Advanced Engine Cooling Systems for Vehicle Application

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April 2015
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EDUCATION

- Mechanical Engineering Master Degree
- Scientific High School Degree

BACKGROUND

- (2014) FIAT CHRYSLER AUTOMOBILES EMEA - Engine Systems Unit Responsible
- (2013) FIAT GROUP AUTOMOBILES EMEA - Fuel System Responsible
- (2008) FIAT GROUP AUTOMOBILES - Cooling System Responsible
- (2006) FIAT POWERTRAIN TECHNOLOGIES - Cooling System Manager
- (2001) FIAT AUTO - Cooling System Engineer
- Association of Engineers member
Engine Systems: Overview
Cooling Systems: the Reason and the Operation
Cooling Systems: Roadmap
An innovative concept: the Smart Cooling System
Open questions
OUR MISSION

INTAKE system

EXHAUST system

COOLING system

FUEL system
Cooling System: Why?

Typical energy split for a vehicle engine

- 25% Useful Power (mobility and accessories)
- 40% Exhaust Gas
- 30% Coolant
- 5% Frictions

Which is the reason of a cooling system?

- Only a fraction of the fuel power is usable
- The main part is rejected through the exhaust line or is rejected as heat
- The cooling system is used to transfer the heat in excess to the ambient and to keep the engine temperature within the limits

The cooling system is composed by several subsystems:

- Water
- Fan & Shroud
- A/C condenser
- Charge air
- Oil
Water subsystem

The excess of engine heat is transferred from the engine metal structure to the coolant, which through the heat exchanger (radiator) installed in front of the vehicle is cooled by the ambient air.

A centrifugal pump, usually driven by the engine shaft, circulates the coolant.

Usually the coolant liquid is a water/ethylene glycol mixture with specific cleaning and anticorrosion agents.

This mixture presents the following advantages:
- High specific heat (and heat capacity)
- Low viscosity, so low pressure losses and good heat exchange
- No significant variation of the physical properties along the time and a wide range of temperature
- High latent heat of evaporation

Ethylene glycol is added to lower the water freezing temperature below -30 °C.

The radiator is the main component of the system. Its size may impact the complexity and the cost of the whole system integration.

Component of the water system:

1. Radiator
2. Radiator inlet hose
3. Radiator outlet hose
4. Clamp
5. Expansion tank
6. Degassing pipe
7. Filling pipe
8. Cabin heater inlet hose
9. Cabin heater outlet hose
10. 4-ways heater inlet/outlet
11-14. Radiator fixation parts (with rubber insert)
The main goal of the Fan & Shroud system is to guarantee the needed amount of cooling air through the cooling module.

At low vehicle speed the fan contribution is fundamental to increase the air flow.

The main constraints are:

- The heat exchange according to the vehicle thermal balance
- The packaging limitations inside the engine bay, the installation constraints and the safety requirements
- The maximum allowed electric power
- The noise emissions and component vibrations
The goal of A/C condenser is to reject the heat of the A/C evaporator and A/C compressor in order to assure the cabin thermal comfort.

The main constraints are:
- The heat exchange according to the HVAC requirement
- The packaging limitations inside the engine bay, the installation constraints and the safety requirements.
The main goal of the Charge Air cooling system is to decrease the temperature of the pressurized air after the turbocharger.

- A low air temperature guarantees a good combustion inside the engine, lowering the pollutant emissions and the fuel consumption.
- Also, the system should assure the best trade-off between pressure drop and air volume from compressor outlet to the intake manifold to enable an optimal power supply.

The main constraints are:
- The heat exchange according to the vehicle thermal balance.
- The packaging limitations inside the engine bay, the installation constraints and the safety requirements.

Components of the charge air cooling system:
1. Charge Air Cooler (CAC)
2. Clamp
3. CAC inlet flexible hose
4. CAC outlet flexible hose
5. CAC outlet rigid hose
The main goal of the Oil cooling system is to limit the oil temperature, in order to:
- reduce the cracking risk
- optimize the engine/gearbox oil temperature during warmup
- reduce the engine frictions
- guarantee the maximum temperatures of the engine moving parts (cylinders, valvetrain, pistons...)

