Cool running

Ian Bamsey considers the technology behind the water, oil and charge air coolers keeping today's race engines alive

These days a Formula One V8 will keep on running for a lap or so after its coolant system has failed, so good is its piston cooling provision of oil squirt jets. Then it will grind to an expensive halt. Almost all race engines need a constant supply of cool water and cool oil, much to the dismay of the chassis designer since managing those vital fluids invariably creates aerodynamic drag. So it is that the engine designer and the aerodynamicist clash at the interface between air flowing over or through the car and the fluid passages exploiting that airflow to keep the engine alive.

We looked at the complete race engine coolant system in *RET* 39 (June/July 2009). Here we'll put the spotlight on water/air radiators (otherwise known as coolers), oil/air radiators and in-system oil/water heat exchangers, plus air/air and other forms of charge air aftercooler (otherwise known as intercoolers). Technically, all of those items are *heat exchangers*, which function primarily by means of conduction and convection, with very little radiation going on, leaving one to wonder how the term 'radiator' ever came into use.

A typical water/air or oil/air racecar heat exchanger works by conduction of the heat from the fluid travelling through the tubes forming its core (sometimes known as its matrix) from whence, often assisted by fins, it is convected/radiated to the passing airflow. Air must flow through the core – if it were stationary within, its temperature would soon rise close to that of the coolant, making the process of heat transfer extremely slow. Nevertheless, one solution is not to flow cooling air through a core at all but to flow it along the outer face of a specially designed core. That core face is then set flush with an area of bodywork over which there is a suitable, smooth, well-attached airflow to which heat can be transferred.

This concept of surface cooling was exploited by Supermarine seaplanes of the 1920s, which were pure racers rather than workhorses so could afford to accept even dangerously marginal cooling in the all-important quest for minimising aerodynamic drag. Malcolm Campbell used a Supermarine engine in his 1928 Bluebird land-speed record car, and adopted the surface cooling concept. However, the experiment lasted for only a year – the 1929 Bluebird reverted to conventional coolers. So did Gordon Murray's 1978 Brabham BT46-Alfa Romeo Flat 12 Formula One car, which used surface coolers only in pre-season testing.

Cooler performance

The aerodynamic implication of any conventional heat exchanger can rarely be considered in isolation, for often in the racecar environment it is situated within ducting that minimises its aerodynamic impact and maximises its effectiveness compared to mounting it naked and jutting into the free stream. In theory, duct design can actually reduce overall aerodynamic drag. As it passes through the cooler core the airflow is heated and expanded, gaining energy which, in conjunction with optimum nozzle and exit design, can create net thrust instead of drag.

It was claimed that the cooling system package on the piston-engined P-51 Mustang World War II fighter would produce a net thrust when the aircraft was operating at certain speeds and power settings. However, such a 'ram jet' effect only works across a narrow range of speed as dictated by the geometry of the duct so, given that variable aerodynamic devices are normally outlawed, it is only really practical in the case of racecars that operate within a narrow range of road speed. Even then, it is such a marginal gain that other considerations influencing the overall aero package will take precedent.

Moreover, for all the sophistication of wind tunnel and CFD-assisted duct design, in the case of a contemporary Le Mans car, the cooler flows can account for as much as 20% of the overall drag. Thus the main aim is to make the coolers as small as possible, so that not only is their aero impact minimised but also their weight (including the weight of the fluid in the system). As noted Le Mans car designer Peter Elleray put it in *RET* 48 (August 2010), "Racecar designers do not like to be over-generous in providing radiator face area or intake/exit area, while engine designers always want a safe reserve. The art of diplomacy comes in agreeing what is safe, because if a racecar has too many large reserves it will usually be very safe and very slow at the same time."

In general, an engine produces optimum power within a relatively narrow running temperature band, and the cooling system should be tailored to maintain that. The mass of the cooled components and of the cooling fluid itself gives any cooling system thermal inertia. It follows that it is not necessary to provide cooling system capacity capable of instantly dissipating all the heat generated at maximum power, only the average around a lap of the circuit in question. A racecar typically spends most of its time at medium speed, so the cooling system is generally designed for that, meaning that the car is, in effect, under-cooled at high speed.

