How to be cool

Ever wondered how a cooler is designed to meet specific motorsport requirements? We did too, so Racecar visited renowned expert PWR Performance Products in Australia for a cooling master-class

By SIMON McBEATH

In recent years top level motorsport engineers have chased ever smaller performance gains, and one area that has now come in for much closer attention is cooling system design. Whereas this might once have simply focussed on the aerodynamics and efficiency of the ducting leading to and from a stock radiator, increasingly it is the radiator itself (or whatever type of cooler) that is being purpose-designed to achieve improved performance. An operation that is at the forefront of this endeavour is Queensland, Australia-based PWR Performance Products. Racecar has been to see this company at work.

Time was when a radiator was universally a simple rectangular matrix and a racecar designer’s choices for meeting cooling needs were limited to face area, core thickness and possibly some decision over fin size and density, and tube size and design. More to the point, the ability to select which of those parameters to use was probably based on past experience, following a path trodden by others, or just good old fashioned guesswork. Now, with the additional demands of overall aerodynamic performance going hand-in-hand with effective cooling, a data-driven approach is demanded.

As we saw in the previous feature, this is what’s given PWR a substantial market share in most of the world’s top motorsport categories within a small number of years, following the decision by co-founders Kees Weel and his son Paul to build a bespoke wind tunnel cooler test facility in their purpose-built factory near Brisbane.

Design process

So how is this data-driven approach used to design a more efficient cooling system? PWR design engineer Andi Scott, formerly a race and design engineer with top level teams based in the UK, who emigrated to work at PWR, explained. ‘Firstly we need the boundary conditions for the core. This will be either the maximum face area or the complete core dimensions including the size of tube and the stack height. For a non-rectangular shape we would use an average tube length and face area with which to begin our modelling. Then we ask

Boundary conditions to model cooling requirements might include vehicle speed and duct expansion ratio. British Touring Car Championship cars use PWR intercoolers – this is the Subaru Levorg’s radiator and intercooler inlet duct installation

A small part of PWR’s library of samples for all cooler types. This contains hundreds of different cooler core configurations
PWR’s modelling enables heat rejection and air side pressure drop predictions to help narrow down the core specification. This data is also useful for a customer’s CFD simulations.

Further design validation may also involve testing a new core sample in the wind tunnel. Designs pass on to the drawing office for the practicalities; this is an F1-style installation.

PWR uses SolidWorks CAD in its design office. After this step a first-off cooler core is made and validated for the ambient operating temperature, plus either the car speed and the duct expansion ratio or a mass flow figure for the ‘air side’, and the coolant (e.g. water) and its temperature for the ‘water side’. We may also be supplied with a target outlet temperature or perhaps a heat rejection requirement, for an array of input conditions. Additionally, we will ask for a pressure drop versus velocity curve that the customer would like to stay below. The water pump specification may dictate a pressure drop requirement on the water side.

‘From this we can either provide a single point prediction for a specific core design or a matrix of target points,’ Scott adds. ‘A single point prediction would involve a specific condition, like the lap average inputs for face velocity, inlet temperatures and flow rates of both fluids to meet an average heat rejection target, whereas a matrix output will allow the team to generate the performance curves of the cooler for more detailed analysis of varying conditions. Usually we will have received an outline model of the core shape or an average tube length from which we can work out the stack height to design a core to meet the customers’ requirements.

What is different at PWR is that predictions are based on physical samples tested in the wind tunnel. ‘We will have an applicable heat rejection curve for a 300x300mm sample and we can run a range of tests to bracket the extremes of the desired performance range, and then interpolate for the specific application,’ Scott says. ‘We have a library of hundreds of samples for all cooler types (with different core configurations, for example; thickness, fin height and pitch, tube size and type, and so on) which can provide several solutions from which...’
to choose for a given application. We can then go on to refine these choices to tailor for the desired air side or water side pressure drop.

'We then take the wind tunnel data and feed it into our model to re-process and provide the pressure drop curves for both fluids, be they air/water or other, along with the heat rejection figures in kilowatts, and send them to the customer so they can look at the necessary velocity ratios or mass flow needs,' Scott adds. 'For example, if we get a request for a specific heat rejection value we can pick a range of configurations at different velocity ratios with similar pressure drops. This data will obviously also be useful for the team’s CFD simulations too. And we will also have temperature readings from the rear of the cores from the thermal imaging cameras in the wind tunnel. '

Then, once a configuration has been selected, we can, if required, build a core sample to that configuration to test in the wind tunnel to further validate the predictions. This might be a 300x300mm sample again, or we might test the customer’s specified face area or a different aspect ratio (of tube length to stack height) to evaluate potentially more efficient solutions.

