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Electric Vehicle Cooling System. Comparison of Ethylene Glycol-Water and Fluorinert FC72

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Valeo Engine Cooling

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ABSTRACT

The cooling conditions of electric vehicles are completely different when compared to the cooling conditions of internal combustion engines for passenger cars, particularly the liquid flow rate and the coolant temperature. The electric vehicle has a flow rate of approximately 500 L/h at low coolant temperatures and the internal combustion engine may have a flow rate as high as 5 000 L/h at high coolant temperature. Without optimization the same size radiator for the heat dissipation for an internal combustion engine of 30 kW can only satisfy 3 kW of heat dissipation for the electric vehicle.

We have developed two solutions to cool the electric vehicle:

- A conventional cooling solution by using the same cooling liquid mixture, Ethylene Glycol-water 50-50%, that is to say, we adapted and optimized the cooling radiator for low flow rate and low coolant temperature.
- An evaporative cooling solution by using a new fluid, called, Fluorinert FC72. This new fluid has the boiling temperature of 56 °C at atmospheric pressure and is compatible with the electric vehicle specification.

INTRODUCTION

In order to reduce air pollution particularly in the big cities caused by the vehicle equipped with the internal combustion (IC) engine, the electric vehicle (EV) is considered as a better solution to day and in the future. These EV need a cooling system for the electric motor, the electronic converter and the batteries. Fortunately the total heat dissipation of these components is not so high. For the small cars in Europe this heat could be 3 to 5 kW depending on the type of battery. This heat represents 5 to 10 times less than the heat dissipation for the IC engine.

This paper presents the optimization of the cooling system for the EV by using the conventional cooling system and the nucleate boiling cooling system.

We have developed two solutions to cool the electric vehicle:

- A conventional cooling solution by using the same cooling liquid of mixture Ethylene Glycol-water 50-50%, that is to say, we adapted and optimized the cooling radiator for low flow rate and low coolant temperature.
- An evaporative cooling solution by using a new fluid, called, Fluorinert FC72. This new fluid has the boiling temperature of 56 °C at atmospheric pressure and is compatible with the electric vehicle specification.

A specific test bench adapted for low flow rate and low temperature has been built.

Two types of radiators and 5 different sizes have been adapted and tested on the test bench for each solution.

For the mechanically assembled radiator technology and with the conventional cooling solution, a 40% frontal area reduction has been shown.

For the evaporative cooling solution, a comparison of radiator heat dissipation has been conducted.

COOLING SPECIFICATION

There are two types of electric motor drive:

1. The brushless AC motor (synchronous or asynchronous) cooled generally by liquid.
2. The conventional DC motor (with brush) cooled generally by air.

The choice of the electric motor depends on the efficiency, the cost and the technology available. The second proposal is less expensive than the first one because it is existing technology.

To control these electric motors according to the real use conditions, an electronic unit has been designed using power chips with a heat dissipation of up to 1 kW or more. This electronic unit is cooled generally by liquid to a required temperature of 55 °C.

The following is an example of a specification for an electric vehicle cooling system having an brushless AC electric motor and an electronic unit (modulator, electric motor control, ...). The specifications are:

1. Heat flux to dissipate:
   - Electric motor of 2 kW,
   - Electronic unit of 1 kW.
2. Temperature:
   - Liquid at the inlet of electronic unit of 55 °C,
   - Ambient air: 40 °C
3. Electric water pump:
   - Coolant flow rate of 400 to 500 L/h,
   - Anticipated Life 15 000 h.
4. Test conditions:
   - Vehicle speed of 40 km/h at full load of motor,
   - Max. speed of 120 km/h at full load of motor.
5. Assuming the electrical consumption of the cooling system to be less than 100 watts.
6. Small package and low cost.

