Applications – Power train – Heat exchangers

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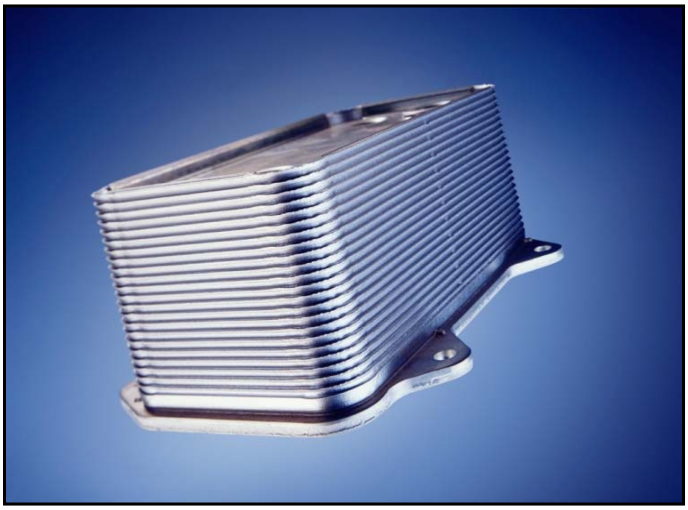
7 Heat exchangers

7.1 General aspects

Today's heat exchangers must meet a variety of highly demanding requirements. In terms of performance, they have to ensure maximum heat transfer while keeping size to a minimum. Furthermore, the durability of heat exchangers must be extremely high, providing trouble-free performance throughout its service life at low manufacturing costs. Aluminium, in its various forms, offers clear possibilities to achieve these goals and is also well positioned to meet the challenges of the increasing market demands for cost effective, energy-efficient products and new customized, innovative applications. This is made possible by the large variety of aluminium-based materials and product forms that empower system designers and manufacturers with multiple options for significant design improvement and cost reduction.



Oil cooler
Source: Behr GmbH & Co. KG

7.1.1 Brief history

- As early as 1950, aluminium heat exchangers made moderate inroad into the automotive industry.
- With the introduction of the vacuum brazing technique, large scale production of aluminium-based heat exchangers began to flourish.
- Significant growth in the use of aluminium heat exchangers resulted from advantages of the controlled atmosphere brazing process (Nocolok brazing process introduced by ALCAN).
- Introduction of “long life” (highly corrosion resistant) alloys further improved performance of aluminium heat exchangers.
- Additional demands for aluminium heat exchangers resulted primarily from the growth of automobile air-conditioning systems and new applications due to the increasing engine performance.

7.1.2 Applications of heat exchangers

Aluminium heat exchangers are used in one of the following main application categories:

- Engine cooling (radiators)
- Oil cooling (oil of the engine main lubrication circuit, the manual and automatic transmission, the power steering, etc.)
- Condensers and evaporators for air-conditioning systems
- Heaters
- Charge air, exhaust gas and fuel cooling.

In each application, the heat exchanger must fulfil specific performance requirements asking for different design and manufacturing concepts as well as material characteristics. On the other hand, due to intensifying demands on compactness combined with light weight, heat exchangers are increasingly being produced as modules. The combination of up to four heat exchangers in a vehicle’s front structure is currently state-of-the-art, significantly reducing the overall volume, weight and cost of the total cooling system.

7.1.3 Advantages of aluminium in the design of heat exchangers

The business case for aluminium heat exchangers is based on two components, the cost savings realized by substituting an expensive raw material, copper, with a less expensive raw material, aluminium, and, the cost savings that are made possible by implementing higher performance products and more efficient fabrication processes. Aluminium offers a number of advantageous material characteristics for heat exchangers:

- Significant potential for lightweight design
- Highly automated, reliable manufacturing process (brazing)
- High thermal conductivity, also when joined by brazing
- Excellent corrosion resistance
- Good formability
- Adequate strength to resist temperature and pressure cycles
- Easy recyclability, i.e. an environmentally friendly solution
- Commercial availability of a wide range of aluminium alloys and product forms to meet different design options.

7.2 Design and manufacturing of aluminium heat exchangers

Although a wide variety of design concepts for aluminium heat exchangers exist, they invariably fall into one of the following categories:

- Tube / fin
- Plate-fin
- Plate-bar
- Extrusion / fin.

The majority of the heat exchangers used in today's automobiles are based on tube / fin designs. In special applications, however, conceptual designs based on other aluminium product forms may well show clear advantages.

Charge air cooler in a tube / fin design

Source: Behr GmbH & Co. KG

There are three types of tubes for heat exchanger applications:

- Welded tubes
- Folded tubes
- Extruded tubes, and these can be round tubes (RT) or multiport extrusions (MPE).

Round extruded tubes can be subjected to a drawing operation for further reduction of the wall thickness and a closer control of the geometrical tolerances. MPE tubes are flat tubes with multiple small channels running the length of the tube, i.e. they could be described as one large tube split into multiple smaller parallel ports. The flat geometry of MPE tubes results in reduced aerodynamic drag and an advantageous development of the heat transfer boundary layer leading to larger heat transfer coefficients on the air-side. The enhanced heat transfer of MPE tubes results from the increased ratio of the heat transfer area to the internal volume, and a favourable impact on the coolant flow regime and the dominant heat transfer mechanism.

Two distinct assembly techniques are used for the manufacturing of tube / fin aluminium heat exchangers:

- Mechanical assembly and
- Brazing.

The fabrication of these two types of heat exchangers requires different processes, equipment and often different alloys. The primary advantage of mechanically assembled heat exchangers compared to brazed heat exchangers is the lower investment cost. But brazed heat exchangers have a better thermal performance rating in comparison to mechanically assembled ones. Consequently, brazing is today the dominating assembly method for aluminium heat exchangers. In specific cases, also other joining technologies can be applied in the production of heat exchanger components, e.g. adhesive bonding or mechanical joining methods such as clinching, self-piercing riveting, etc.

The preferred design and manufacturing approach for aluminium evaporators and condensers is to combine the use of multiport extrusions with the brazing process. The considerably improved performance of these heat exchangers offers the potential for a substantial reduction in system cost through reduction of weight and size, reduced fan power requirements, increased durability, etc. Heat exchangers for single-phase liquid coolants or oils are preferably designed using round tubes as the application of multiport extrusions results in a too high pressure drop.

Welded round tubes can be used in mechanically assembled heat exchangers as liquid lines or as header pipes, e.g. in brazed condensers

Source: Sapa

Example of a tube design combining longitudinal seam welding and folding which is normally used in e.g. heaters and radiators

Source: Sapa

7.2.1 Mechanically assembled heat exchangers

A mechanically assembled heat exchanger of the round tube plate fin (RTPF) design typically consists of extruded and sometimes drawn aluminium alloy tubes and fins stamped from rolled aluminium material. The inner surface of the tubes may be smooth or may have an enhanced surface. The enhancements can have a variety of geometrical shapes. Likewise, a great deal of effort has gone into improving air-side heat transfer using plate fins in a variety of geometries and degrees of complexity, e.g. the use of interrupted surfaces to reduce the resistance in the boundary layer.

The two components are assembled by inserting (“lacing”) the tubes into the formed fin collars. At this point, the tube outer diameter is slightly undersize with respect to the fin collars, making the lacing process easy. The next step is to expand the tube diameter by inserting a mandrel and rod assembly into the tube that is larger than the tube’s inner diameter. The result is a mechanical “joint” between tube and fin that provides the conduction path for heat transfer from the refrigerant to the tube wall, to the fin and finally to the air.

Mechanically expanded RTPF heat exchangers have some inherent weaknesses. Although the mechanical bond between tube and fin provides good contact, there is still a significant amount of contact resistance that reduces the effective heat conductivity. This contact resistance is may be due to oxides and/or other contaminants present in the interface between the outer tube surface and the fin collar, but also any geometrical irregularity which results in a less than perfect contact during the tube expansion process. The contact resistance will generally increase during service, further deteriorating heat transfer performance over time. The primary problem is that corrosion will result in the growth of oxides and other corrosion products that act as insulators at the fin/tube interface.

Mechanically assembled aluminium radiator
Source: Behr GmbH & Co., KG

7.2.2 Brazed aluminium heat exchangers

Brazed aluminium heat exchangers show a metallurgical bond between tube and fin which has a positive impact on several performance measures. Most important is the elimination of the contact resistance between tube and fin leading to significantly improved heat conduction. Different brazing processes have been used commercially to manufacture aluminium heat exchangers:

- Controlled atmosphere brazing
- Vacuum brazing
- Salt bath brazing
- Neitz process
- Ni brazing.

However, aluminium heat exchangers for automotive applications are today generally produced by controlled atmosphere brazing (dominating method) and vacuum brazing. Ni brazing of automotive heat exchangers is executed today only by one major company. Salt bath brazing is still used, but only for small volume production.

The manufacturing of brazed heat exchangers using tube and fin components is well established within the automotive heat exchanger industry. Highly-automated assembly and brazing processes suitable for high volume production provide both high throughput and excellent quality leading to heat exchangers comprised of joints made with 100% metallurgical bonding.

Aluminium producers, brazing flux producers and furnace builders actively work together to improve and further develop the brazing processes for better economy and environmental friendliness. A wide range of heat-treatable and non heat-treatable aluminium alloys are available both for tubes and fins. Suitable aluminium materials for brazing applications (coils, sheets and tubes) can be delivered in a large variety of alloy combinations, clad ratios, sheet thicknesses and widths according to customer specifications.

Brazed oil cooler
Source: Novelis

7.3 Material requirements and functions

Aluminium alloys are now well established materials for the manufacture of automotive heat exchangers. They offer properties that can be favourably utilised in various components:

- High thermal conductivity
- Low density
- Adequate strength (also at elevated temperatures)
- Good formability
- Excellent corrosion resistance.

Proper selection of aluminium alloys and product forms offers the possibility to develop and produce the various types of heat exchangers used in modern automobiles and to respond to the ever increasing market demands with respect to improved heat transfer performance, but also reduction of weight, size and cost.

For heat exchangers, different types of rolled as well as extruded aluminium products are used:

- Flat rolled materials, e.g.:
  - Unclad fin stock for radiators, charge air coolers, heaters, etc.
  - Clad fin stock for condensers
  - Clad header plates and side plates for various types of heat exchangers
  - Clad strip for welded or folded tubes for radiators, charge air cooler, heaters, etc.
  - Clad plates for evaporators and oil coolers.

- Extruded material, e.g.:
  - Extruded tubes for evaporators, radiators, condensers, etc.
  - Extruded and drawn tubes for radiators, heater cores, evaporators and condensers
  - Multiport extrusion tubes (MPE) for evaporators, condensers, charge air coolers, etc.
  - Extruded shapes.

The specific characteristics of aluminium heat exchanger materials differ depending on the product form and the envisaged application. Consequently, several aluminium alloy systems are used in heat exchangers and there are numerous alloy variants which have been developed for optimum performance during assembly (in particular depending on the applied brazing method: vacuum brazing or controlled atmosphere brazing utilizing potassium aluminofluorate fluxes) and in service (i.e. excellent corrosion resistance).