A common technique when low ambient temperature leads to a racecar being over-cooled is to blank off an area of the core, typically with tape. This reduces the core's wetted area so there is less temperature drop through it. In the case of a NASCAR Cup car, reducing core area reduces drag, to a degree that often more than compensates for any loss of engine performance with increasing engine temperature. This makes it a popular ploy for qualifying. By contrast, in the case of a Formula One car, blanking an area of core modifies the flow through its more optimally designed ducting, hence it is likely to adversely affect overall car aero performance.

Exchanging heat

Racecars need to transfer a portion of the heat generated by combustion to the airstream. This can be done directly if fins set in the proximity of the heat source are wetted by air from the free stream, as in the case of many simple two-stroke motorcycle and kart engines. An air-cooled system can be made more efficient and less sensitive to operating speed by the use of a fan, at a cost in terms of sapping energy from the engine to drive it.

Porsche has won Le Mans using the approach of engine-driven fan cooling, although by its own admission its victorious 917 of the early 1970s was in reality jointly air and oil cooled. Around that same time Ferrari experimented with a Formula One engine that was purely oil cooled. Compared to water, oil has greater thermal inertia and a lower temperature gradient, making it less sensitive to car operating speed. However, oil isn't as easy to cool in a heat exchanger as water. Compared to water, the viscosity of oil implies lower flow rates, which causes it to form a boundary layer on the inner wall of the tube; that boundary layer will be well cooled while hotter oil flows through the centre.

Heated through a given temperature range, water absorbs more heat than almost any other substance, and it also rejects heat faster than oil through a cooler. Moreover, engine water cooling compared to oil or air cooling invariably wins when seen in the context of the overall car aero performance. These days though, the race engine is typically water and oil cooled, in particular oil spray jets bringing vital cooling to the piston underside and to the valve springs. As we noted in *RET* 39, such jets can have their own pressurised oil supply separate from the main lubricant system, and sometimes even benefit from their own oil cooler.

Often these days the oil cooler is encased in an aluminium container, which in turn is plumbed into the water cooling system. As Elleray noted in *RET* 48, "By and large, engine people tend to prefer such oil/water heat exchangers, as they can then maintain a constant temperature delta between the water and the oil. The downside here is if one or the other system is running too close to the limit, as rectifying that cannot be done independently.

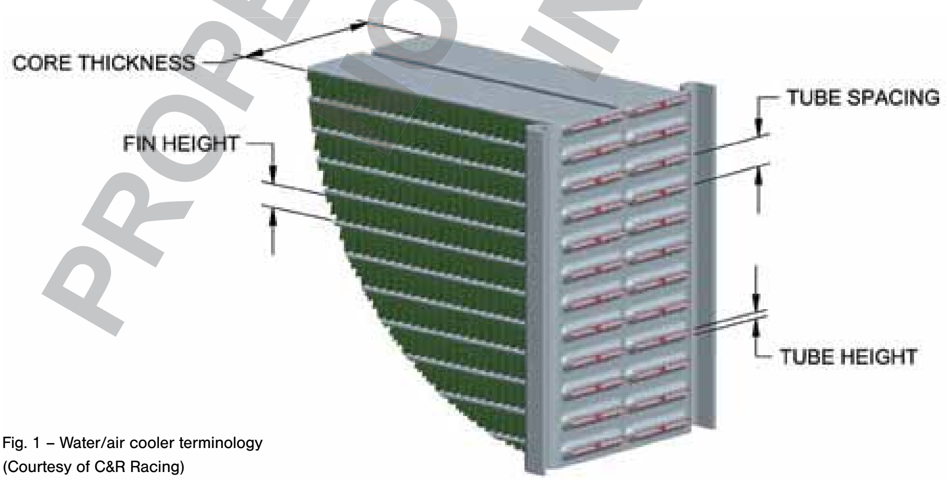
"From the car designer's perspective, it is often easier to package an oil/water heat exchanger than an extra cooler or two, but the water radiators themselves will need to be larger than strictly required to deal with the water alone, as they will also be extracting heat from the oil, via the water."