CONVENTIONAL COOLING SOLUTION

PROBLEMS AND NEEDS – Thermal performance of cooling radiator – The cooling conditions of EV are completely different when compared to the cooling conditions of IC engines for passenger cars, particularly the liquid flow rate and the coolant temperature. The EV has a flow rate of approximately 500 L/h at low coolant temperatures reaching only 60 °C and the IC engine may have a flow rate of 5 000 L/h at high coolant temperature reaching until 118 °C. Without optimization the same size radiator with the heat flux dissipation for IC engine of 30 kW can only satisfy 3 kW of heat dissipation for EV. Two main physical parameters are:

- coolant flow rate 500 L/h instead of 5000 L/h (10 times less)
- Delta T 20 °C instead of 80 °C (4 times less).

If we consider the radiator of a typical 30 kW internal combustion engine, it can will only transfer 3 kW because of the low flow rate and the small temperature differential. This difference can be mathematically expressed in the following classic heat transfer equation:

$$\mathbf{P = h.S.Delta\ T} \quad \text{(Eq. 1)}$$

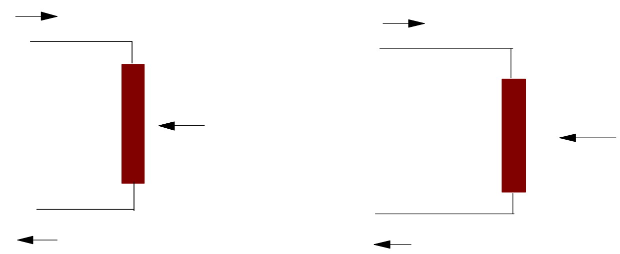

Figure 1. Heat performance of the same radiator for thermal vehicle and electric vehicle

At the same air speed Ua through the radiator, the h global heat exchange coefficient is a complex function of several parameters:

$$\mathbf{h = f(qv, Ua, Tc, Ta, fluids)} \quad \text{(Eq. 2)}$$

At the same value of Ua, Tc, Ta and with the same fluids, the coefficient of h depends only on qv the liquid flow rate per pass of radiator. In order to reduce the packaging and the cost of the radiator it is necessary to adapt the liquid flow rate per pass qv by increasing the number of passes of radiator (see figure 2).

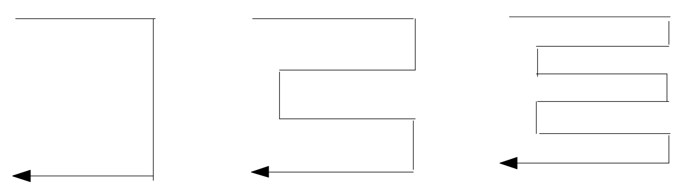

Figure 2. Number of coolant passes

Electric water pump – With a low flow rate of only 400 to 500 L/h, an electric water pump of only 15 to 20 Watts is adequate for this type of cooling system. The most important specification is the life of 15 000 h. These needs make it necessary to find a new type of electrical water pump which uses:

- A brushless DC electric motor,
- A new coupling between pump and the electric motor and the water pump gasket has to be suppressed.

COOLING CIRCUIT – There are different possibilities for the coolant circuit depending on the cooling of the battery, and whether the heater core for the passenger compartment is included. Figure 3 shows an example of coolant circuit for an electric vehicle. This circuit includes a 3 way thermostat for conserving the heat loss of the electric motor and an electronic unit to control the heat or control the preheat of the passenger compartment. This 3 way thermostat made in wax technology is installed at the outlet of cooling radiator. It's purpose is to control the inlet coolant temperature of the electronic unit. The battery park is cooled by air, separate from the coolant circuit.

This ethylene glycol circuit has a flow rate approximately of 400 to 500 L/h depending on the type of the cooling radiator. The liquid pressure drop of the circuit is about 0.15 bar. The electric consumption of the electric pump is approximately 15 W (see figure 8).

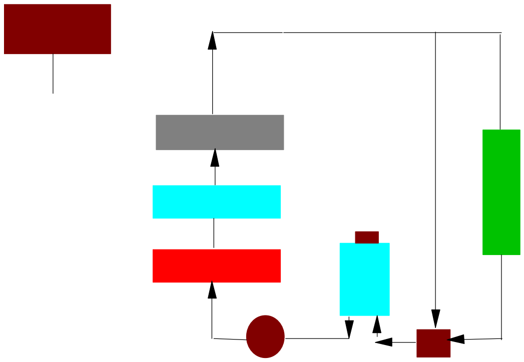

Figure 3. Coolant circuit of an electric vehicle, a conventional cooling system.