Non heat treatable (NHT) and heat treatable (HT) aluminium alloys can be selected for the different heat exchanger components. In pure aluminium and NHT alloys, strain hardening by cold deformation increases the basic strength achieved through solid solution and dispersion hardening. Recovery and recrystallization processes during brazing, however, will eliminate any strength increase by strain hardening. HT alloys are strengthened by cold deformation as well, but offer in addition the possibility of precipitation hardening. Brazing processes carried out at approx. 600°C are ideal to dissolve the soluble alloying elements. Subsequent fast cooling will retain these elements in supersaturated solution. Precipitation hardening, i.e. the nucleation and growth of fine precipitates in HT alloys can then lead to a significant strength increase, both at room temperature (natural hardening) or by ageing in the temperature range 150-200°C either in a separate heat treatment step or – immediately after brazing - by controlled fast cooling and holding of the brazed component in the critical temperature range for a certain time.

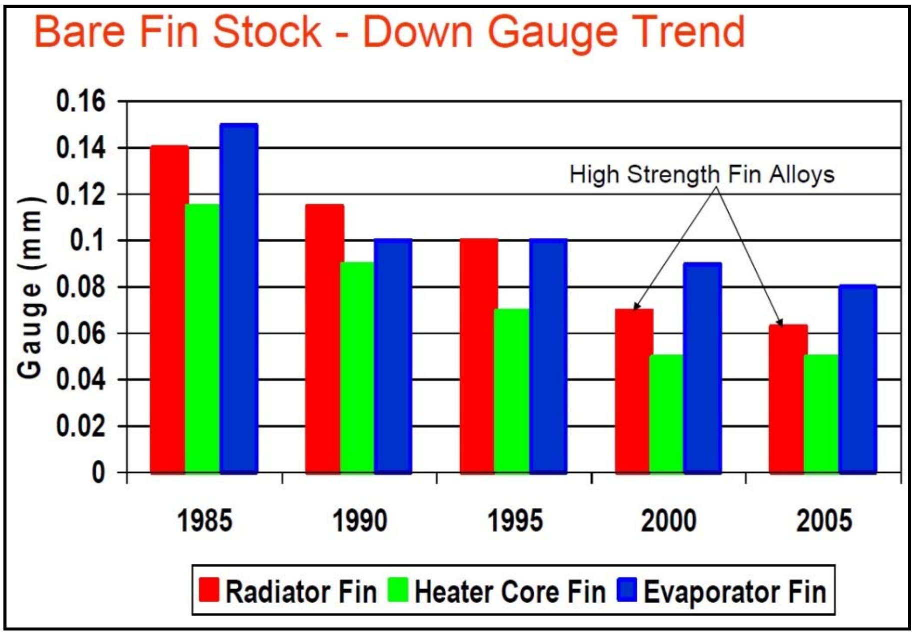
7.3.1 Fin material

Fins require a high thermal conductivity, an advantageous strength-to-weight ratio and good corrosion resistance. Most important is also the ability of aluminium alloys to be formed into complex fin geometries. In mechanically joined heat exchangers, high formability is essential to the trouble-free production of collar fins. Typically, alloys like EN AW-1050, EN AW-1100, EN AW-1200, EN-AW 8006 or EN AW-8079 are used, the production of which is tailored to meet this highly exacting requirement in fin forming.

In brazed heat exchangers, fin materials are typically based on the alloy EN AW-3003, but in general slightly modified compositions are used for optimum performance. Small additions of Cu and/or Mg (if allowed by the applied brazing technique) are made for increases strength. Other alloy variants contain higher amounts of Mn and sometimes also Si to ensure a higher strength after brazing, and a good sagging resistance during brazing. These alloy compositions favour the formation of large grains during brazing, which is beneficial for the sagging behaviour and hinders braze metal penetration into the core. Also low alloyed heat treatable alloy of the AlMgSi system (6xxx series alloys) are sometimes used (e.g. EN AW-6060 or EN AW-6063).

Additionally, fin stock alloys can be tailored for the cathodic protection of tubes or header alloys against corrosion by adding zinc in different levels (up to 2.5 % Zn). The range of the applied fin stock materials is further increased by clad fin variants where the clad composition is adapted to the composition of the core ally and to whether it is intended for vacuum brazing or brazing in controlled atmosphere with or without flux.

Over the years, extensive alloy development activities and product-specific process optimization efforts have allowed a significant downgauging of the aluminium heat exchanger materials, enabling a considerable reduction of weight and cost.

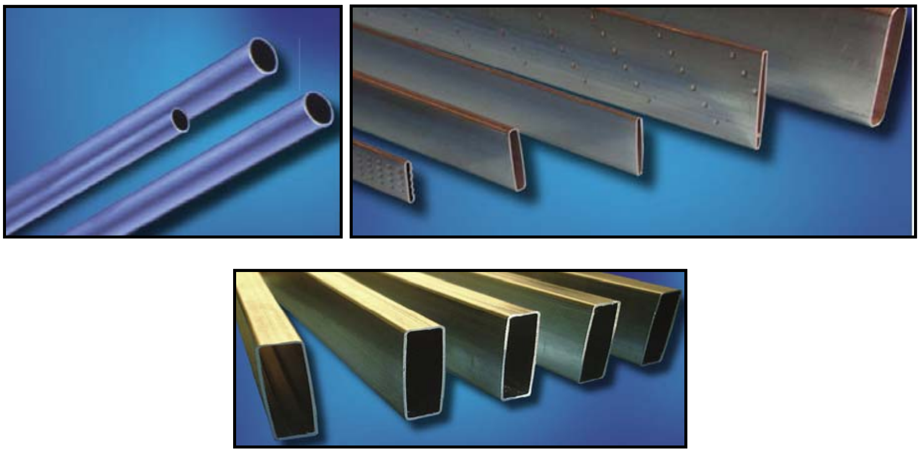


Source: Aleris

7.3.2 Bare and clad rolled materials for headers, plates, longitudinally welded tubes, etc.

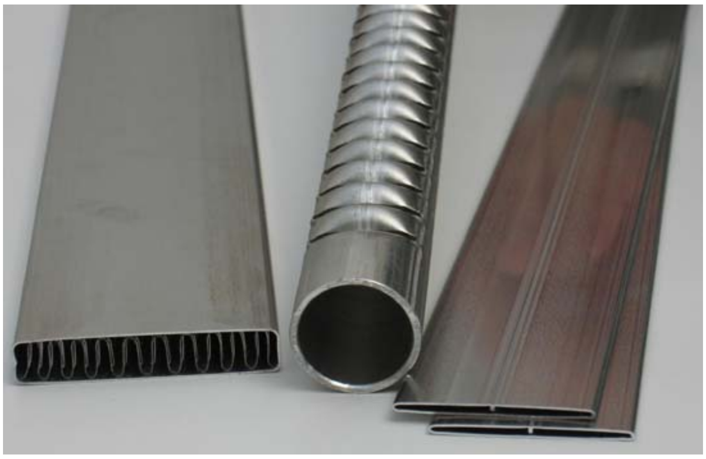
The alloys (core alloys for clad variants) used for rolled strips and sheets for headers, side supports, tubes, etc., have essentially the same compositions as those listed above for fins (with the exception of the Zn-containing variants). For brazing applications, the core is clad with Al-Si alloy layers which act as the source for the filler metal during the brazing process. The thickness of the brazing clad layer is generally 5 - 20 % of the sheet thickness for one side clad variants, and 5 – 15 % if both sides are clad. Typical clad alloys for controlled atmosphere brazing are EN AW-4343 and EN AW-4045, for vacuum brazing EN AW-4004, EN AW-4045 and EN AW-4047. But there are also numerous modifications of these basic compositions in use.

Aluminium brazing sheet is a highly engineered material consisting of multilayer composite materials of varying complexity. Depending on the requirements of the specific application, these materials can comprise 2, 3, 4 and even 5 layers. Each layer either serves a specific purpose during the production process or is used to meet a heat exchanger functional requirement while in service. For example, a 3XXX core alloy layer for post-braze strength can be clad with a modified 3XXX alloy layer for corrosion protection and a 4XXX alloy layer to provide the filler metal needed for the brazing process. Even more complicated version may be necessary for controlled atmosphere brazing (CAB). Magnesium additions significantly improve the mechanical properties of aluminium alloys. Unfortunately, magnesium interferes with the activity of many commercial fluxes. Nevertheless, multiple cladding layers can still permit the use of higher strength magnesium-bearing core alloys for CAB applications. Magnesium-free intermediate claddings serve as barriers to the diffusion of magnesium from the higher strength magnesium-bearing core alloy, and thereby reduce or eliminate any “poisoning” of the flux.



Welded aluminium tubes for heat exchangers, offered predominantly as clad aluminium products
Source: Hydro Aluminium Precision Tubing

Clad aluminium tubes for brazing applications, adapted to the different brazing processes, are produced on roll forming lines from flat rolled strips in flat oval, rectangular and round profiles by longitudinal welding (generally using the high frequency welding process). Mostly, only a 2-layer composite consisting of the core alloy (typically EN AW-3003 or a modification of this alloy) and the brazing layer at the outer surface is used. If necessary, the core alloy can be covered on the other (inner) side for corrosion protection, e.g. with EN AW-1145 or EN AW-7072.

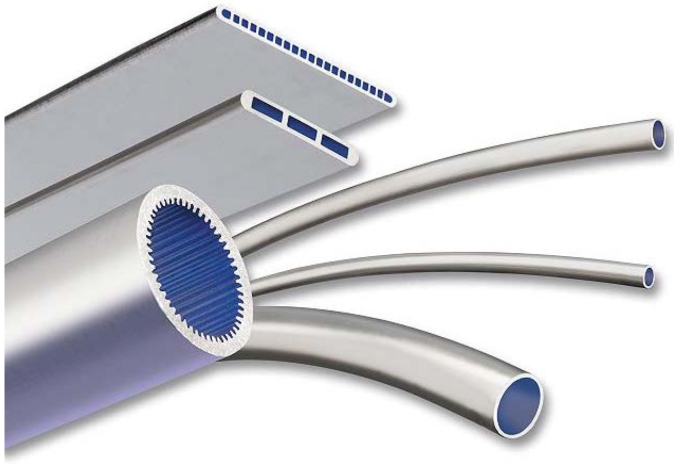


Examples of welded tubes for brazed heat exchangers
Left: Double side braze clad tube with an unclad inserted inner fin ("stuffed tube")
Middle: Thick gauge, punched header pipe for condensers
Right: Tube combining longitudinal seam welding and folding, e.g. for radiators and heaters

Source: Sapa.

7.3.3 Extruded tubes

Extruded tubes are available in various shapes, sizes and alloys. Apart from simpe extruded tubes, heat exchanger tubes include in particular round or oval precision drawn tubes as well as multi-port extrusion (MPE) tubes. Although extruded aluminium tubes do not have the same performance characteristics as precision drawn tube, they can present a cost-efficient alternative in less demanding applications.



Extruded tubes in a variety of designs and complexity for heat exchangers, both brazed and mechanically assembled, and for liquid lines

Source: Sapa

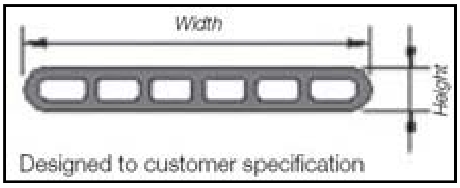
Round tubes are often smooth walled, but their performance may be also enhanced with axial, straight or helical micro-fins on the inner diameter surface to improve the refrigerant-side heat transfer by increasing the surface area. In case of precision drawn tubes, the calibration process ensures a high outer surface quality as well as narrow geometrical tolerances. Furthermore, precision drawn tubes offer highest quality and excellent processing capabilities for operations as bending, end forming, expanding, etc. Typically, aluminium alloys like EN AW-1050, EN AW-3003, EN AW-5049 and EN AW-6106 and modifications of these compositions are used both for extruded and precision drawn heat exchanger tubes. Long life (high corrosion resistant) alloys can also be used.