The main constraints are:
- The heat exchange according to the vehicle thermal balance
- The layout packaging inside the engine bay, the installation constraints and the safety requirements

Components of the oil cooling system:
1. Oil radiator
2. Radiator inlet pipe
3. Radiator outlet pipe
4. Bracket
Cooling System – Components Lay-out

- Expansion tank
- Filling pipe
- CAC outlet hose
- Degassing pipe
- Cabin heater outlet hose
- Cabin heater inlet hose
- Radiator degassing pipe
- Radiator outlet pipe
- Radiator inlet pipe
- CAC inlet pipe
- Fan & Shroud
- Charge Air Cooler
- A/C Condenser
- A/C Condenser
- Cooling Systems April 2015
The packaging study of the cooling system components shows the interactions with the engine bay:

- engine
- crash cross beam
- mounting/fixing
**Cooling System Components: Radiator**

Typical materials:
- Aluminum for the core
- Plastics for the tanks

The main parameters are:
- Core technology (mechanical or brazed)
- Size and weight
- Heat exchange per surface unit
- Air and coolant side pressure drop
- Structural resistance
Cooling System Components: Charge Air Cooler

Ambient air fins

Charge air fins

Box

Brick

Full Face
Inside a condenser, a **phase transition** occurs.

To improve the heat exchange, **several tubes are dedicated to the subcooling**, a process decreasing the temperature when the refrigerant is already in the liquid phase.

The exchanger core assembly is similar to the radiator one, but **tubes are extruded**.
As general trend, all the carmakers are introducing secondary loop circuits working at lower temperature than the engine cooling loop. This “cold” coolant circuit can be used to serve several auxiliaries, mainly the charge air cooler.

Performance:
- reduced air pressure drop & volume
- improved air cooling
- charge air thermal management (control of the air charge temperature)

Emissions:
- charge air thermal management (control of the air charge temperature / density)
- with LP EGR: possibility to avoid icing and condensation
- with LP EGR: EGR rate setpoint reached more quickly

Packaging/Integration
NVH improvements
From the Air Cooled to Water Cooled heat exchangers

**Charge Air Cooler ➔**
**Water Charge Air Cooler (WCAC)**
- WCAC integrated in Air Intake Manifold

**Condenser ➔**
**Water Condenser (WCND)**
- WCND is a Plate Heat Exchanger...
- Fins and louvers replaced by shaped plates
- ...sized to fit in engine bays

**Not integrated dual WCAC system for a V-engine**
Scenario

Approaches to heat rejection

Dual Level Cooling application
  • Alfa Romeo “Giulietta” 1750 QV
  • Fiat “Punto Evo” 1.3 DS MultiJet
  • Alfa Romeo “Mito” 1.4 MultiAir QV

Dual Level Cooling: experimental results
  • Engine cooling
  • A/C performances
  • Fuel consumption

Dual Level Cooling: packaging

Conclusions
Scenario

- The European Commission is promoting the reduction of the CO$_2$ and GreenHouse gases emissions of road transports (EC 443/2009).
- The target should be achieved with effective and sustainable solutions
- Also in NAFTA market, OEMs are interested in gain CO$_2$ credits using “off-cycle” technologies or improved air conditioning systems

The onboard thermal management system is becoming more and more relevant to assure the engine performance improvement minimizing the impact on the vehicle layout, cooling drag and cost.
Heat rejection: the standard approach

Each subsystem (i.e. water, A/C condenser, charge air cooler, transmission oil...) has its own cooling system bringing the fluid to be cooled on the front of the vehicle and then back to the engine bay.

This implies that:

• The front thermal module is not standard (it depends on engine and optional equipment)
  ➔ difficulties in optimizing the aerodynamics
• All the subsystem share the same cooling fan, activated on a single system need
  ➔ energy demand
• New subsystems (e.g. electronics, e-motor, batteries...) require additional heat exchangers
  ➔ negative impact on cooling drag
• Small accidents damage several heat exchangers
  ➔ fluids are dispersed into the environment
Heat rejection: **Smart Cooling System**

A secondary loop with coolant at lower temperature than engine coolant is used to locally cool all the subsystems.