COOLING COMPONENTS – Cooling radiator – For the conventional cooling system and to reduce development cost we have used the same radiator technology available in production. Two types of technologies have been used: the mechanically assembled in aluminum and the aluminum brazed (see figure 4 below). The copper brazed radiator has been abandoned for this application because its high weight.

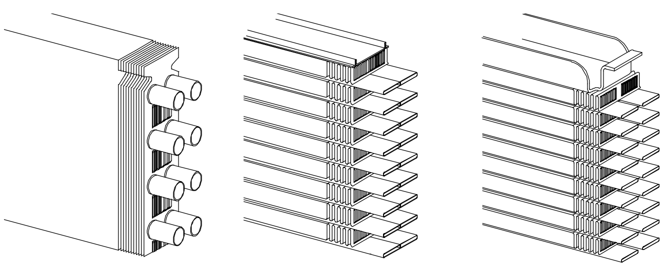

Figure 4. Different radiator technologies

For each radiator technology we have tried to reduce their size, weight and cost. According to the equation (1) and (2) the number of passes have been increased. The number of passes has a direct influence on the heat transfer performance. The maximum number of passes has been limited by six because the importance of pressure drop.

Four mechanically assembled radiators in aluminum with exactly the same geometric definition (same fin, tube, pitches, louvers, ...) except the frontal area, have been tested on the test bench and on the electric vehicle. Also one brazed aluminum radiator has been tested. Table 1 below shows the different radiator sizes.

The technical details of mechanical radiators (reference, A, B and C) are:

- 2 rows round tube of 7 mm diameter, 0.35 mm thickness, 18.5 mm frontal tube pitch,
- fins pitch of 1.15 mm and 0.1 mm thickness,
- core thickness of 23 mm.

The technical details of brazed radiator (D):

- one row plate tube of 1.75 x 16.5 mm, 0.27 mm thickness and 10.25 tube pitch,
- fins pitch of 1.25 mm and 0.1 mm thickness,
- core thickness of 18 mm.

Table 1. Geometric characteristic of the different radiators

Aluminum radiators	**Frontal dimension (w x h) in (m)**	**Frontal surface in (m²)**	**Differential Vs reference in (m²)**
Mechanical 2 passes (reference)	.43 x .377	0.162	
Mechanical 6 passes (A)	.31 x.377	0.117	-0.045 (-27.8%)
Mechanical 4 passes (B)	.31 x .377	0.117	-0.045 (-27.8%)
Mechanical 4 passes (C)	.31 x.31	0.096	-0.066 (-40.7%)
Brazed 2 passes (D)	.31 x .31	0.096	-0.066 (-40.7%)

Heat performance of the different radiators – The five radiators in table 1 have been calculated and tested in our test bench. The test conditions were as follows:

- coolant: mixture ethylene glycol-water 50%
- coolant flow rate = 400 L/h
- coolant radiator inlet temperature Tc = 60 °C
- air radiator inlet temperature Ta = 40 °C

The comparison of the heat performance is shown in the figure 5 below. The radiator (A) in six passes is better than the reference in spite of a frontal area reduction of 27.8%. The radiator (B) in four passes is almost the same as the reference in spite of the frontal area reduction of 27.8%. The radiator (C) in four passes is little less than the reference but it has 40.8% less front area. Finally radiator (D) in two passes is better than the reference even if it has 40.8% less frontal area as compared to the aluminum brazed technology.