Round tubes are found as header pipes in automotive heat exchangers such as condensers and as fluid lines in e.g. AC systems.

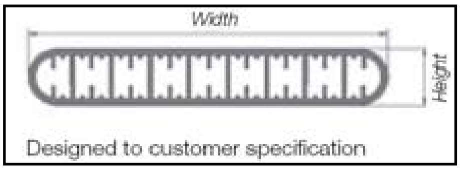
MPE tubes are manufactured to meet specific requirements with respect to alloy, outside dimensions, wall and web thickness, hydraulic diameter, and other attributes. With their large internal surface area, the MPE profiles (or micro-channel tubes) achieve a more efficient heat transfer and are therefore ideal for use in highly effective heat exchangers. The tube material must have adequate strength (high pressure resistance) and fatigue resistance together with good air-side and waterside corrosion resistance. As more and more complex tube designs are used, the formability of the tube alloys becomes of greater importance. Thus MPE tubes are typically made from the alloys EN AW-1050, EN AW-3003 and modifications of these alloys.

Depending on the envisaged application, two kinds of MPE tubes can be differentiated:

- The aluminium micro MPE profile with a height of 1.2 – 3 mm and a width of 12 – 30 mm is primarily used for:
  - Condensers
  - Evaporators
  - Oil coolers
  - Radiators
  - Heater cores.



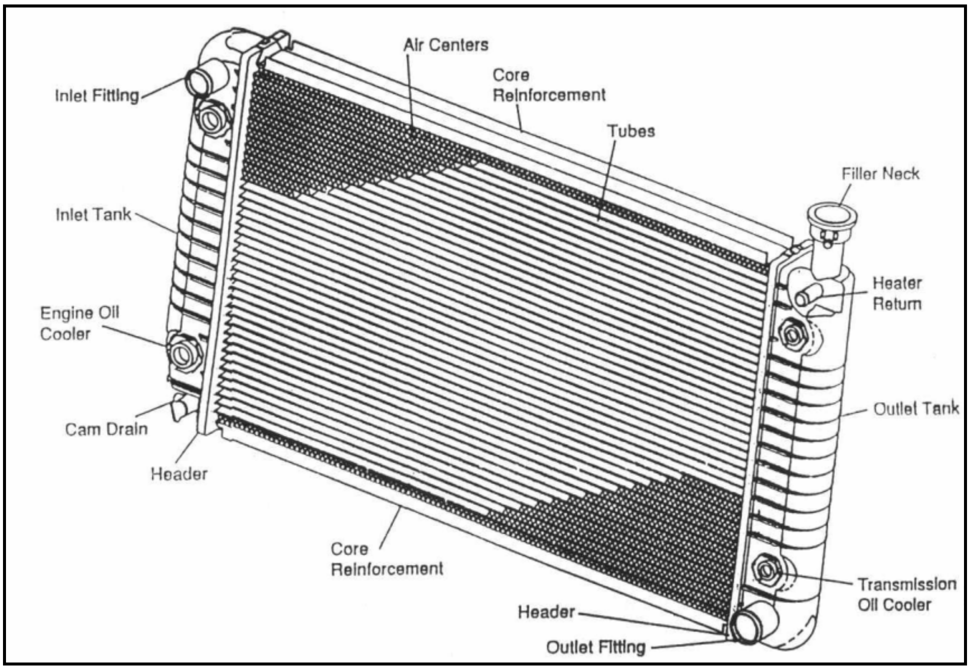
- The aluminium macro MPE profile with a height of 2 –8 mm and a width of 80 –120 mm is primarily used for the following applications:
  - Charge air coolers
  - Oil coolers
  - Fuel coolers.



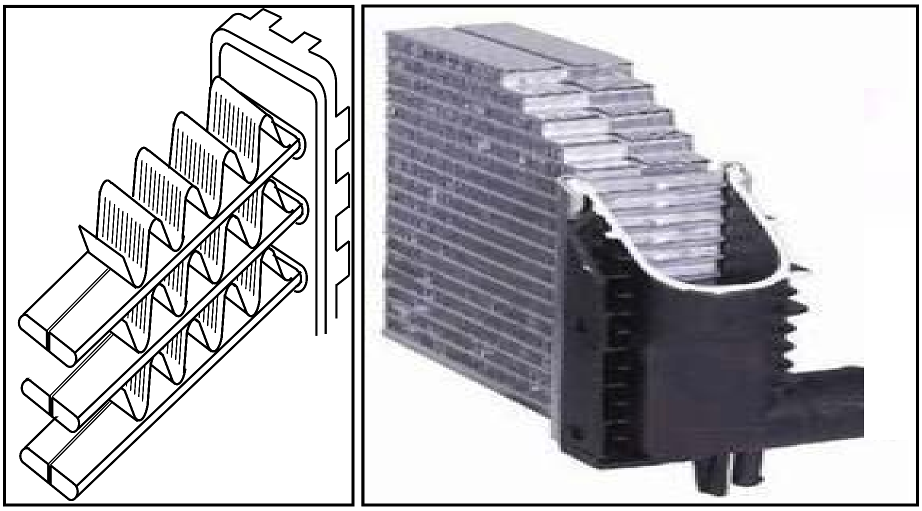
7.4 Applications

7.4.1 Engine cooling system (radiators)

Radiators are required for the cooling of internal combustion engines. They operate by passing a liquid coolant through the engine block, where it is heated, then through the radiator where it loses the heat to the atmosphere. The coolant is generally water (with some additives, e.g. anti-freezing agents, corrosion inhibitors, etc.). Usually the coolant is circulated by means of a pump and a fan is used to blow air through the radiator.



Configuration of a radiator (schematic)



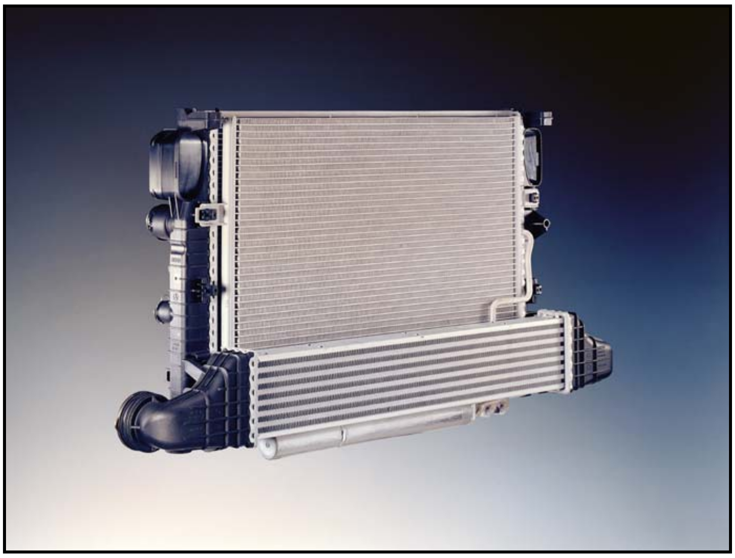
Key detail elements of the radiator
Source: Valeo (photo)

In general, the radiator consists of the aluminium radiator core and two header tanks that cover the ends of the radiator and all of the required connections and fastening elements. The header tanks allow for the appropriate coolant volume to be circulated through the tubes. The radiator core is usually made of flattened aluminium tubes (although multiport extrusions can also be used) and aluminium fins that zigzag between the tubes. These fins transfer the heat in the tubes into the air stream to be carried away from the vehicle.

On most modern radiators, the tubes run horizontally with the header tanks on either side. But the tubes may also run vertically with the tanks on top and bottom. There are gaskets between the aluminium core and the header tanks to seal the system and to keep the coolant from leaking out. The header tanks are generally made of plastic (e.g. fibre glass-reinforced polyamide), but there are also all-aluminium radiators. All-aluminium radiators are lighter than the versions with plastic tanks, have a much smaller packaging depth, and are fully recyclable.

Simple brazed aluminium radiator with plastic tanks

Source: Sapa



Engine cooling module of the Mercedes-Benz E-Class

Source: Behr GmbH & Co. KG

All-aluminium radiator of the BMW 7 series

Source: Behr GmbH & Co. KG

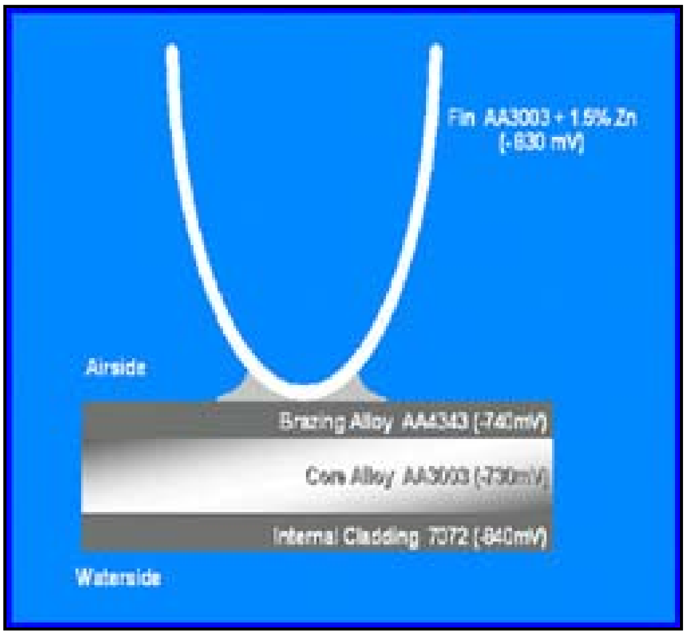
On older vehicles, the radiator core was made of copper and the tanks were brass. The brass tanks were brazed to the copper core in order to seal the radiator. The modern aluminium radiator systems are much more efficient and durable, not to mention cheaper to produce.

Engine cooling system – Air side corrosion

Over the years, a strong down-gauging trend has been observed for the various automotive radiator materials answering the continuing pressure for weight and cost reduction. Down-gauging, on the other hand, requires an improvement of the corrosion resistance of both tube and fin stock alloys. Historically, air-side corrosion resistance has been ensured by the application of suitable pre-treatment and corrosion protection systems. But with the introduction of highly corrosion resistant ("long-life") alloys for tube stock products with optimized compositions e.g. based on EN AW-3110 or EN AW-3005, it has been possible to eliminate these costly and sometimes environmentally hazardous surface treatments.

Additional protection of the external surface of the tube can be achieved by using fin stock alloys that preferentially corrode in contact with the tube alloy (i.e. the fins act as sacrificial anodes). For this reason, the fin alloy must be more electronegative than the tube alloy. The preferred option for achieving a fin that protects the tube against corrosion is the addition of zinc, typically in the range of 1.0 to 2.5 wt. % Zn. However, in vacuum brazing, the low vapour pressure of Zn means that a significant proportion evaporates and the remaining Zn level in the fin is difficult to control. Thus for vacuum brazed radiators, the use of alloying elements with a high vapour pressure like tin or indium is sometimes preferred to lower the electrochemical potential.

The low melting point Al-Si alloys which are used to clad the tube stock are – in the brazed condition – already slightly electronegative to most of the Al-Mn based tube alloys, i.e. the addition of Zn to the clad alloy is often not necessary.