'The recommended configuration is then passed to the drawing office to look at the manufacturing practicalities, for example whether fabricated or billet machined tanks are required, whether internal ribbing will be needed in the tanks to handle pressures, and so on. There are plenty of options but our experience helps to narrow the choice. We then make a first-off core and possibly validate that again in the wind tunnel in the configuration it would be run in in the racecar.'

The process described above was for a single core in isolation. It is also possible to have complex core assemblies, combining perhaps engine oil, gearbox oil and energy recovery system cooling in one matrix, with baffles between sections and separate inlets and outlets on each section. It’s also possible to piggy back systems, too, in one cooler, so there might be a water radiator sitting behind an intercooler. As long as there is a temperature delta, heat can be rejected; making the most efficient use of the available temp delta ensures an optimised package is designed. It is also possible to thermally isolate separate panels with an air gap or an insulating layer; by doing this, efficiency can be improved to help achieve tough targets, and although this approach adds complexity and cost it is all part of providing solutions in challenging applications.

Scott says: ‘With plenty of information available we can see where improvements can be made on cooling, pressure drops and weight of a component. We also work hard to minimise package weight for a specific task and provide predictions of weight before making a final assembly. There are lots of components, and estimates are made for everything from the core and tanks, through to the weld allowance.’

**Physical testing**

The on-site wind tunnel built by PWR to replace its earlier, smaller facility clearly plays a pivotal role in the design and development process. As well as adding to the company’s library of sample core test data that the original smaller wind tunnel was conceived for, it facilitates the testing and validation of proposed designs as outlined in the foregoing section and, in some instances, the ongoing optimisation of those designs. Racecar was privileged to sit in on one such test session involving the charge cooler of a high end team. This therefore was a completed product rather than a test sample and as such it encompassed the full size and complex shape together with the tanks and connections, as would be found on the racecar itself.

Wind tunnel operator Julian Conlan (JC) was finalising the installation of the test component on our arrival, connecting the multiple lines and cables to supply charge air to the test
The thermal gradients across the sections of the core had changed

part and gather the necessary data. There were two temperature probes on the inlet side of the cooler face and thermocouples monitored core temperatures along the centreline, as well as temperature sensors in the charge air inlet and outlet pipes. Pressure sensors sat upwind and downwind to provide ‘air side’ pressure drop characteristics. Charge pressures were also measured on the upstream and downstream sides of the cooler too. A pair of thermal imaging cameras, one within the tunnel looking at the upstream face of the cooler, and one outside monitoring the downstream face provided real time imaging of temperature distributions; static thermal images are taken at the same time as data points are being logged and are provided with the client’s report. The control and data logging software, all developed in-house, provide automatic control of test functions and enable manual override should circumstances require. Test protocols, or ‘recipes’ as they are known in-house, drive each test program through its pre-planned sequence.

This time the map involved a range of air side inlet velocities (determined by mass flow, air density and face area) versus a range of charge air mass flow rates, all at representative charge air pressures in excess of 2bar. Ambient (inlet) air temperature is also controllable up to 45degC and tests were carried out at 40degC in this case.

Charge air

The choice of inlet velocities and charge air mass flow rates broadly bracketed the expected on-track values. JC explained that ramping up the temperature and pressure of the charge air system takes roughly half an hour for safety and stability reasons, so after systems were checked at ambient conditions the charge air was heated and pressurised to head for the first data point and the test was underway.

This particular non-rectangular core featured a variable core density across the matrix stack to compensate for the differing tube lengths across the core. It was this aspect that was being refined in order to try and achieve as even a temperature gradient across the matrix as possible. Comparison between the thermal imaging pictures taken during testing of the previous core iteration with the latest one enabled an immediate view to be formed on progress made. It was evident that the thermal gradients across the various sections of the core had changed and that the temperature distribution across this

The PWR wind tunnel

The current PWR wind tunnel took a year to build and was commissioned in 2012 following a design process that was assisted by some of the leading race teams around the world. The schematic graphic (below) shows the overall blown open-jet design of the

The 30 metre long and two metre wide PWR wind tunnel is a blown open-jet design. The coolers which are under test are attached to the downwind end of the test section