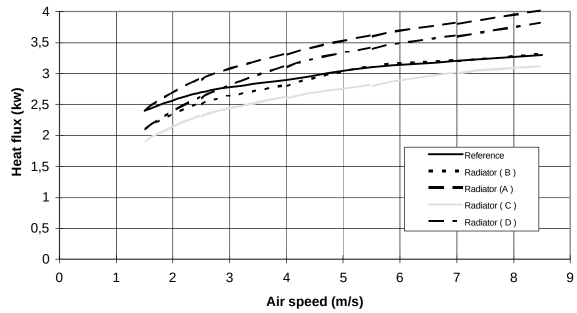

Figure 5. Heat performance of different radiators

Figure (6) shows an example of pressure loss of radiator (A) in six passes versus the coolant flow rate. This is the maximum value we could accept in order to reduce the electric consumption of electric water pump. The best compromise between heat performance and the pressure loss is a radiator with four passes (B) or (C).

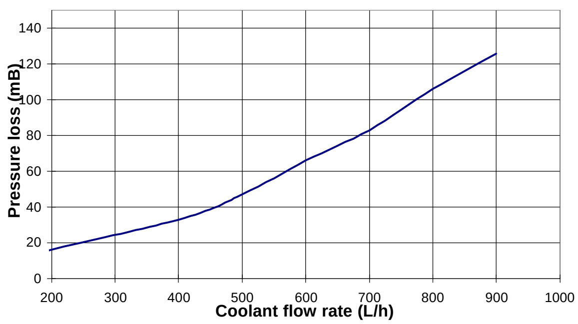

Figure 6. Pressure loss of mechanical radiator (A)

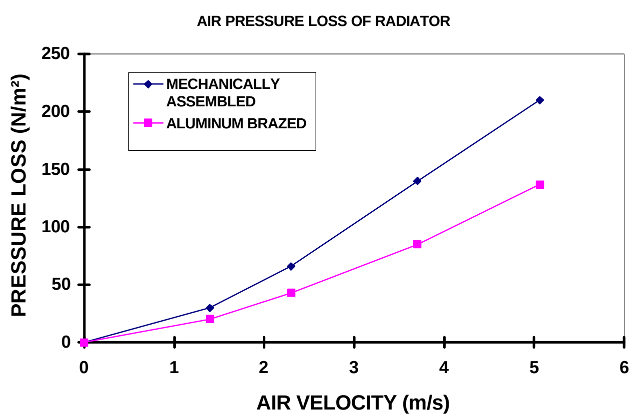

Figure 7. Air pressure drop of radiators

Electric water pump – Because of the EV specification particularly the 15 000 hours of anticipated life, a compact and a new generation of electric water pumps (figure 8) has been tested in the car. The main features of the pump are:

- Electric motor: brushless electronically commutated, with a current draw of 15 Watts at 12 Volts DC.
- Pump: a new magnetic coupling between pump and electric motor and without a gasket.

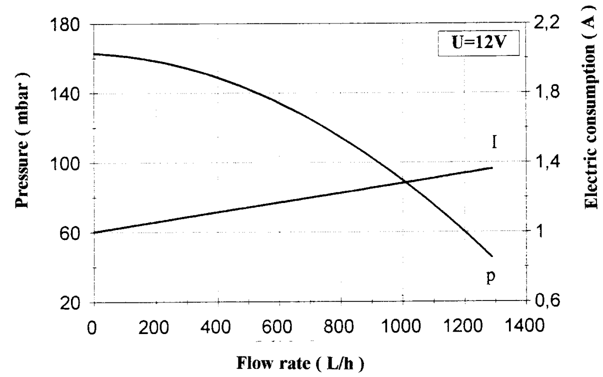

Figure 8. Hydraulic characteristic of electric pump

Electric fan – A electric fan module from a production vehicle has been installed in the EV. The airflow characteristics are shown in figure 8 The main characteristics are:

- Electric motor: 60 mm diameter and 80 Watts under 13 Volts DC.
- Fan: 7 blades and 290 mm diameter