Electrochemical protection of a tube – fin system based on alloys of the type EN AW-3003 for long "life tube" (highly corrosion resistant) alloys, the addition of Zn to the fin alloy and the internal clad of the tube is optional).

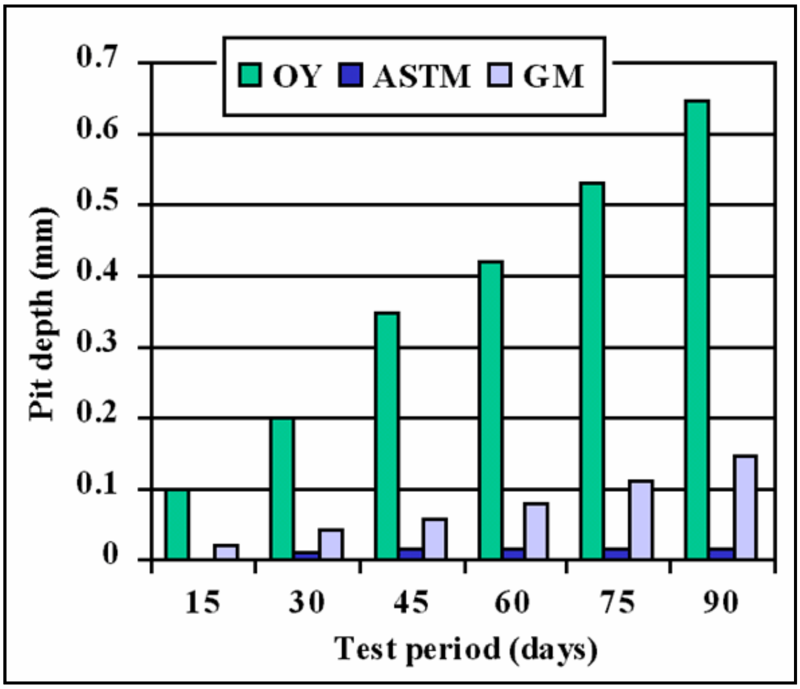
Engine cooling system – Water-side corrosion

Together with other additives, engine coolants generally contain chemical anti-corrosion agents. However, the anti-corrosion agents remain only effective as long as the recommended levels are constantly maintained. Therefore, some radiator manufacturers favour water-side cladding alloys for improved corrosion protection. It has been shown that the optimum Zn level for internal clad alloys is about 1% (depending on core alloy).

In practice, heat exchanger materials are subjected to customer-specific qualification tests. There are a number of qualification test procedures in use to evaluate the resistance of radiator materials to water-side corrosion:

- simulated service test as described in ASTM D2570 and
- immersion tests in a specified test solution for an extended period at elevated temperature, typically 80 to 95°C. Examples of such test solution are shown below (all composition values are in ppm):

	Cl^-	SO_4^{2-}	Cu_2^+	Fe_3^+	HCO_3^-
OY solution	195	60	1	30	0
ASTM solution	100	100	0	0	100
GM solution	100	300	0	0	200



Relative corrosivity of the three test solutions

Source: Ando *et al.*, SAE 870180

In some of these qualification tests, the "long life" (highly corrosion resistant) tube alloys have shown adequate corrosion resistance even without internal cladding.

7.4.2 Oil coolers

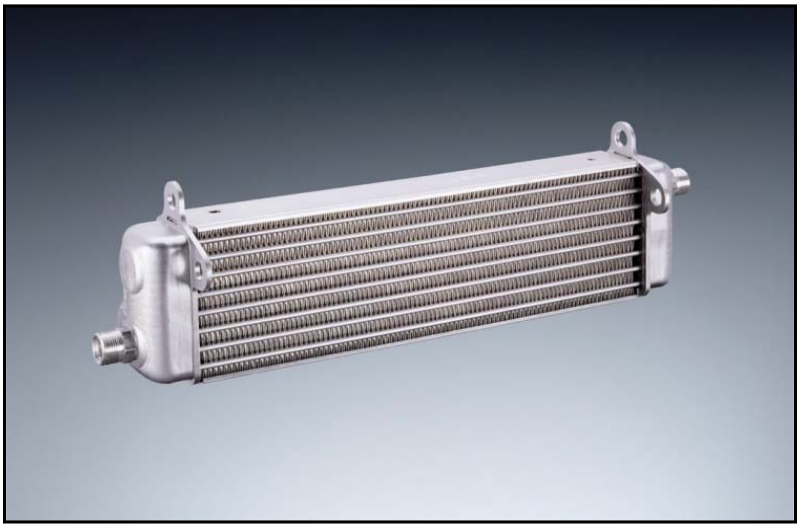
Oil coolers (and warming systems) are necessary to keep the temperature of the oil, needed for the functioning of the engine and other automotive systems under control. In highly stressed engines the engine oil has to be cooled. Vehicles with automatic transmissions and highly stressed manual transmissions require transmission oil coolers. In fact there may be also heat exchangers for cooling the oil of the power steering, the hydraulic components for brakes and absorbing systems for improving the driving comfort, etc., in a car. Oil cooling raises the viscosity and hence the oil lubricating power. Thus the oil change intervals are prolonged and the protection of the mechanical parts against wear, etc., is improved.

Oil cooling can be accomplished by air-cooled heat exchangers or coolant-based oil coolers (i.e. the coolant in the engine cooling circuit). The latter involves simplified oil circuits and lower cost if compared to the oil-air solutions which offer higher performances and do not lead to an additional thermal load for the radiator. Air-cooled oil cooler are generally positioned in the cooling air flow in cars and equipped with an additional fan. Coolant-cooled oil coolers can be incorporated in the coolant tank or engine block, or fitted externally on the engine, transmission, cooling module, or oil filter housing, as required.

Oil coolers are produced in a large variety of designs. Due to the typical service conditions in terms of pressure (up to 15 bar) and temperature (up to 150 °C), they cannot be mechanically assembled, but must be brazed. The main material requirements are pressure resistance (i.e. strength, also at elevated temperature) and corrosion resistance.

Brazed liquid-to-liquid oil cooler

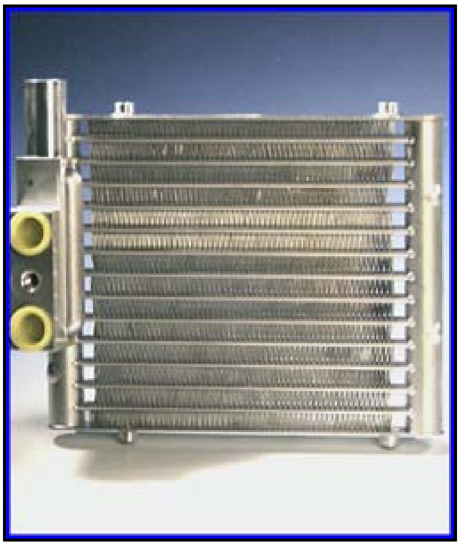
Source: Sapa



Power steering oil cooler

Source: Behr GmbH & Co. KG

Other interesting design solutions for oil coolers are presented below:



Air cooled transmission oil cooler
Source: Behr / Photo: Hydro Aluminium Precision Tubing

The vacuum brazed transmission oil cooler (positioned in front of radiator in the cooling air flow) shown above is extremely flat and compact. It is an extreme lightweight design with header tanks consisting of hydroformed aluminium tubes. The pressure valve with the oil connections is brazed to the header tank.

Engine oil cooler with attached oil filter housing
Source: Behr / Photo: Hydro Aluminium Precision Tubing

A special requirement of the shown oil cooler is its optical appearance due to its visibility when the bonnet is open. With its stacked plate design for operation with the water based engine coolant, it is an extremely compact unit. It is produced by vacuum brazing, the plate stock is clad with a braze liner on both sides. The extruded tubes are also brazed to the cooler. The oil filter housing is made by die casting and bolted onto the cooler.

Engine oil cooler with welded oil circuit connection
Source: AKG

The oil cooler shown above has been designed for high performance V8 engines. It is an oil cooler in a plate & bar design to be used with water based coolant and equipped with internal turbulators to increase the turbulence of the fluid. The oil cooler is attached to the cylinder block between the V-shaped arranged cylinders with a cast plate which serves also as a sealing for the coolant. Both the cast plate and the connections for the oil are welded to the salt brazed cooler.

Transmission oil cooler and its assembly in radiator water tank
Source: AKG

This transmission oil cooler in a drawn cup & plate design, equipped with internal turbulators fits into the radiators water tank. The oil cooler was produced by salt bath brazing, the connectors with the oil circuit are brazed to the cooler.

Power steering cooler
Source: Source: Hydro Aluminium Precision Tubing

The concept of this power steering cooler consists of a U-bended tube with 0.3 mm AA4017 H14 fins. The tube and fins are connected in a press fit. The placement of the fins, the size, the tube dimension, the bending radius and the length are all parameters decided by the customer, a concept which offers high flexibility and ensures a robust production process at the same time.

7.4.3 Heater cores

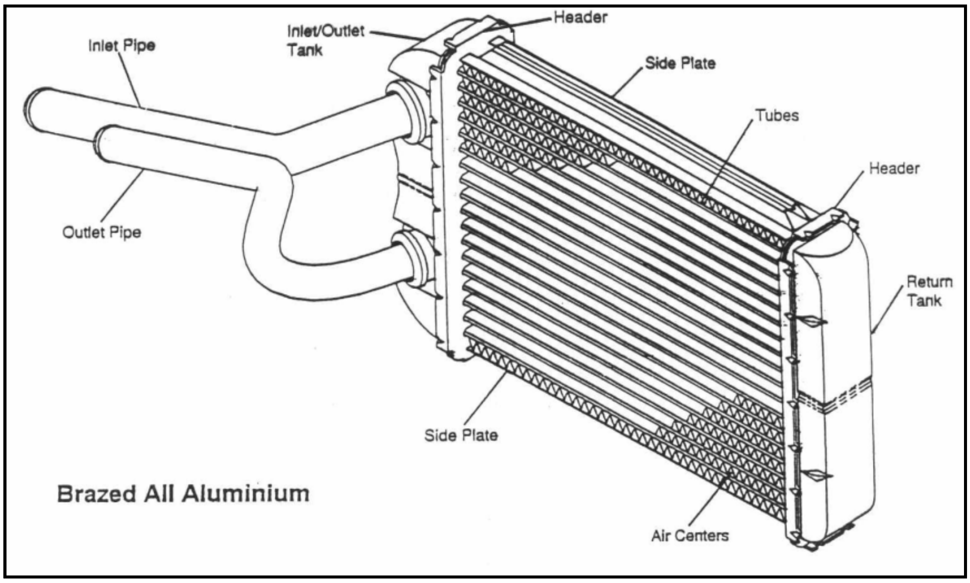
The hot engine coolant is used to provide heat to the interior of the vehicle when needed. This is a simple and straight forward system that includes a heater core which is connected to the cooling system with a pair of rubber hoses. One hose brings hot coolant from the water pump to the heater core and the other hose returns the coolant to the top of the engine.

All-aluminium heater core
Source: Sapa

The heater core is a small radiator like device which is usually mounted under the dash board or - if the car is equipped with an air conditioning system - in the HVAC housing. The coolant flow through the heater core is controlled by a heater control valve. A fan blows outside air through the heater core and directs the heat into the inside of the automobile. The temperature of the heated air is regulated by a blend door that mixes cool outside air. In an air conditioning system, the heater core reheats a portion of the air cooled by the evaporator by exchanging heat with engine-cooling water. The reheated air is then mixed with the remaining evaporator-cooled air and the mixed air is blown into the vehicle cabin.