Core design

The amount of heat transferred to the airflow is directly proportional to the mean temperature difference between the airflow and the operating fluid, to the volume of the former and to the area of interface between the two. Clearly the mean temperature difference is influenced by ambient temperature (and also the presence of any other coolers upstream). The volume of airflow through the cooler is a function of the speed at which the vehicle is operating, and is also a function of the ducting (if any) within which the cooler is located. The area of interface is a function of the design of the cooler [Fig. 1].

The tubes carrying the liquid coolant are normally connected to fins to maximise the surface area from which heat is rejected while minimising resistance to the airflow. By concentrating the liquid tubes and air fins that comprise the core it is possible to obtain an overall wetted area that is in the region of 100 times greater than the frontal area of the cooler, without creating unacceptable parasitic aero drag.

When it comes to the compromise between the aero performance of the car and the thermal efficiency of the cooler, one prominent manufacturer remarks, "We work very hard to match the air side of the cooler – that is, fin density, tube height and core thickness – to the calculated air velocity of the given application. In open-wheel, single-seater racecars, there's typically a decent opportunity to ▶



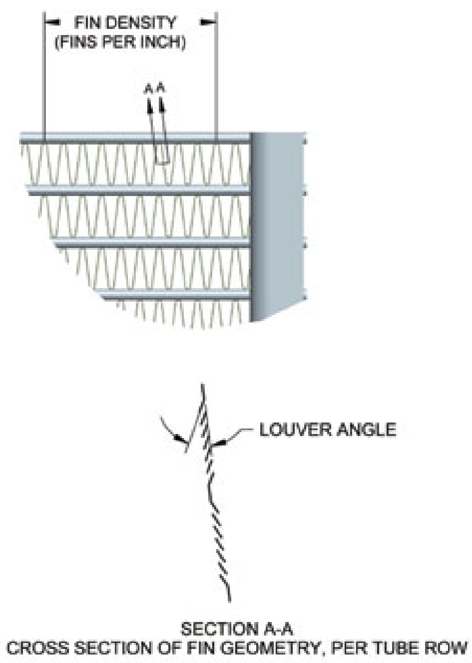


Fig. 1 – Water/air cooler terminology
(Courtesy of C&R Racing)

design a proper duct. In full-bodied applications such as NASCAR, the proximity of the radiator to the grill opening doesn't allow for adequate ductwork, therefore the air distribution across the core face is very poor in many cases. We compensate in various ways such as fin design and tube spacing, always trying to get the maximum of cooling with the minimum of air velocity."

The aerodynamic drag attributable to a given core is primarily a function of fin density and core thickness. The louvre angle of the fin needs to be optimised for a given application based on air speed and the cooling requirements. Clearly, any cooler needs to be tailored to the temperature and speed ranges of the airflow in which it will operate – for example, the Monte Carlo Rally versus the Indianapolis 500.

All conventional race applications use aluminium brazed cores, and the integrity of the tube-to-fin braze joint is critical in terms of the thermal efficiency of these coolers. In terms of maximising thermal transfer between the flow of coolant and the airstream, another critical element is tube geometry, since that controls the velocity of the flow through it. The flow rate is a function of the number of tubes, tube diameter and the length of tubing. One expert remarks, "We like to achieve the highest possible velocity to increase 'turbulation' (turbulent flow) within the tube, since that greatly enhances thermal transfer."

Materials

Traditionally, copper and brass were used to fashion coolers, right up to the level of Formula One, but nowadays aluminium is the favoured material [Fig. 2]. Copper and brass are thermally more efficient than aluminium, and such coolers are easier to modify and repair. However, advances in aluminium brazing and fabrication have made the aluminium cooler feasible and, compared to the equivalent copper/brass production, it will be significantly lighter.