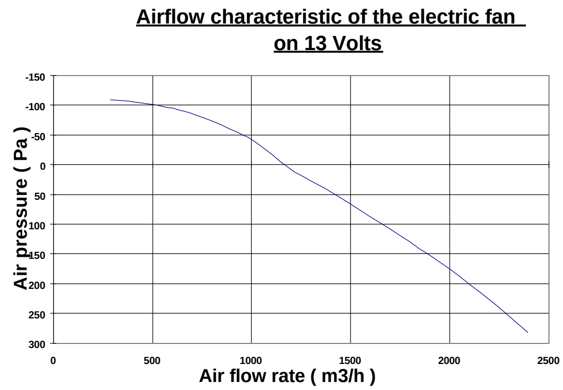

Figure 9. Airflow characteristics of electric fan

Thermostat – A conventional 3 way wax pellet actuated thermostat has been used in the coolant circuit (figure 3). This thermostat gives the ability to conserve the heat loss from the electric motor and the electronic unit to heat the passenger compartment. Of course this heat is not enough to reach the comfort temperature but it could be used to complement the other heating system. One kilowatt of heat loss has been measured during the test of the EV in our climatic wind tunnel.

Degassing, fill and expansion tank – The maximum temperature of coolant at the inlet of the radiator is approximately 65°C. The liquid expansion from -20 °C to 65 °C represents only 6% of the total volume. The tank volume of 0.8 liter is enough for the EV. Continuos circulation of coolant through this tank is recommended for fill and degassing. This tank has been made in plastic and has been equipped with a valve cap of 0.2 bar pressure.

COMPONENTS INTEGRATION – Several components can be integrated in the same unit. For example the electric water pump, the thermostat, the filler neck and degassing tank can be integrated into the water tank of radiator. This integration will not only reduce the cost of system, but also the manpower on the production line, plus the volume of coolant.

INNOVATIVE COOLING SOLUTION: EVAPORATIVE COOLING

Heat exchange by nucleate boiling is more interesting than by forced convection. The nucleate boiling engine cooling system has been studied for the internal combustion engine (see references). We have in the past used the same coolant (ethylene glycol-water) as the conventional cooling system. For the EV cooling system we have had to find a new fluid to satisfy the EV cooling specification. Among the fluids available in the market, there is a new fluid called « Fluorinert FC72 » that could be used for EV cooling applications. The design of electronics have been modified particularly the power chip. These electronic components can be immersed directly in the coolant. The nucleate boiling on the surface of power chip reduces their critical temperature particularly their junction temperature.

NEW FLUID CHARACTERISTICS (FLUORINERT FC72)

The main features of this fluid are:

- Boiling temperature at atmospheric pressure = 56 °C
- Solidification temperature = -90 °C
- Density at 25 °C = 1730 kg/m3
- Specific heat at 25 °C = 0.25 kcal/kg.°C
- Latent heat at the boiling point = 22 kcal/kg
- Thermal conductivity at 25 °C = 0.057 W/m°K
- Expansion coefficient = 0.0016 cm3/cm3 °C

According to the main features of this fluid we can use FC 72 as a new fluid for EV evaporative cooling system.

COOLING CIRCUIT – The coolant circuit could be exactly the same as the conventional coolant circuit (see figures 10 and 11) except the expansion tank. This tank has to be equipped with a membrane in order to contain the liquid coming from the electronic unit and electric motor when the cooling system works in the nucleate boiling conditions. The filling of coolant system is exactly the same as the conventional system. At the cold start of the EV this system works exactly the same as the conventional cooling system (Figure 10). At normal and during full load conditions of the EV this system works in the evaporative cooling mode (Figure 11). The radiator functions in one way like a conventional radiator and in another way like a condenser. The level of coolant in the expansion tank increases because there is a change of phase during the cooling of the electronic unit and the electric motor. For this circuit we need an electric pump of 30 to 40 W instead of 15 W for the conventional cooling system with ethylene glycol-water. This extra electric consumption is due to the pump's impeller design being optimized for the ethylene glycol-water fluid system and not to the FC72 fluid system.

The figures 12 and 13 show the detail of the special expansion tank. The main parts of this tank are:

- the total volume is approximately 1.5 liter: 0.5 liter for the liquid reserve and 1 liter for the expansion,
- a membrane made in rubber material,
- a valve cap of 0.1 bar of pressure,
- a liquid level detector.