Different examples of heater cores
Source: Valeo - Alcan

Design and manufacturing



Schematic drawing of a typical heater core assembly

The heater core consists of an assembly of tubes and fins with tanks on both sides. One of the tanks, made either from aluminium or plastic, is fitted with inlet and outlet tubes. The heater cores are today mainly brazed (generally by controlled atmosphere brazing), but could also be mechanically assembled. Subsequently the tanks are crimped to the headers.

The tubes are produced from clad aluminium strips with the braze filler on one side. In addition, the other side may be clad with a more corrosion resistant alloy for better corrosion performance. The fins are generally unclad aluminium alloys. The header and side supports are stamped from rolled clad aluminium alloy stocks. Header materials are two side clad whereas the side supports are one side clad aluminium alloys.

The operating conditions of heater cores are quite moderate (pressure 1.0-1.5 bar, temperature 100-120°C). The main material requirements are an adequate strength, excellent resistance against external and internal corrosion and good brazing performance.

New design developments are typically aimed at achieving a more uniformity coolant flow between the inlet and the outlet tanks, the reduction of the size and the weight of the heater core. Consequently, brazed heater cores are preferred due to their generally better thermal performance compared to mechanically assembled cores. Most important is also the trend towards thinner tubes (diameter as small as 1.3 mm) and smaller fin heights for improved heat exchange efficiency. Also a zinc diffusion layer can be applied onto the tubes to improve their corrosion resistance, resulting in a very thin tube plate thickness (0.2mm).

7.4.4 Air conditioning

The air conditioning system is used for the following purposes:

- temperature control
- air circulation control
- humidity control
- air purification.

If the car is equipped with air conditioning, the heater core is integrated with the air conditioning system into a single-unit.

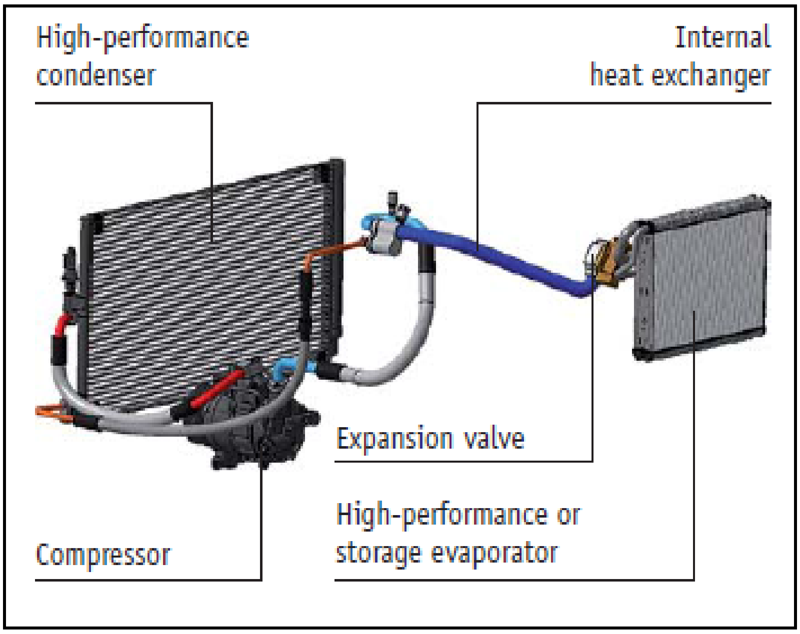
General considerations

Automotive air conditioning is similar to stationary air conditioning in the sense that it also requires the cyclic flow of the refrigerant through an evaporator to absorb the heat and dissipating that in the condenser. However, automotive air conditioning faces several additional challenges:

- temperature parameters involved with the evaporator and condenser
- variable air flow characteristics within the system
- variable compressor speed (depending on engine speed)
- variable air flow through the condenser (related to the vehicle speed).

The last two variables not only differentiate vehicle air conditioning from stationary types of air conditioning, but are also very demanding requirements. Package limitations, high demands on fuel efficiency and pollution control place additional stringent requirements on the design of air conditioning systems.

A blower unit, a heating unit and a cooling unit are the main components of automobile air conditioning system. The cooling unit in turn consists of an evaporator, compressor, condenser and an expansion valve and the attached control systems. The heating unit consists of a heater core and the associated control mechanisms.



Refrigerant circuit of an automotive air conditioning system

Source: Behr GmbH & Co. KG

In the cooling unit, a suitable refrigerant enters the evaporator, picks up the heat from the air and becomes vapour. The vapour is then compressed by the compressor and the compressed vapour enters into the condenser where the hot compressed vapour is cooled and further condensed, i.e. the vapour to liquid phase transformation takes place. The excess heat is transferred by the condenser to the outside air. The liquid refrigerant passes through an expansion valve before it is returned into the evaporator.

Refrigerants

Until concerns about depletion of the ozone layer arose in the 1980s, the most widely used refrigerant in automobile air conditioning was the chlorofluorocarbon (CFC) R-12. Today, the hydrofluorocarbon R-134a and certain blends have totally replaced chlorinated compounds. However, following the ban on CFCs and HCFCs, substances such as FCs and HFCs which are used as substitute refrigerants have also come under criticism because of their global warming potential.

In 2006, the European Union adopted a regulation on fluorinated greenhouse gases which makes stipulations regarding the use of FCs and HFCs with the intention of reducing their emissions. This regulation plans to eliminate auto air conditioning refrigerants with GWP's higher than 150 between 2011 and 2017. A similar regulation has been established in California with the same 2017 deadline.

New refrigerants which will meet European Union's 2011 mobile air conditioning (MAC) directive are currently evaluated by the automotive industry, e.g. CO_2 (R-744), HFC-152a and hydrofluoro-olefin (HFO)-1234yf. However, there are still many controversial opinions within the industry.

In particular HFO-1234yf shows the potential to replace hydrofluorocarbon (HFC)-134a in MAC systems globally:

- Lower total greenhouse gas emissions versus current HFC-134a and other candidates, as a result of good energy efficiency, low global warming potential with a GWP of 4 (the GWP of CO_2 is 1) and good cooling performance in hot and moderately hot climates.
- Lower operating pressures than CO_2 systems.
- Compatibility with existing technology, enabling a cost-effective transition away from HFC-134a, higher reliability and lower warranty costs.

HFO-1234yf is already introduce in some 2011 North American car models.

In Europe, new refrigerant systems based on CO_2 (R-744) are generally favoured. But at the moment, these systems are not yet ready for introduction into a car, partly owing to the engineering challenges posed by CO_2. One of these challenges is the high pressure required in the system, up to 10 times that of fluorocarbon-based systems. Another is the inefficiency of operating transcritically, or above the refrigerant's critical temperature (T_c) (CO_2 has a very low T_c of 31°C).

A third alternative would be to use the fluorocarbon R-152a. R-152a has a GWP of 140; however, because it is flammable, it cannot be used in systems now found in cars. Instead, the air conditioning unit must be equipped with an isolating secondary loop to protect passengers, meaning added weight and expense.

Condenser

If the car has air conditioning, there is an additional heat exchanger called the air conditioner condenser, which also needs to be cooled by the air flow entering the engine compartment. Its location is usually in front of the radiator, but in some cases, due to aerodynamic improvements to the body of a vehicle, its location may differ. Condensers must have good air flow anytime the system is in operation.

By exchanging heat with air, the condenser cools the high-temperature, high-pressure gas refrigerant sent from the compressor and condenses it into liquid refrigerant. This heat exchange allows the air conditioning system to emit the heat absorbed by the evaporator from inside the vehicle to the outside.

Condenser in the Mercedes-Benz C-Class
Source: Behr GmbH & Co. KG

In the condenser, the refrigerant (today R-134a) is circulating with a high-pressure range (maximum about 20 bar). The normal operating temperature ranges from room temperature up to 35 – 40 °C. The main tube material requirements are:

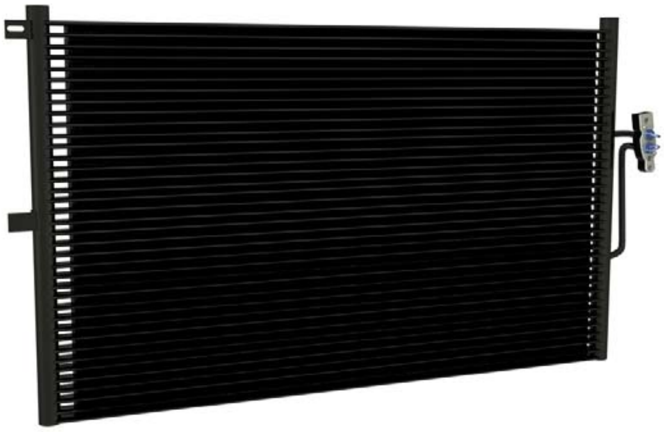
- Pressure resistance (i.e. adequate strength)
- Sag resistance (stability during brazing)
- Corrosion resistance.

As for all heat exchangers, in terms of performance, condensers must ensure maximum heat transfer while keeping size to a minimum. Furthermore, condensers must be of an extremely high quality, providing trouble-free performance throughout its service life at low manufacturing costs.

Typically air conditioning condensers are of either of the parallel flow or of the serpentine type design. A very small fraction of condenser designs are based on mechanically assembled solutions. Practically all condensers are produced by brazing (in general using the controlled atmosphere brazing method).

Serpentine condensers consist of a refrigerant tube bent in the form of a "serpentine". The refrigerant tube is normally an extruded or precision drawn tube. Clad fins are brazed to the tube. This design is quite robust, but characterised by a high refrigerant pressure drop. Consequently, this type of design is very rarely encountered today.

In the parallel flow design, a pair of parallel vertical header tanks distributes the refrigerant to horizontally aligned tubes which in turn are connected to fins. Extruded multi-port tubes are mostly used for the refrigerant tubes. Aluminium multi-port extrusions offer favourable heat transfer area to volume ratio, which makes these extrusions ideal for heat exchangers with high performance requirements. The headers, end caps, baffles, brackets and side supports are produced from rolled aluminium alloy stocks. Depending on the specific design, the header stock can be clad on one or two sides with a braze liner.



Brazed and painted condenser
Source: **Sapa**

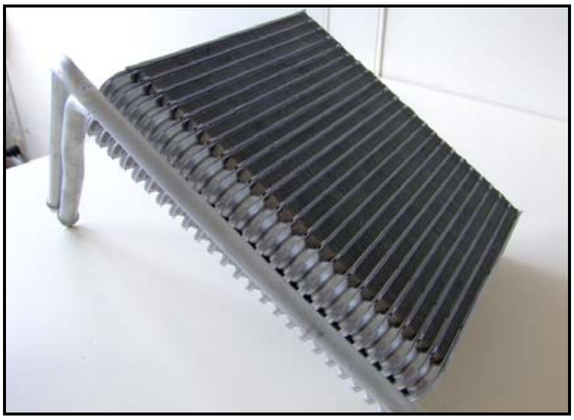
Parallel flow designs are thermally more efficient than the serpentine type condensers. New developments in condenser design are typically aimed at providing an increased heat transfer area and reducing the pressure drop on the refrigerant side.