This concept brings to:

- **Standardize** the front thermal module
- **Simplify** the front aerodynamics optimization
- **Reduce** the fan energy demand buffering the heat rejection needs
- **Reduce** the fluid to be cooled amount (e.g. charge air or A/C refrigerant)
- A **modular approach** simplifying the integration of additional systems (e.g. batteries, e-motor...)
- Achieve a **higher integration level** (e.g. the charge air cooler placed inside the air intake manifold)

We refer to this system as **“Smart Cooling”**
From baseline to *Smart Cooling System*

- A low temperature cooling loop allows to cool all the vehicle and subsystems locally (e.g. charge air cooler, condenser, oil cooler...)
- This simplifies the front thermal module that is constituted by only two exchangers, allowing to make the vehicle and engine subsystem more compact and more efficient.
- The low temperature loop acts as a sort of “buffer of cold” reducing the need of forced ventilation (front fan) and related power demands.
All the investigated vehicle application gave the following results:

**Engine cooling**
- Compliant with FCA requirements
- Better charge air cooler performances

**Air conditioning**
- Better A/C performances also in very hot climate
- A/C overconsumption reduction

**Fuel economy**
- Benefits thanks to the lower air intake temperature
- Benefits in “real life” (with A/C ON)

**Packaging**
- Simpler and more compact layout
### Smart Cooling System: Application on Alfa Romeo “Giulietta”

<table>
<thead>
<tr>
<th>Reference vehicle:</th>
<th>Alfa Romeo Giulietta 1750 QV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cylinders:</td>
<td>4</td>
</tr>
<tr>
<td>Max. Power:</td>
<td>173 kW @ 5500 rpm</td>
</tr>
<tr>
<td>Max. Torque:</td>
<td>340 Nm @ 1900 rpm</td>
</tr>
<tr>
<td>Displacement:</td>
<td>1742 cc</td>
</tr>
<tr>
<td>Max. speed:</td>
<td>242 km/h</td>
</tr>
<tr>
<td>Other features:</td>
<td>turbocharger, fuel direct injection, scavenging</td>
</tr>
</tbody>
</table>
The water cooled charge air cooler (WCAC) allows to cool the intake air **first with the engine coolant, than with the secondary loop**, reducing the thermal load on the low temperature loop (**cascade WCAC**).

- Water cooled condenser compliant with C/D segment requirements
• Standard refrigerant-to-air condenser is replaced by a water cooled condenser (WCDS)
• WCDS is a plate heat exchanger
• Subcooling is guaranteed by the intermediate heat exchanger (IHX)
• IHX is a coaxial tube minimizing the refrigerant pipes length
• IHX is usually used in order to improve the A/C performance
Smart Cooling System: Alfa Romeo “Giulietta” on board installation

High Temperature Radiator

High Temperature WCAC

IHX

Low Temperature WCAC

Low Temperature Radiator

Water Cooled A/C Condenser
**Smart Cooling System: Engine cooling results on Alfa Romeo “Giulietta”**

**Benefits of the WCAC system on the charge air temperature:**
- **Uphill:** - 8 K vs baseline
- **Max speed:** - 9 K vs baseline
- **Towing:** - 34 K vs baseline

Small vehicles too!
**Smart Cooling System:**
Fiat “Punto Evo” 1.3 DS Multijet Application

<table>
<thead>
<tr>
<th>Reference vehicle: Fiat “Punto Evo” 1.3 DS MultiJet</th>
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<tbody>
<tr>
<td>No. of cylinders: 4</td>
</tr>
<tr>
<td>Max. Power: 70 kW @ 4000 rpm</td>
</tr>
<tr>
<td>Max. Torque: 200 Nm @ 1500 rpm</td>
</tr>
<tr>
<td>Displacement: 1248 cc</td>
</tr>
<tr>
<td>Max. speed: 175 km/h</td>
</tr>
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</table>

- Front cooling module
- Charge air pipe
Smart Cooling System:
Fiat “Punto Evo” 1.3 DS Multijet Application
Smart Cooling System: A/C performances on “Punto Evo” application

**NEDC driving cycle***
- Ext. temperature: 28 °C
- A/C setpoint: 22 °C
- A/C mode: Fresh air

*procedure developed within the B-COOL EU project (2008) to assess the impact on the A/C fuel consumption