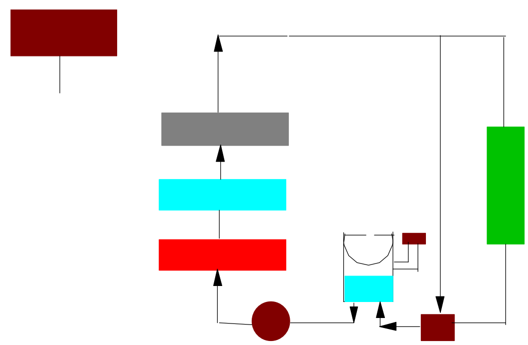

Figure 10. Coolant circuit for the Fluorinert FC72 at the cold start of EV.

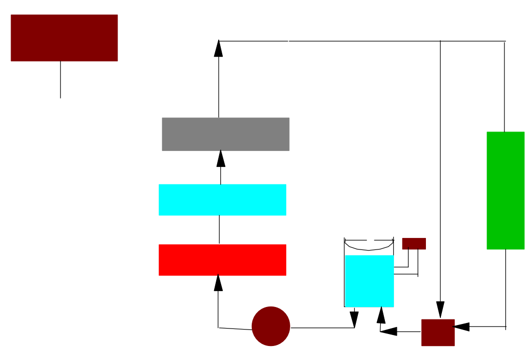

Figure 11. Coolant circuit for the Fluorinert FC72 at the normal and full load of EV.

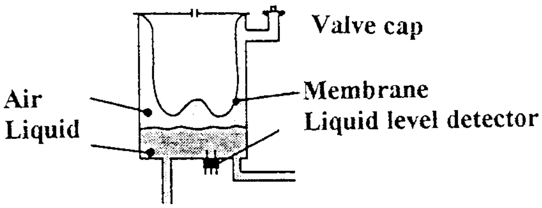

Figure 12. Expansion tank at the cold start and low load of EV

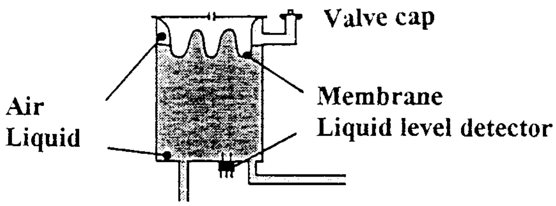

Figure 13. Expansion tank at normal and full load of EV

THERMAL PERFORMANCE TEST BENCH – Before testing in the vehicle this new system including the new coolant has been tested on the bench. A specific test bench has been built (see appendix 1). The test bench has two parts: the first one called the primary circuit simulates the EV and the second one called the secondary circuit simulates the external coolant circuit of EV. The coolant in the primary circuit is the mixture of ethylene glycol-water 50% and the coolant in the secondary circuit is Fluorinert FC72. The behavior and the heat performance of this system has been measured. The dynamic percentage of boiling Db can be defined as the ratio of the radiator heat flux in the boiling phase (Pt - Pl) to the total heat flux Pt exchanged included the evaporative part of the heat flow. The total heat flow Pt has been measured in the primary circuit of the plate type heat exchanger and the heat flow in the liquid phase Pl has been measured in the secondary circuit during the liquid phase in the radiator.

$$Pt = Pl + m \,.\, L \qquad \text{(Eq. 3)}$$

$$Db = m \,.L / Pt = 1 - Pl / Pt \qquad \text{(Eq. 4)}$$

$$Pl = qf \,.\, Cpf \,.\, (\, Tfi - Tfo \,) \qquad \text{(Eq. 5)}$$

$$Pt = qe \,.\, Cpe \,.\, (\, Tei - Teo \,) \qquad \text{(Eq. 6)}$$

TEST RESULTS: COMPARISON OF ETHYLENE GLYCOL-WATER AND FLUORINERT FC72

THERMAL PERFORMANCE – Three coolant flow rates 200, 350 and 500 L/h and two radiators (C and D) have been tested in different conditions of ambient air and air speed represented by the different voltage of the electric fan. The figure 7 shows the air pressure drop for these radiators. With the same electric fan the radiator (D) has a air velocity higher than the radiator (C) (see figure 14). For each flow rate of FC72 the heat performance has been compared to the conventional coolant ethylene glycol-water. Figures 15 to 20 show the heat flow comparison of two fluids for different coolant flow rates, dynamics boiling and radiators (C and D). According to these results we can say:

- The coolant FC72 with dynamic boiling rate about Db = 0.4 to 0.5 is equivalent to the ethylene glycol-water
- To get a better heat performance of radiator the coolant FC72 has to work with a dynamic boiling rate over than 0.6
- Using the FC72 as a coolant without nucleate boiling is not efficient
- The mass flow rate of FC72 evaporated in our test varied between 50 to 100 kg/h.
- Radiator (D) is better than (C).

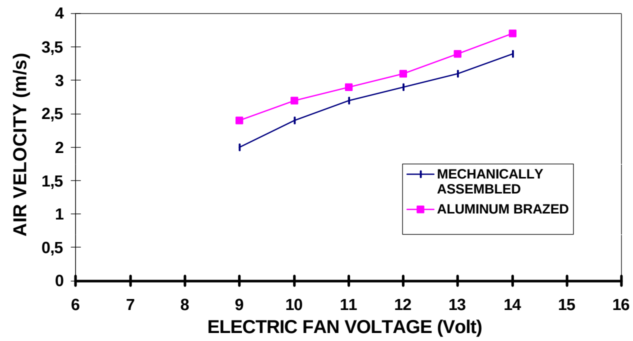

Figure 14. Air velocity across the radiators

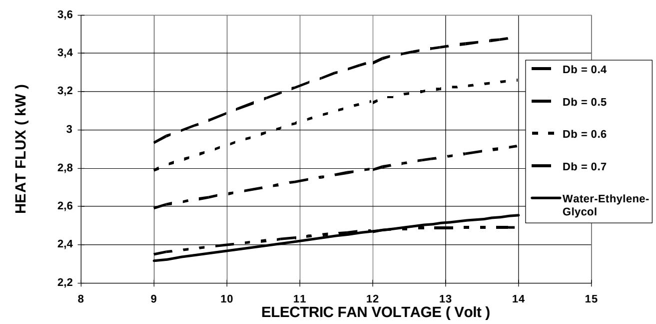

Figure 15. Heat flux comparison between ethylene glycol-water and FC72 for radiator (C) at 200 L/h flow rate and (Tc - Ta) = 40 °C

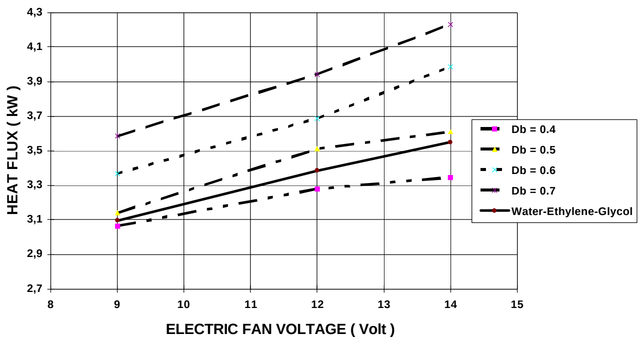

Figure 16. Heat flux comparison between ethylene glycol-water and FC72 for radiator (C) at 350 L/h flow rate and (Tc - Ta) = 40 °C

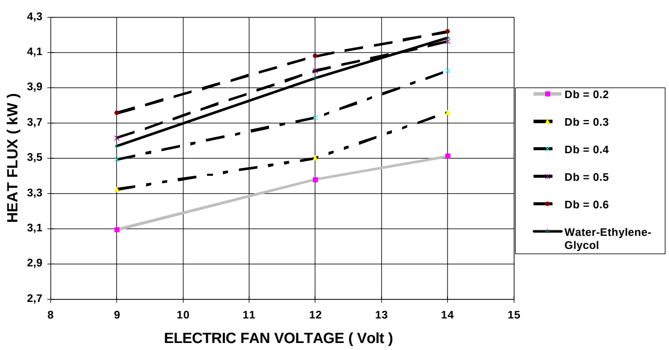

Figure 17. Heat flux comparison between ethylene glycol-water and FC72 for radiator (C) at 500 L/h flow rate and (Tc - Ta) = 40 °C

