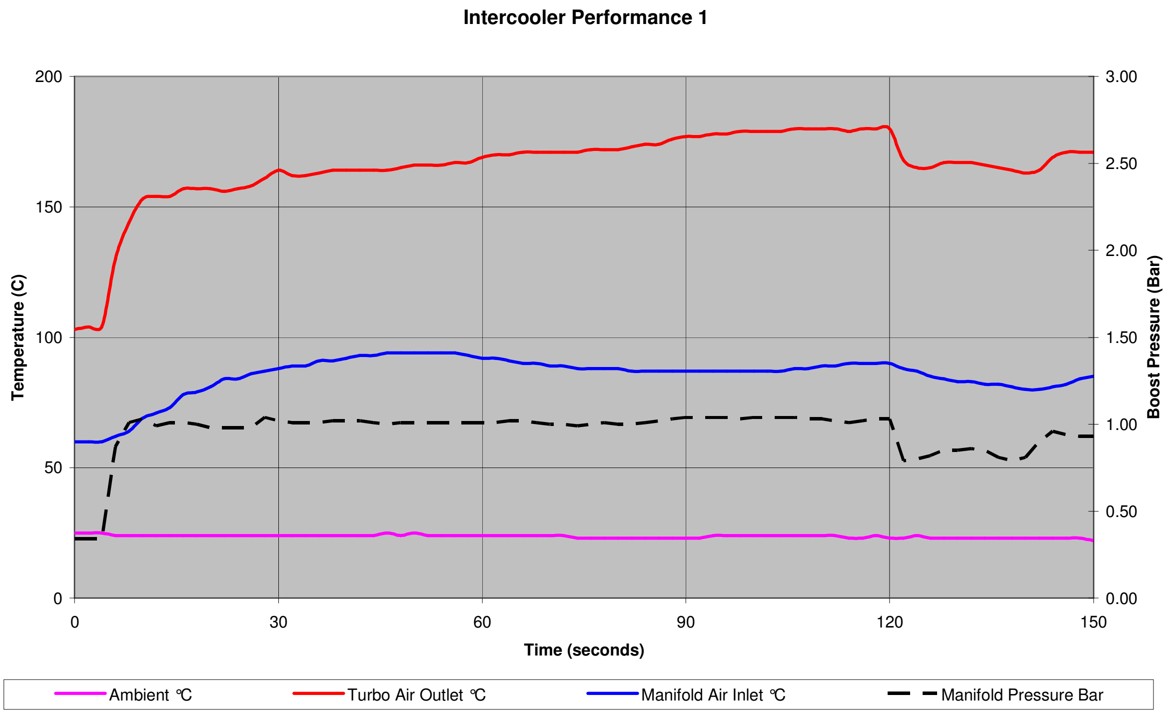
[1] The boost pressure before and after the intercooler is assumed to be the same. It was measured only after the intercooler.

The first chart shows the vehicle encountering a steep climb from a steady cruise. The boost pressure (Black dashed line) quickly increases from about 0.3 Bar to about 1.0Bar (the wastegate setting), indicating full load. Notice that the Turbo Air Outlet temperature (Red line = charge cooler inlet) increases almost instantaneously with boost. However, the Manifold Air Inlet temperature (Blue line = charge cooler outlet) increases slowly over about 30 or 40 seconds.

This is because the several kilograms of aluminium forming the charge cooler (and it's interconnecting pipes and hoses) form a fairly large heat sink. That is, they absorb much of the heat from the charge air before they themselves become hot and begin radiating that heat to the ambient air flow.

From about the 60 second mark, the manifold air temp actually drops a little. I believe this is due to a couple of effects. The now-hot charge cooler is now effectively transferring heat to the ambient air and the vehicle speed has probably increased a little, further improving the heat transfer.