This is due to the superior Specific Thermal Conductivity (STC) of aluminium, which in turn is a product of the thermal conductivity of the material together with its density. The STC tells us the conductivity per unit mass of the material. Aluminium has a thermal conductivity of 172 W/mK compared to 384 W/mK for copper. However, copper has a density of 8930 kg/m^3 compared to 2700 kg/m^3 for aluminium, hence the STC of aluminium is 0.0637 compared to 0.0430 for copper.

Interestingly, graphite foam has a thermal conductivity comparable to that of aluminium, and so light is it, with a density of 600 kg/m^3, that its STC is a remarkable 0.25. On paper, graphite foam allows production of a water/air cooler that is significantly lighter for a comparable size – or, even more interestingly, one that is both smaller and lighter. The material was investigated for racecar coolers around ten years ago but so far, to the best of our knowledge, practical applications remain unproven. The material is brittle and we hear that experimental graphite foam coolers produced for aerospace applications have proved hard to seal.

Cooler types

The typical aluminium water/air or oil/air cooler consists of a pair of aluminium tanks sandwiching the core, welded to its endplates. The tanks can be one above and another below, with the coolant flowing down through the core, or they can flank the core for a crossflow arrangement. In the crossflow case, the coolant can flow from one side to the other or it can flow across in one direction through the upper half of the core and then back in the other direction through the lower section. Such a double-pass cooler is used where an adequate coolant flow rate isn't otherwise obtainable. Increasing velocity in the tubing, it increases turbulation, to the benefit of thermal transfer.

There can also be two (or three or four) rows of tubes, one behind the other, or with the rows of tubes offset from each other to present more tube area to the airstream. For a given core area, this maximises the tube length, while at the same time the coolant is flowing through a shorter length of tube than if the same cooler had been wider and only single-row. That shorter length reduces the pressure drop to which the coolant is subjected.

In the case of the common tube and fin core, the coolant or lubricant flows through tubes that run perpendicular to the fins [Fig. 3]. Tube and fin cores are easily adjustable in terms of design, although the complex core shapes required these days for Formula One are difficult to obtain. Typically the fin is somewhat delicate, but a new 'hemmed fin' technology has greatly increased the strength of the leading edge of the fin, making this type of core more durable for high-speed race applications.

Although tube and fin cores are common in racing, these days racecars in top series often use the more expensive bar and plate type core [Fig. 4]. These are typically fitted with a baffle to increase the wetted area, often having a brazed internal turbulator, which adds

Fig. 2 – Construction of an aluminium cooler (Courtesy of Docking Engineering)

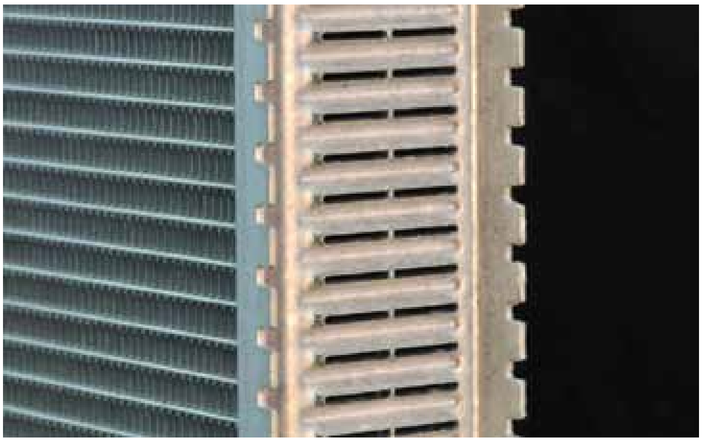


Fig. 3 – End detail of a crossflow tube and fin water/air cooler (Courtesy of C&R Racing)