**“Real life” conditions:**
- Lower condensation pressure and PWM fan control bring to lower A/C overconsumption
- Shorter refrigerant lines and smaller condenser permit to reduce (up to -30%) the refrigerant charge

Fuel consumption with A/C ON: -5%
A/C overconsumption: -20%

Cool down conditions: Lower condensation pressure than baseline vehicle
Severe conditions: The system works efficiently also in very hot conditions

Ext. temp. 49 °C, R.H. 19%, 1100 W/m² sun load
Smart Cooling System: 
Alfa Romeo “Mito” 1.4 MultiAir 170 hp QV Application

Reference vehicle: Alfa Romeo “Mito” 1.4 MultiAir QV

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>No. of cylinders:</td>
<td>4</td>
</tr>
<tr>
<td>Max. Power:</td>
<td>125 kW @ 5500 rpm</td>
</tr>
<tr>
<td>Max. Torque:</td>
<td>250 Nm @ 2500 rpm</td>
</tr>
<tr>
<td>Displacement:</td>
<td>1368 cc</td>
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<tr>
<td>Max. speed:</td>
<td>220 km/h</td>
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The vehicle with air cooled charge air cooler (ACAC) has been compared with the one equipped with water cooled charge air cooler (WCAC)
SFTP-US06 driving cycle has been performed at two different ambient temperatures:
- 22 °C – ordinary temperature in EU
- 35 °C – hot temperature in EU

ACAC

Tair @ 35 °C: 52 °C
Tair @ 22 °C: 38 °C

WCAC

Tair @ 35 °C: 40 °C
Tair @ 22 °C: 29 °C
**Smart Cooling System:**
Fuel consumption expected benefits

<table>
<thead>
<tr>
<th>External temperature</th>
<th>Manifold temperature</th>
<th>WCAC vs. ACAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACAC</td>
<td>WCAC</td>
</tr>
<tr>
<td>22 °C</td>
<td>38 °C</td>
<td>29 °C</td>
</tr>
<tr>
<td>35 °C</td>
<td>52 °C</td>
<td>40 °C</td>
</tr>
</tbody>
</table>

\[
P_e = MEP \cdot V \cdot \frac{\text{rpm}}{60} \cdot \frac{2}{\tau} \quad P_e = C \cdot \omega
\]

\[
MEP = \frac{\lambda_v \cdot \rho_c}{\alpha} \cdot \frac{C_s}{C_a}
\]

\[
\rho_c = \rho_a \cdot \frac{p_c}{p_a} \cdot \frac{T_a}{T_c}
\]

\[
P_e \propto \frac{1}{T_c}
\]

Engine power and Torque decrease when air intake temperature \(T_c\) increases

**Homologation:**
- A WCAC system guarantees lower air intake temperature
- A specific calibration taking into account this opportunity promises fuel economy advantages

⇒ Expected fuel consumption benefit: -2% on SFTP-US06 cycle

“Real life” (with A/C ON)
- Fuel consumption -5% on NEDC cycle @ 28 °C, 50% r.h.
Smart Cooling System: Layout advantages

**Baseline**

- ECM package reduction: Up to -70 mm

**Smart Cooling**

**Important impacts on:**
- AZT insurance crash test
- Pedestrian crash box constraints
- Ramp angle

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The **Smart Cooling System** achieves:

- **Good engine cooling performances**
- **Better air intake cooling at high load conditions**
  - around -10 K vs. baseline vehicle
- **Improved air conditioning performance**
  - lower condensation pressure vs. baseline vehicle
  - A/C operation guaranteed also in severe ambient conditions
- **Fuel Economy improvement**
  - -2% expected with new engine calibration
  - real life: -5% with A/C ON
- **NVH improvement**
  - Lower A/C compressor noise
- **Benefits from layout and packaging**
  - reduced turbolag (> 1 s improvement)
  - A/C refrigerant charge reduction
  - thinner front thermal module (up to 70 mm on the “Giulietta” application)
    - Possible overhang reduction
    - Better insurance class
    - Better ramp angle
  - safer use of flammable refrigerant because the front module contains only the water/glycol mixture