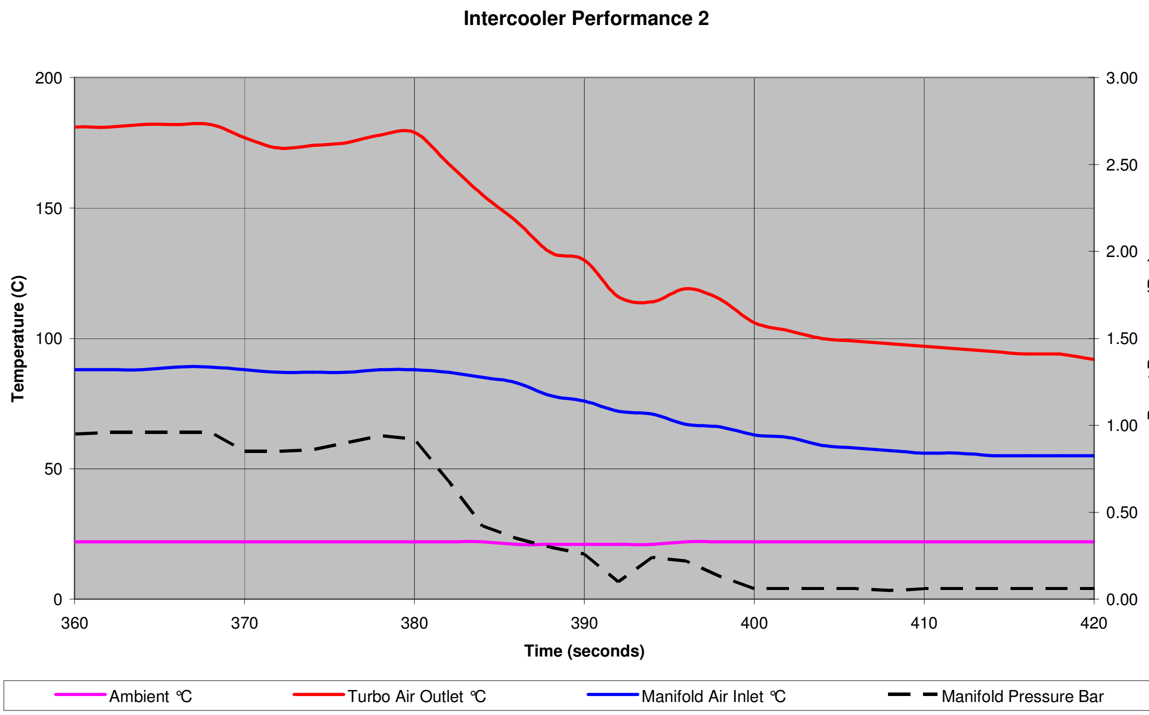



The second chart shows the opposite effect when the load is reduced. In this case, the engine comes off full load at the 380 second mark and slows to a stop at about 400 seconds. Again, the Turbo Air Outlet temperature falls almost in line with the boost pressure. The Manifold Air Inlet temperature falls at a much slower rate as the charge cooler "heat sink" gives up its accumulated heat to both the ambient air and some to the now much cooler charge air.

What does this all mean in real world driving? Well, for short bursts of full load acceleration (traffic light 'drags' or performance testing?), just about any charge cooler will do quite a bit of good as it removes heat from the charge air via its heat sink effect. However, once the vehicle has been at full load for some time (tens of seconds+), the actual heat transfer efficiency of the charge cooler becomes more important.

Sustained full load operation means the charge cooler has to be effective at transferring the heat to the ambient air, either directly by an air-to-air cooler or via the coolant circulating system in an air-to-water cooler. Otherwise the actual engine charge air temperature will continue to rise toward that of the turbo outlet. Among other things, this must increase the load on the engine cooling system and increase the exhaust gas temperature.




This is why I much prefer front mounted air-to-air coolers. Regardless of the vehicle speed (and especially when operating in low gears at full load, such as heavy sand driving or towing up steep gradients), the engine's standard viscous and/or electric fans will keep up a strong flow of ambient air through the cooler. Top mounted coolers on the other hand, often rely solely on the vehicle's forward motion to create air flow through the cooler. At low speeds this may be negligible and, at standstill, these coolers will often be acting as air <u>heaters</u>, absorbing the high temperatures from the engine bay and transferring this to the otherwise cool charge air.

Despite their cost and complexity, air-to-water charge coolers have the potential to give the very best performance. Firstly, they have a much larger heat sink effect for short term loads, due to the much higher thermal mass of the water jacket around the cooler core. Secondly, if all is correctly sized and operating properly, they have the potential to very effectively transfer large quantities of heat from the cooler core to the ambient air via their own radiator, which is usually front mounted.

# Next?

Charge cooling is a fascinating topic and there's lots more we could discuss, including ways to overcome the pressure drop across a charge cooler and the possibility of adding short term water-spray cooling to air-to-air coolers. But we've now spent quite a bit of time on the air side of things. Next time we might look in more detail at how diesel [CI] engines go about getting the fuel into the air and combusting it.