Parallel flow condenser with multiport aluminium extrusions
Source: Valeo – Alcan

Evaporator

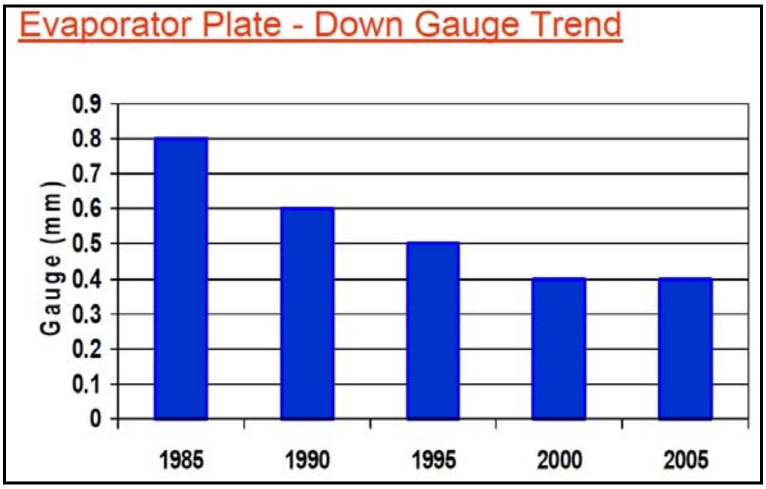
Located inside the vehicle, the evaporator serves as the heat absorption component. The evaporator provides several functions. Its primary duty is to remove heat from the inside of the vehicle. The refrigerant enters the bottom of the evaporator as a low pressure fluid, almost always as a mixture of liquid and gas. The warm air passing through the evaporator fins causes the refrigerant to boil, i.e. the refrigerant absorbs heat. This heat is then carried off with the refrigerant to the compressor and finally to the condenser.

A secondary benefit is dehumidification. As warmer air travels through the aluminium fins of the cooler evaporator, the moisture contained in the air condenses on its surface. Dust and pollen passing through stick to its wet surfaces and drain off to the outside.



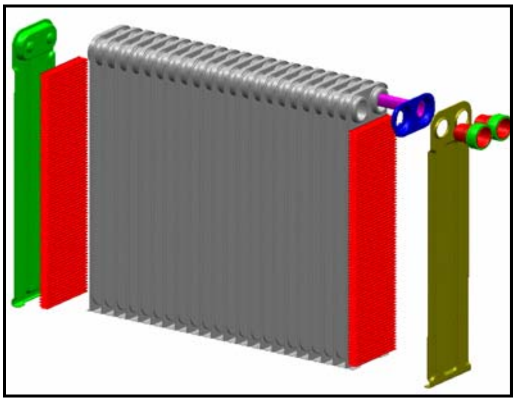
Drawn cup plate evaporator
Source: Visteon

In the design of the evaporator, it is most important to achieve maximum heat transfer, but to limit its weight and size to a minimum. In the evaporator, the refrigerant (i.e. R-134a) is circulating through with a low-pressure range (max. ~ 6 bar) and with temperatures in a range around -10°C to +30°C. But the pressure can get much higher when the AC is not operating. Thus the main material requirements are an adequate strength (pressure resistance), excellent external corrosion resistance, formability and brazing performance. Any improvement of the material characteristics is immediately exploited to enable further downgauging for weight and cost reduction.



Source: Aleris

Evaporators for automobile air conditioning are primarily of the drawn cup plate type. The application of evaporators of the less efficient serpentine design has declined. An alternative design involves the use of extruded micro-channel tubes. Further developments in evaporator design are typically aimed at reducing the size of the evaporator, achieving a more even distribution of the refrigerant and the proper adaption of the arrangements of inlet and outlet connections.



Schematic of a drawn cup plate type evaporator, plate and fin assembly before brazing
Source: Valeo-Alcan

Drawn cup plate evaporators are produced by brazing aligned pairs of properly shaped stamped plates which results in the integral flow tubes and header pipes. Although some evaporators are still produced by vacuum brazing, controlled atmosphere brazing is today the dominating manufacturing technique. Since both internal (turbulators formed by opposing ribs) and external (header pipes) brazing requirements must be met, the material for core plates are clad on both sides with braze liner. In general, long life (highly corrosion resistant) aluminium brazing alloys are used for producing the evaporator core plates. Extruded tubes are used for the manifolds and are joined for example by induction/plasma brazing.

As a consequence of their specific design, the drawn cup plate type evaporators do not facilitate a smooth drainage of the water condensed on the surfaces of plate tubes and interposed fins. Therefore, a hydrophilic/anti-bacterial coating is applied to allow the smooth drainage of condensed water collected on the surface of core plate tubes and fins. Newly developed, highly corrosion resistant alloys eliminated the need for a special corrosion protection, i.e. the earlier used chromate coating is today obsolete.

Flat tube evaporator used in R134a refrigerant circuits
Source: Behr GmbH & Co. KG

In 2002, the flat-tube type evaporator was first introduced into serial production. In comparison with the plate/fin evaporators previously used, flat-tube evaporators take up less room for the same performance. Evaporators are usually coated to ensure optimum water drainage and prevent odours from microorganism deposits. Such environmentally friendly coatings (e.g. BehrOxal®) also provide for better corrosion protection without the use of chrome (VI) and thus comply with the guidelines of the EU Directive on End-of-Life Vehicle.

Air conditioning liquid lines

Apart from the application of aluminium in condensers and evaporators, air conditioning liquid lines are also an important application for aluminium tubes.

CO_2 air conditioning systems - future developments

The introduction of new refrigerants for mobile air conditioning, in particular the change to CO_2 (R-744) with its highly challenging technical operating conditions, asks for new aluminium solutions. The condenser which is used in current air conditioning systems based on R-134a will be replaced by a CO_2 (R-744) gas cooler replaces. In the gas cooler, the hot R744 supplied by the compressor is cooled down and condensed as a function of the outside temperature.

R-744 gas cooler which replaces the condenser used in current R-134a-based A/C systems
Source: Behr GmbH & Co. KG

Evaporator used in R744 A/C circuits
Source: Behr GmbH & Co. KG

A newly developed aluminium internal heat exchanger concept, which can be used in a variety of air-conditioning applications, is shown below. The co-axial design is specifically optimized for the use in R-744 (CO_2) mobile air conditioning system. The "CO2AX" system features a low weight of below 240 g/m, a compact design of only 16 mm outer diameter, and a narrow bending radius of less than 15 mm. Moreover, it ensures a safe and efficient operation of any R744 A/C system due to its high burst pressure and a low pressure drop.

Internal heat exchanger for R-744 (CO_2) air conditioning systems

Source: Hydro Aluminium Precision Tubing

Another design concept (Piflex®) includes a tube which is able to absorb large torsional movements and is flexible under high pressures. It also offers narrow bending radii and other significant advantages.

Piflex®, a new high-pressure flexible all-aluminium tube solution for automotive CO_2 air conditioning systems

Source: Hydro Aluminium Precision Tubing)

7.4.5 Charge air coolers

An engine charge air cooler (CAC), also called an intercooler, is a heat exchanger used to cool the charge air of an internal combustion engine after it has been compressed by an exhaust driven turbo charger, an engine driven turbo charger, or a mechanically or electrically driven blower. Feeding the engine with compressed air increases its power as extra oxygen is added to the combustion process. During compression, the air tends to warm up and its density is reduced. This partly thwarts the effect of compression itself. Thus, a charge air cooler is used to reduce the temperature of the compressed air in order to fully exploit the supercharging effect.

There are different heat exchanger designs for charge air cooling, all providing improved engine volumetric efficiency for a specified engine performance. Typical cooling media include the engine's coolant, ambient air, or another external coolant source. Air-cooled charge air coolers can be packaged in the engine-cooling module along with radiators and condensers, below engine-cooling modules, or in wheel wells for performance-vehicle applications. With indirect charge air cooling, the charge air cooler is placed very close to the engine rather than in the front end. The additional low-temperature radiator needed for indirect charge air cooling is an integral part of the cooling module. Due to the smaller depth of the low-temperature radiator compared to a conventional charge air cooler, more space is available in the front end, which can then be used for pedestrian protection, for example. The location close to the engine allows shorter charge air lines, cutting the pressure loss by about 50%. The dominant solution in today's market is direct charge-air-cooling with air using chassis mounted systems in various locations. But there is also a trend towards indirect charge air cooling which is preferable in terms of packaging size and dynamic response.

Figure 1: A box type CAC fitted on the engine close to turbo charger to have low pressure drop. However, ambient air supply is insufficient, particularly at low vehicle speeds.

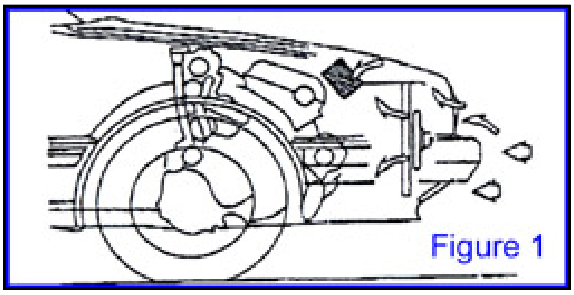


Figure 2: A box type CAC fitted in the wheel housing or beside the radiator. Ambient air supply is good, but inlet and outlet ducts are long, pressure drops are high.

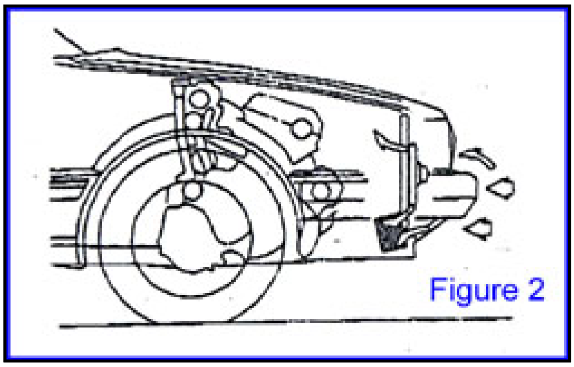
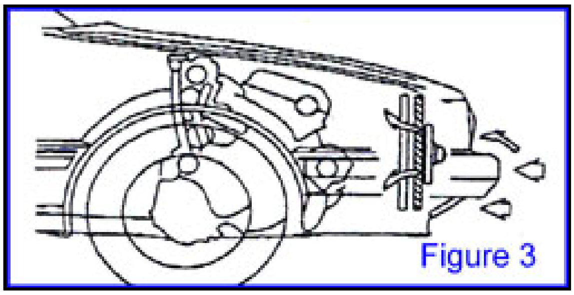


Figure 3: A full face CAC is located in front of the radiator and takes full advantage of the dynamic and forced ventilation. Thermal efficiency is generally high, but ducts to the engine are long. A further drawback for this location is the overcrowded front space already occupied by the radiator, the air conditioning condenser and electric fans.



The charge air cooler (CAC) is a slightly different heat exchanger as the fluid is air. Its operating conditions are:

- Air inlet temperature 150-240°C
- Air input pressure 2 – 6 bar
- Output air temperature < 70°C.

The critical material requirement is sufficient strength at elevated temperatures. Due to the low heat transfer coefficient between air and surface, a large internal surface is needed in the tubes. Generally, welded aluminium tubes (large rectangular or flat-oval tubes) with inserts or large multi port extruded tubes with internal webs are used for this type of heat exchanger.

The specific design of a CAC is determined by factors such as package size, price, weight, location in the vehicle and the availability of an appropriate cooling medium. The most important technical aspect is the balance between high heat transfer performance and low charge air energy (i.e. pressure) loss. The selection of the type of charge air-cooling, either coolant or air cooled, depends on the temperatures which must be attained.