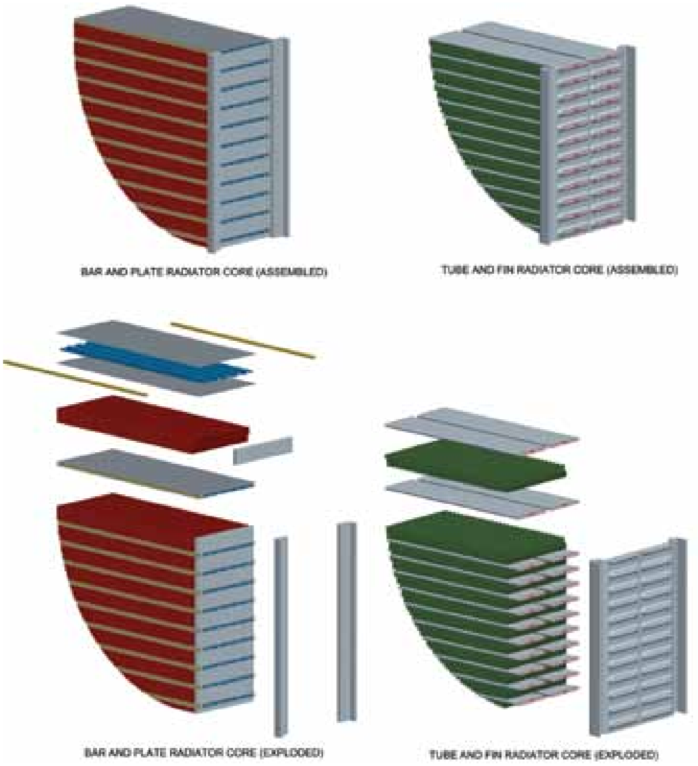


Fig. 4 – Tube and fin versus plate and bar construction (Courtesy of C&R Racing)

a great deal of strength to the tube. They offer greater heat rejection and are more robust, but are inherently heavier and create more flow restriction.

Says one manufacturer, “Bar and plate is conducive to shaping a core to fit special applications. It can have internal water passage control not currently possible with tube and fin cores. The downside is the difficultly in building these cores in a production environment: they are very complex cores that are typically hand built and very expensive. In high-speed or high-pressure applications we typically use bar and plate cores, which can be vacuum brazed with high-magnesium alloys that create a much stronger fin than most tube and fin designs.

“For most other applications we use a tube and fin core; those are applications that don’t see the speed and/or pressure associated with top-level racing. It is easier to stock inventory for a wide range of applications using tube and fin technology.”

Plate and bar cores often use an extruded tube design that can be constructed with internal supports, allowing the core to withstand very high pressures. Shorter tube spacing and hence shorter cooling fins makes for even higher operating pressures due to the added column strength of the fin.

“Nowadays we are tailoring our radiator cores to higher pressure,” remarks one manufacturer, acknowledging the trend to run higher coolant pressure to push up the boiling point and thus reduce the cooling requirement – provided the engine can withstand the implied running temperature increase. He adds that the next step is to sculpt the tank that surrounds the core, following Formula One practice. “We have developed a better shape for what has become a pressure vessel; it makes the radiator as a whole lighter and more durable.” ▶

Fig. 5 – Micro-channel cooler (Courtesy of Mezzo Technologies)

An interesting departure by one manufacturer is an angled radiator core. If a conventional core is placed not upright but canted so that it meets the oncoming airstream at an angle – as is often the case in racecar applications – then clearly the streamlines are forced to change direction to pass over the tubes and fins. To keep them parallel to the airstream when the radiator is canted, this manufacturer has taken a stepped approach to the core. The stepping of successive layers is arranged to provide the required degree of installation rake, while keeping the core parallel to the airstream. It is a simple but effective solution, which has been patented.

An alternative to the well established tube and fin, and bar and plate cores is the so-called 'micro-channel' core. This consists purely of tubes (no fins), that are less than 1 mm in outer diameter, again linking aluminium tanks [Fig. 5]. Those tubes are made from stainless steel, and have smooth inner and outer surfaces. This pioneering manufacturer of water/air coolers using this type of core won the Louis Schwitzer prize for technical innovation at the 2010 Indianapolis 500 race. Its product was claimed to have a higher ratio of heat transfer to pressure drop than the conventional core coolers used in IndyCar. The 2012 Dallara-spec IndyCar is supplied with conventional coolers but the micro-channel technology is expected to find its way into Formula One.