The 30 metre long and two metre wide PWR wind tunnel is a blown open-jet design. The coolers which are under test are attached to the downwind end of the test section

30m long by 2m wide (maximum) wind tunnel. Atmospheric air is drawn in by the centrifugal fan and passes through a diffuser before entering a flow conditioning contraction section which contains flow-straightening screens. The flow is then diffused into a settling chamber, the purpose of which is to achieve uniformity in the flow, and in this case a large heater matrix is also incorporated in this chamber to heat the air to 40-45degC to simulate high ambient temperature conditions. The flow then enters the contraction zone where its velocity increases, thus further reducing flow turbulence and non-uniformity before passing into the test section, where another mesh screen further conditions the flow quality. At the end of the test section coolers under test are bolted to large adaptor plates which in turn are bolted on to the periphery of the test section outer walls.

Temperature and pressure probes upwind and downwind of the test cooler provide cooling efficiency and pressure drop data. Further temperature and pressure probes also monitor all coolant and, where appropriate, charge air inlet and outlet conditions, and temperature probes are also inserted into the cooler(s) under test to provide a centreline temperature profile. Thermal imaging cameras monitor the upwind and downwind faces of the test cooler(s).

Test recipes

Control software uses ‘recipes’ to run through a test sequence, which might be a matrix of inlet air speeds versus charge air mass flow rates, as in the test run Racecar witnessed, but obviously conditions appropriate to the type of cooler under test would be used. Water radiators, engine oil coolers, transmission oil coolers and charge air intercoolers can all be evaluated. Air velocity, temperature and pressure, oil temperatures and coolant flow rates can all be controlled, and heat transfer,
latest iteration had been improved, but equally that further refinement might be achievable. For example, parts of the centre of the core on the downwind side did not seem, from the thermal images, to be as hot as others, meaning they were not rejecting as much heat as they might. JC suggested that perhaps the local core density could be reduced further to aid performance.

It was evident from watching this test session that the measured and visualised performance of a finished cooler is another step on from testing and analysing the 300x300mm sample cores that provide the initial configuration. Testing the finished cooler under repeatable laboratory conditions highlighted the areas where efficiency had been improved but also where further improvements could be made. An example of where this has proved valuable in the past is where a PWR-specified core went to the customer who then fabricated his own tanks. The finished product fell well short of expectations but when the full assembly was wind tunnel tested it became clear that the tank design was not effectively distributing charge air across the core. So, while defining a core specification is a key part of the process it is just one part of the design and development process. PWR works with its clients on tank design to aid flow distribution and ensure the full face area is used in the most efficient way possible.

Coming back to our test session, the programme continued through intermediate face velocities to the lowest face velocities used in the session and it was apparent that the charge air outlet temperatures had climbed considerably on the values obtained at the medium and high velocities. And the thermal images also showed higher temperatures on the downwind face of the cooler.

Needless to say the lower velocities used here were intended to replicate the extreme low end of range likely to be seen perhaps only briefly on the race track.

Customers and teams regularly visit the PWR test facility to evaluate the performance of their coolers, benchmarking them against earlier or alternative designs. If a cooler does not perform as well as hoped, with all component parts and manufacturing processes being available on site, a new test item can be manufactured for re-test in a matter of hours.

Iterative process

So PWR’s engineers not only generate cooler designs using wind tunnel-tested reference samples and data but, in some instances, those designs are evaluated further using the wind tunnel to validate or refine the design. These abilities, coupled with the possibility of making quick physical changes to cooler designs for rapid re-test, quite clearly give PWR’s customers a competitive advantage.

The installation and optimisation of the wind tunnel stems from the desire of CEO Kees Weel and engineering manager Matthew Bryson to provide ever more accurate data and predictions for high-end customers. The tunnel is a key tool for PWR and often accommodates customer visits from various categories when, for example, they wish to have further input in the benchmarking of several cores. If required, PWR can modify or build an entire new assembly for test in just a few hours to help with a company’s product development.

A wide variety of coolers can be tested, too. After the test on the high end race team charge cooler described in the main article, a large water radiator from a commercial bus was next up, followed by a rally car oil/water heat exchanger, which was not directly connected to the wind tunnel itself – a water radiator matrix that conditioned the water feed to the heat exchanger was cooled by the wind tunnel. So flexibility is the name of the game in this interesting test facility.

PWR can modify or build an entire new assembly for test in just a few hours to help a team’s component development

Oil/water heat exchangers (above) can also be tested here. This one is from a rally car.