Charge air cooler in a tube/fin design

Source: Sapa

Air-to-air solutions

The competitive advantage of aluminium in CAC heat exchangers is the combination of low density and good thermal properties in comparison to copper or steel solutions. A potential disadvantage of aluminium has been corrosion resistance and strength at elevated temperatures. These aspects have been well addressed during the recent years which have brought several new high performing alloys to the market.

The most critical failure locations of aluminium CACs are the tube to the header joints. The determining factor for the life time of CAC tubes is their response to a combination of axial compression and bending stresses which are induced by the cyclic temperature changes. The resulting phenomenon of lateral thermal expansion is called "thermal breathing". This is a descriptive term that describes the tendency of the core to "belly up" in the centre with the tube ends pinned to the header, increasing with tube length and number of tubes. Proper design solutions must reduce the stress build-up at the joints.

Cores of charge air coolers (without tank)
Source: Valeo

For the assembly of CAC heat exchangers, the same joining technologies are used as for other automotive heat exchangers (i.e. controlled atmosphere brazing and vacuum brazing). The core is usually completed with plastic end-tanks and acrylic gaskets.

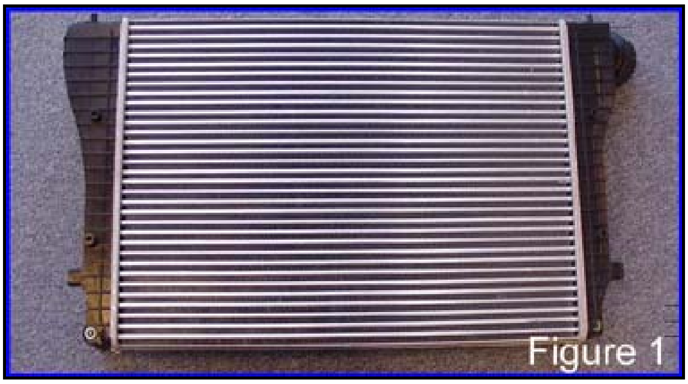


Figure 1: Flat front-mounted (full face) charge air cooler

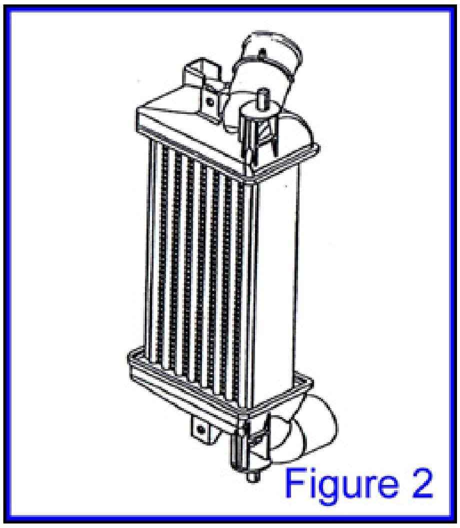
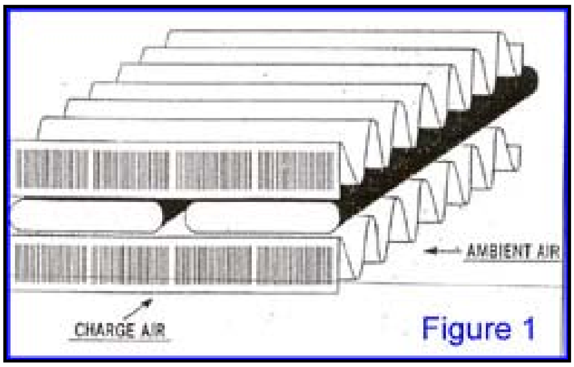


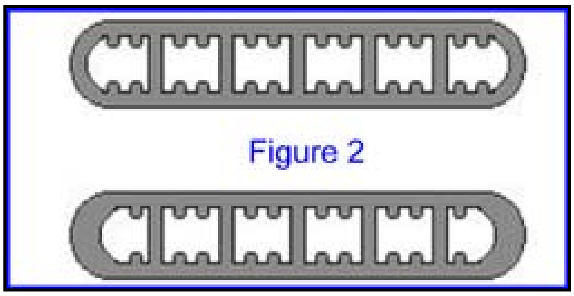
Figure 2: Air-to-air charge air cooler for a box type configuration with a vacuum brazed core (with plastic end-tanks and acrylic gaskets).

In a full face type configuration, the depth of the CAC heat exchanger is typically about 30 mm for passenger cars. In a box type configuration, the depth is typically in the range of 40–85 mm.

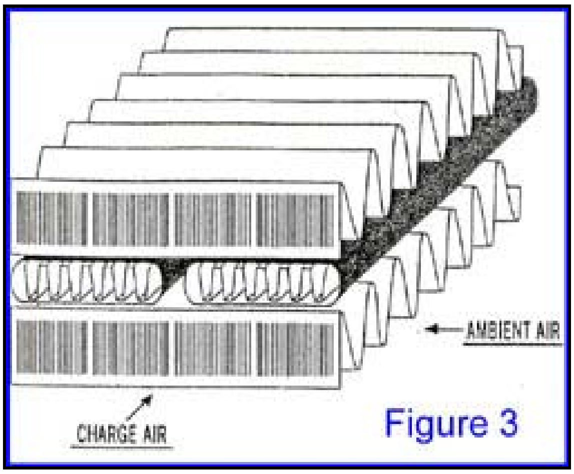
The following figures 1 – 3 show examples of typical tube/fin designs applied in CAC heat exchangers:



The most common type is the standard tube design with fins (Fig. 1). Alternatively, the welded standard tubes can be substituted by extruded tubes (typical width 28 - 34 mm, height 5 - 8 mm). The application of extruded tubes offers more flexibility in performance and strength because the wall thickness may be increased (e.g. for heavy duty applications) and/or enhancements can be introduced for improved heat transfer Fig. 2).



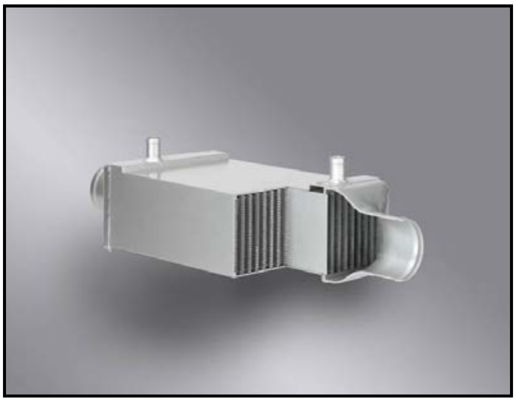
Another option for significantly improved cooling efficiency is the additional insertion of fins into a standard tube design (Fig. 3).



Air-to-coolant cooler

Charge air cooling can also be done with a liquid coolant, but requires a relatively low coolant temperature (below 45°C). In this case, two heat exchangers are needed, one for the air-to-water cooling and one for the water-to-air cooling. The coolant (usually water) must first circulate through an auxiliary "low temperature" radiator and then through a water-to-air cooler. The water cooled charge air cooler provides considerably reduced pressure losses compared with air-to-air cooling. It can be located in the engine's intake manifold, eliminating the need for hoses between the engine and the front-end of the vehicle. The reduced volume between the compressor outlet and inlet valves also improves acceleration response time significantly. ,

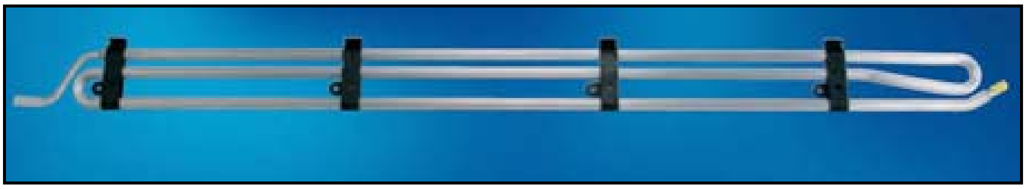
The charge air cooler's coolant circuit is totally independent of the engine's cooling circuit. The coolant is cooled by a small radiator and fed by small diameter (approximately 20mm) coolant hoses. The flow is driven by a low-powered electric pump. The air-to-coolant cooling would be carried out in a small radiator of a standard design concept, located either next to the main radiator or in front of the main radiator. The coolant-to-air heat exchanger is based on conventional cores for water cooling enveloped by a housing ensuring controlled air flow. Air-to-water CAC systems also offer the possibility to cool other fluids such as engine oil, power steering fluid, etc., at the same time.

Indirect charge air coolers for passenger cars
Source: Behr GmbH & Co. KG

7.4.6 Diesel fuel cooling

In some fuel system, mainly for diesel engines, not all fuel is burned. The remaining diesel must be transported back into the fuel tank. High injection pressure provides many benefits, but one side effect is a large increase in the fuel temperature (from approximately 80°C to 110°C) when the fuel is depressurized and sent back to the tank via the return line. The extremely hot return fuel may exceed the limitations of the fuel tank (which is often plastic) and the fuel-injection equipment. To counter this effect, a variety of fuel-cooling designs have been developed. The fuel coolers are designed for easy integration into the existing fuel system, with numerous ways to bend and to add bracket for assembly. Most of these coolers are designed for underbody mounting (where the fuel is cooled by ambient air), but engine-mounted, liquid-cooled solutions are possible as well. Their design is optimised for maximum heat rejection performance and miniumum space requirement.

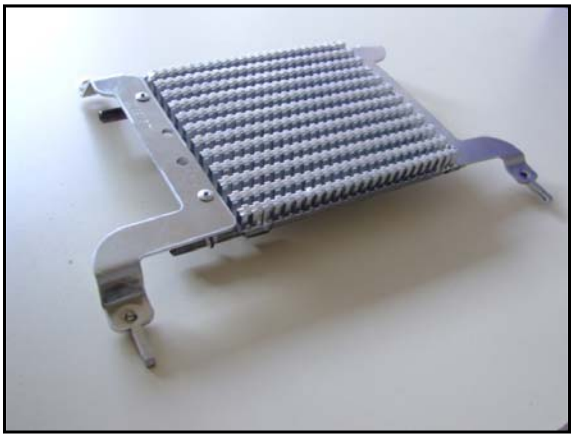


Aluminium diesel fuel cooler to reduce the fuel temperature in the return line
Source: Hydro Aluminium Precision Tubing

The aluminium cooler profiles are extruded and shaped in one piece, which eliminates potential leaks and aggressive corrosion in joints. The standard alloy used for the coolers is a "long life" (corrosion resistant) alloy, thus no further surface protection has to be added. The brackets used for the coolers are typically manufactured in PA66 plastic, which safely withstands the harsh car underbody environments, where the fuel cooler usually is located.

Other types of diesel fuel coolers are shown below:

Diesel-air-coolers in a special flat design for special mounting requirements under the chassis
Source: Valeo-Alcan



“Fin plate pair” diesel fuel cooler
Source: DANA Thermal Products France

Plate & fin type suitable for applications in which fresh ambient air can be channelled into the cooling system.

7.4.7 Exhaust gas heat exchangers

The new emission standards for diesel-powered cars can no longer be met with adjustments to the engines alone. An ideal way to comply with the new limits is cooled exhaust gas recirculation. This involves removing a portion of the main exhaust flow between the engine outlet and the turbine, cooling it in a special heat exchanger, and mixing it back into the inlet suction air after the charge air cooler. This lowers the combustion temperature in the engine, thus reducing the formation of nitrogen oxides (No_x).