Oil cooling

A significant difference between oil and water coolers is in the amount of internal pressure an oil cooler must withstand; it must have the ability to withstand at least 10 bar to handle any spikes in oil pressure. In the case of conventional oil/air coolers, another difference is the greater need for an internal turbulator. It is more important to turbulate oil than water using a finned component brazed into each tube. However, the effect of this is to contribute to the pressure drop. As one expert remarks, "The secret of a good oil cooler is to balance the pressure drop against temperature drop to achieve the best result for given parameters."

Our expert says, "A double-pass system is to be avoided in an oil cooler because the longer the passage, the greater the pressure drop. I know of a case where the designer of a works GT car specified a tube and fin oil cooler 1 m wide, 100 mm high with inlet and outlet at the same end, because he could package it more easily. He then wasted six months of development trying to work out why the engine was not being properly lubricated."

Fig. 6 – Finned tubular core oil/water heat exchanger (Courtesy of Laminova)

Many off-the-shelf oil coolers used in racing are pressed plate coolers. This method of manufacture is suited to quantity production and is claimed to produce lightness and strength which is equal to bar and plate, and superior to tube and fin for comparable performance. The downside is that they are only available in one back-to-front measurement and relatively few widths and heights.

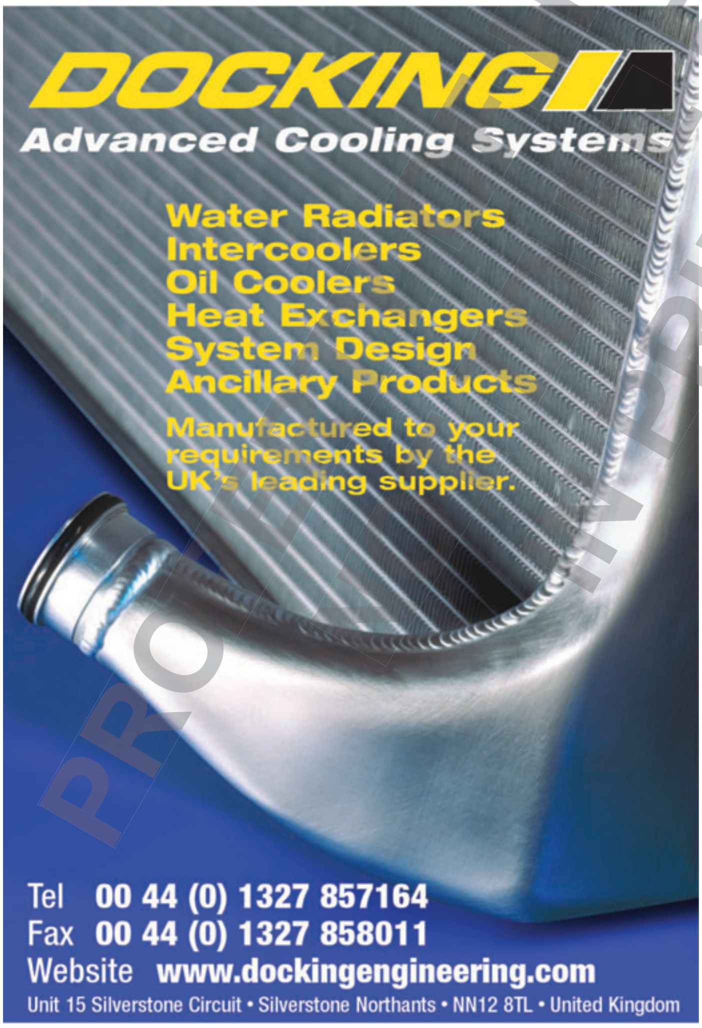
As mentioned above, engine oil coolers often take the form of oil/water heat exchangers. While these can employ a conventional core design within a sealed housing, one interesting alternative used right up to Formula One level is the patented finned tubular core shown in Fig. 6. In this design the core can be envisaged as a tube with fins projecting from it. Normally the tube is plugged while the coolant is channelled from one end of it to the other through longitudinal passages within its wall. It thus flows adjacent to the many fins. It should be noted that in this design the fins are in direct contact with the lubricant rather than the coolant. An outer housing channels the lubricant over the fins, as shown.