Exhaust gas heat exchanger module
Source: Behr GmbH & Co. KG

7.4.8 Parking heaters

Parking heater
Source: Webasto

The basic principle on which a parking heater is based on is the heating of the element from within the device. The initial energy (usually electric energy) is provided from an outside source and starts to heat. At the same time, a pump causes a small amount of fuel to be directed from the fuel tank and into the heating chamber, alongside with air from the outside of the car. Just as it happens in the combustion chamber of an engine, the air-fuel mix explodes once the heated element creates the proper temperature for that explosion. After that, the coolant fluid that circulates around the device is slowly being warmed. It first reaches the car's heat exchanger, from which the warm air is being redirected towards the inner section of the car via the ventilation system, and after that the actual engine compartment. The next and last step of the cycle is the liquid being headed back to the parking heater device, from which this action will repeat itself for as long as it is necessary in order to reach the desired temperature inside the vehicle.

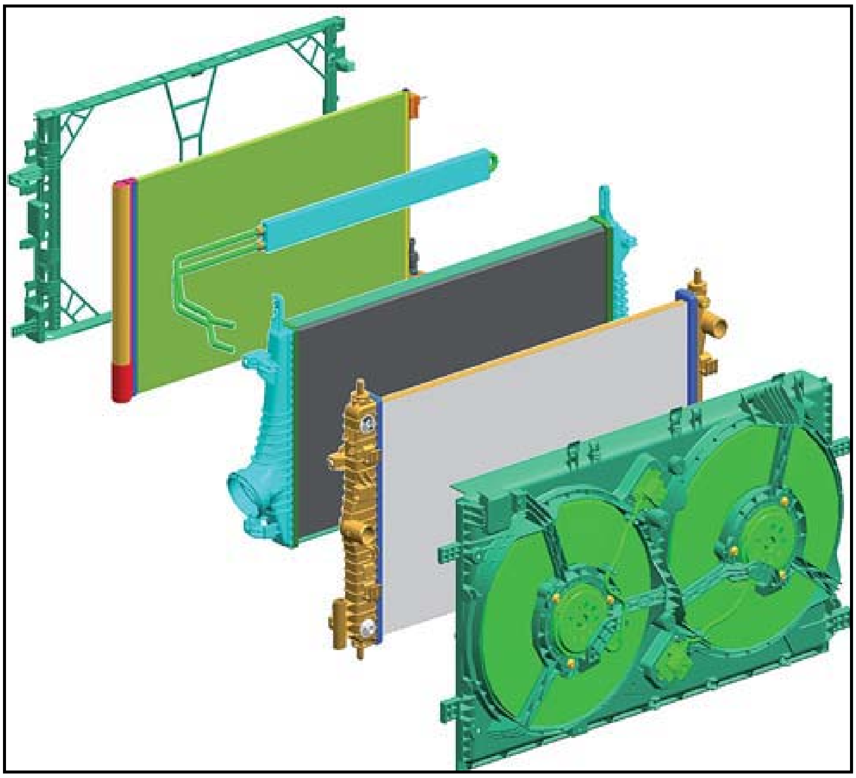
7.4.9 Cooling modules

Due to intensifying demands on compactness combined with lightweight, heat exchangers are increasingly being produced as modules. The combination of up to four heat exchangers in a vehicle's front structure is currently state-of-the-art, reducing the total volume of the cooling system.

Cooling module systems are made up of two thermal loops, one cold and one hot, each feeding different heat exchangers located as close as possible to the unit requiring cooling or heating. The cold loop feeds the charge air heat exchanger located at the cylinder head intake, the fuel cooler and the air conditioning condenser. The hot loop is responsible for cooling the engine and the engine or transmission oil, and heating the cabin. The exhaust gas recirculation (EGR) system cooler and other additional systems may be connected to one or the other of the loops. The cold loop may also provide efficient cooling for the electronics and electric motors of hybrid and fuel cell vehicles, with an engine cooling radiator, air to oil cooler, a charge air heat exchanger and an air conditioning heat exchanger.

The cooling module of the Opel Insignia shown below is a typical example of a cooling module for a current mid-range vehicle powered by an internal combustion engine. It consists of the following elements:

- Condenser frame
- Full face air conditioning condenser
- Power steering oil cooler loop
- Charge air cooler
- Full face radiator with an in-tank transmission oil cooler
- Fan shroud with dual fans.



Opel Insignia cooling module
Source: Behr GmbH & Co. KG

7.5 Future perspectives

The application of aluminium alloys in automotive heat exchangers has been a success story. Full market penetration has been achieved for aluminium in radiators for engine cooling, for heater cores, air condenser and evaporators. Only in specific application (e.g. oil coolers), aluminium faces serious competition from other materials, in particular stainless steel.

On the other hand, this also means that the potential for further growth of aluminium applications in the traditional heat exchanger market is limited. There will be still some additional demand for air conditioning in automobiles, but market saturation will be reached soon because of the already high market share of air conditioning systems in European car models. Some additional demand may arise because the amount of heat to be dissipated by the engine cooling system is increasing due the use of higher engine speeds, increasing engine power output and the use of turbo-charged diesel engines. In addition, items like power steering and other driven units will increase the amount of heat to be dissipated to the environment. However, economical and environmental consideration will continue to push both aluminium suppliers and manufacturers of heat exchangers to improve the applied materials, the manufacturing processes and the design and performance of heat exchangers. Heat exchangers will be more and more integrated into modules to improve their overall efficiency, to save weight and to meet the tightening packaging restrictions. As a result, more demanding functionalities will be achieved with even less material!

But there are other developments which will have an even more important impact on the future heat exchanger market:

- The need for more environmentally friendly refrigerants in mobile air conditioning systems leads to new heat exchanger designs which ask for different material characteristics.
- The introduction of alternative powertrain systems (i.e. hybrid electric vehicles, plug-in electric vehicles, fuel cell technology, etc.) will ask for new functionalities either for the cooling of powertrain components and/or maintaining the accustomed comfort in the passenger compartment.

At the moment, no definite statements may be given. But with its outstanding thermal material characteristics, aluminium will maintain important applications also in the thermal management solutions for the future.

Aluminium solutions for new in mobile air conditioning systems based on CO_2 refrigerants have been described already in chapter 4.4. New vehicle designs with alternative powertrains, however, present entirely new challenges for air conditioning technology. In hybrid vehicles, the electric powertrain emits very little waste heat. Consequently, the heat flows in the coolant of the smaller internal combustion engine will have to be better controlled and it may be necessary to use the energy available in the exhaust gas as an additional source of power. Thus air conditioning systems will have to be designed much more efficiently to ensure a high level of cabin comfort. In electric vehicles, air conditioning comfort can directly affect the potential driving range. Accordingly, energy must also be saved where possible in air conditioning, e.g. through more efficient systems, new designs, and additional functionality such as cabin air conditioning before driving off.

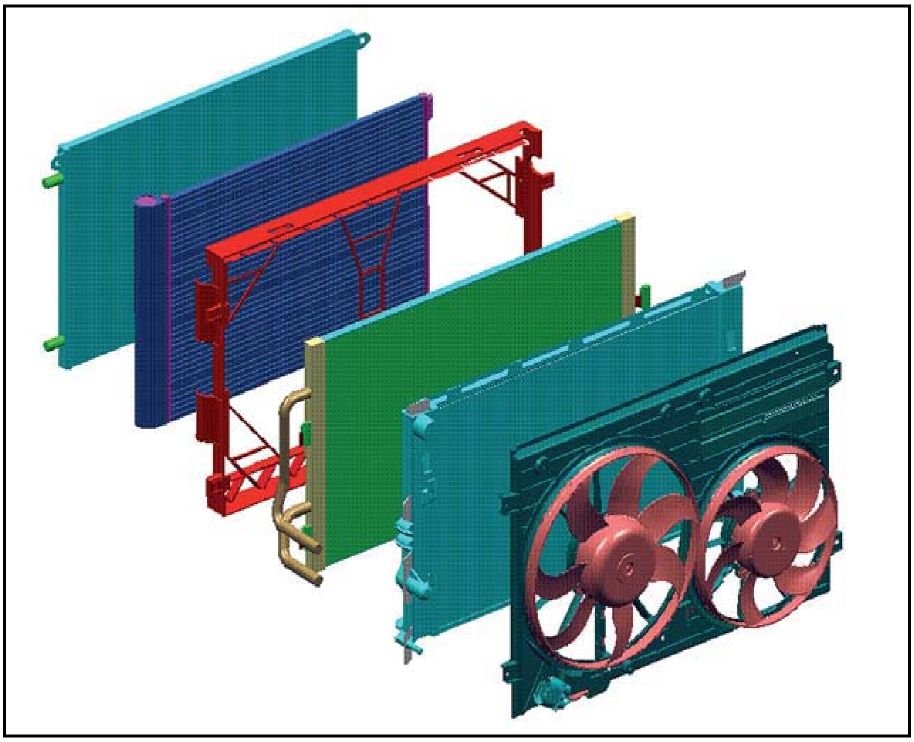
Electric (hybrid and plug-in) vehicles with high driving ranges have two heat sources that both need to be cooled, the “under-the-hood” electronics and the Li-ion batteries. That means that the engine cooling module may need to include two radiators.

When continuous power exceeds a few kW, liquid cooling of heat dissipating “under-the-hood” electronic components becomes mandatory to maintain sufficiently low junction temperature of the power devices.

To avoid premature aging of the temperature-sensitive lithium-ion cells, the cells must be kept below approx. 40°C in all operating conditions. At operating temperatures of 40°C and above, the battery life span is reduced. Momentary peak loads, e.g. when braking (recuperation of brake energy) and accelerating (assisted acceleration), generate powerful electrical currents and cause significant warming of the Li-ion cells due to internal resistance. Coupled with the fact that in particular in warmer climates, the temperature of the vehicle interior can easily rise above 40°C, operating Li-ion batteries without cooling is not an option. At low temperatures (below -10°C), the battery performance declines and efficiency drops markedly. Finally, temperature gradients within a battery must be kept very small.

There are three different approaches to cooling a Li-ion battery:

- Using cooled air. This is usually air conditioned air taken from the vehicle cabin or generated using an air conditioning unit installed specifically for the battery.
- Using a supplementary evaporator in the form of a cooling plate installed within the battery. The battery cells are assembled on the cooling plate which contains channels in which refrigerant from the refrigerant circuit of the air conditioning system evaporates.
- A heat exchanger transfers the low temperature produced by the evaporated refrigerant to a second circuit that cools the cells in the battery.



Cooling module concept for an extended range electric vehicle

Source: Behr GmbH & Co. KG

The cooling module for an extended range hybrid electric vehicle would actually include four heat exchangers instead of the characteristic three of a vehicle with a conventional internal combustion engine:

- At the front of the module: a low temperature battery cooler with a large surface area designed to keep the lithium-ion battery at temperatures around 30°C.

- The second component in line is a full face condenser to maintain a comfortable temperature for the vehicle occupants.
- The third component is a radiator for the hybrid drive's power electronics unit.
- The fourth component is a high temperature radiator optimized for the downsized internal combustion engine.
- Finally, a dual fan and the sealed cooling module frame ensure that the air flow through and around the cooling module can be controlled.

A closer examination reveals that this is much more complex than the cooling circuit of an automobile with a traditional powertrain.