This design allows for a high fin density, while within the space created by the housing the arrangement of fins causes the lubricant to have laminar flow and low velocity (for low pressure drop) as it passes between them. Occasional 'break up' zones stop boundary layer growth adversely affecting heat transfer. The laminar flow characteristics in conjunction with the large heat transfer surface area provides excellent heat rejection. The design is claimed to be 20% more efficient than an oil/water heat exchanger using conventional core technology.

Clearly the unit is plugged into the engine coolant circuit, and in applications that have a high level of flow the centre channel can be used as a bypass for a portion of it. If plugged, that will maximise the flow of coolant through the 'working section', for maximum heat exchange at the cost of greater coolant pressure loss. Since the centre of the core is hollow, it is possible to fit a smaller core within a larger one and thus almost double the finned area while exploiting the same coolant through-flow. In fact, a triple-core arrangement is occasionally used.

The manufacturer's production technology is such that the core is always made from aluminium, while the housing is normally of the same material, although it does not have to be. It is the housing rather than the core that sets the limit on oil pressure. A standard unit can withstand up to 30 bar continuous pressure, while special housings have been produced to withstand as much as 100 bar.


C&R RACING INCORPORATED
C&R RACING, INC.
6950 Guion Road
Indianapolis IN 46268
p - 317.293.4100
f - 317.293.4110
C&R RACING, INC.
301 Cayuga Drive
Mooresville NC 28117
p - 704.799.0955
f - 704.799.1191
www.crracing.com
IMIS INTERNATIONAL MOTORSPORTS INDUSTRY SHOW
December 8, 9, 10, 2011
Indianapolis IN
www.imis-indy.com
We may be known for our cooling system solutions but C&R Racing also provides engineering solutions for our customers that improve designs and reduce manufacturing costs. As a long standing leader in design and manufacturing for the motorsports arena, we have the experience to turn ideas into products quickly and competitively for any industry.
• Engineering Services
• Integrated Manufacturing
• Manufacturing and Supply Chain Management
Our focus is to develop a close relationship with you to deliver design and lean manufacturing solutions.
Contact us for your next project!


DOCKING
Advanced Cooling Systems
Water Radiators
Intercoolers
Oil Coolers
Heat Exchangers
System Design
Ancillary Products
Manufactured to your requirements by the UK's leading supplier.
Tel 00 44 (0) 1327 857164
Fax 00 44 (0) 1327 858011
Website www.dockingengineering.com
Unit 15 Silverstone Circuit • Silverstone Northants • NN12 8TL • United Kingdom


Enhanced engine performance
Laminova heat exchangers provide outstanding engine and transmission oil temperature control in the most severe conditions.
From high performance racing cars to Paris-Dakar rally vehicles, you can rely on Laminova.
New website: www.laminova.se
SEM
OPCON Group
www.laminova.se | Ph +46 532 611 00

This unique core technology can be bought without a housing, allowing the user to combine the housing with other components such as the engine sump for packaging reasons. This form of cooler is widely used for both engine and transmission oil, and also for hydraulic fluid. It is feasible to run two such cores back to back – for example, one for engine oil, the other for transmission oil – using the same coolant through-flow.

Charge cooling

Even the most efficient compressor increases charge temperature, so charge cooling is integral to most applications of supercharging, including turbo-supercharging. Air/water cooling is common in roadcar applications. Since there are two temperature gradients – from the charge to the coolant, then elsewhere from the coolant to the ambient air – there is a limit to how far the charge temperature can be reduced compared to air/air cooling. However, because the specific heat of water is about four times that of air, the cooling element through which the charge passes can be smaller, and it is sometimes combined with the engine plenum to the benefit of packaging, especially plumbing, which can thus be minimised to the benefit of turbo lag characteristics (a significant advantage).

Of course, there is a need for a second water/air cooler as well as a dedicated water pump to circulate the water when needed. Therein lies the inherent limitation of this system. Normally the regular water/air cooler is nowhere near large enough to provide the required charge air cooling in steady-state operation. The net effect is that the outlet temperature of the charge air is continually rising when the system is in use. This is, however, fine for street vehicles that are driven at maximum power for only a few seconds at a time, followed by a long period at low power to restore the water temperature to ambient.

The aforementioned finned tubular core technology can be used for charge air cooling, although since this is air/water cooling it is not common in race applications. However, dragsters such as turbocharged Pro Mod cars do use the technology. In such a short-duration application it is normal to use iced water as the coolant, thereby obtaining a greater charge temperature drop than is feasible given a conventional air/air cooler.

Race engines normally use air/air charge cooling since, with a single temperature gradient, charge temperature can be further reduced to the benefit of maximum power. Air/air charge coolers essentially adapt conventional air/water cooler technology to handle air rather than water internally. The nature of the charge air is such that these coolers require a great deal of surface area and an internal turbulator. On the side of the airstream, the design is similar to that of water or oil coolers. ■

Credits

The author wishes to thank the following: Chris and Debbie Paulsen and Brad Paris, C&R Racing; Alan Docking and Mel Johnson, Docking Engineering; Kevin Kelly, Mezzo Technologies; Rob Potter, Think Automotive; Jerker Fjellman and Lars-Ake Andersson, SEM AB (Laminova) and Adrian Young, Young Calibration.

SOME EXAMPLES OF COOLER/RADIATOR/HEAT EXCHANGER MANUFACTURERS, SERVICE PROVIDERS & SUPPLIERS

AUSTRALIA

Aluminium Radiators & Engineering
+61 (07) 3205 4620 www.are.com.au

PWR Performance Products
+61 (07) 5547 1600 www.pwr.com.au

SWEDEN

Laminova
+46 532 613 00 www.laminova.com

Setrab
+46 4015 8060 www.setrab.com

UK

AH Fabrications
+44 (0)1432 354 704 www.ahfabrications.com

Applied Cooling Technology
+44 (0)121 748 8400 www.appliedcool.com

Docking Engineering
+44 (0)1327 857 164 www.dockingengineering.com

Forge Motorsport
+44 (0)1452 380999 www.forgemotorsport.co.uk

HS Marston Aerospace Ltd
+44 (0)1902 572800 www.hsmarston.co.uk

NAR Group
+44 (0)1604 684850 www.nargroup.com

Radtec Racing Radiators
+44 (0)1543 502525 www.radtec.co.uk

Serck Services Motorsport
+44 (0)208 813 7470 www.serckservicemotorsport.co.uk

Think Automotive
+44 (0)208 568 1172 www.thinkauto.com

Young Calibration
+44 (0)1273 455 572 www.youngcalibration.co.uk

USA

Active Heavy-Duty Cooling Products
+1 215 289 9480 www.activeradiator.com

Applied Cooling Technology
+1 239 217 5080 www.appliedcool.com

Be Cool Radiators
+1 800 691 2667 www.becool.com

C&R Racing
+1 317 293 4100 www.crracing.com

Evans Cooling Systems
+1 860 364 5130 www.evanscooling.com

Fluidyne High Performance
+1 888 358 4396 www.fluidyne.com

Griffin Thermal Products
+1 864 845 5000 www.griffinrad.com

Mezzo Technologies
+1 225 706 0191 www.mezzotech.com

Procomp Electronics
+1 909 605 1123 www.procompelectronics.com

Ron Davis Racing Products
+1 623 877 5000 www.rondavisradiators.com

Saldana Racing Products
+1 317 852 4193 www.saldanaracingproducts.com

Spike Radiators
+1 317 852 7171 www.spikeradiators.com