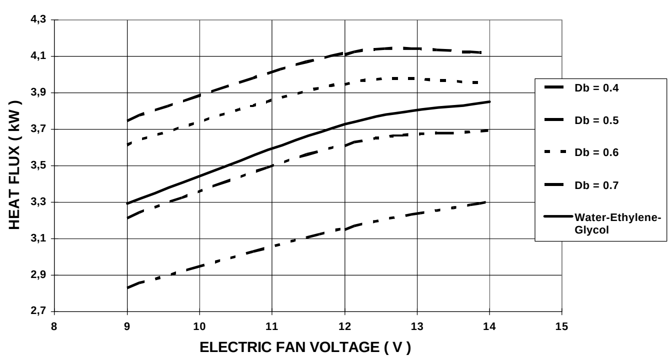

Figure 18. Heat flux comparison between ethylene glycol-water and FC72 for Radiator (D) at 200 L/h flow rate and (Tc - Ta) = 40 °C

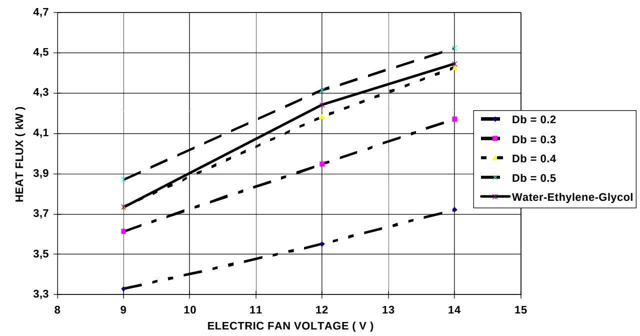

Figure 19. Heat flux comparison between ethylene glycol-water and FC72 for radiator (D) at 350 L/h flow rate and (Tc - Ta) = 40 °C.

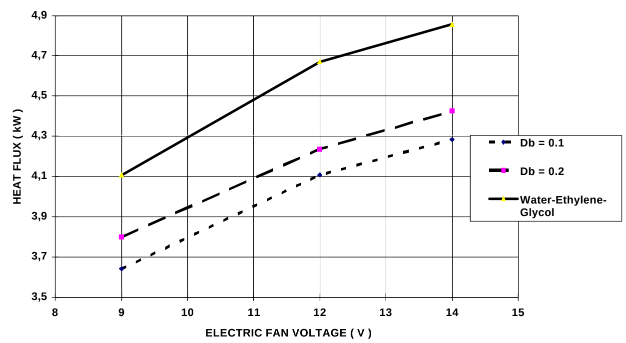

Figure 20. Heat flux comparison between ethylene glycol-water and FC72 for radiator (D) at 500 L/h flow rate and (Tc - Ta) = 40 °C.

RECOMMENDATION

The conventional cooling solution is interesting economically, which would then allow the use of the existing technology even for the cooling radiator of the electronic unit. All of the heat dissipation has to be evacuated by this radiator to the coolant. There is no direct contact between the electronic components and the coolant. This is an application of the cooling of IC engine and this is a proved solution.

The evaporative cooling solution can be interesting if the electronic units design changes completely compared to the conventional design. This allows the electronic components to be immerged in the boiling coolant. Normally the junction temperature of the power chips will be lower than the conventional design. This solution has to be tested particularly the durability test because it is an advanced and new solution.

CONCLUSION

According to the low level of EV market to day, it's more interesting to use the conventional cooling by ethylene glycol-water instead of the FC72. For the ethylene glycol solution the main improvement will come from the improvement of the level of temperature of coolant at the inlet of the electronic unit by the new design and the use of the high temperature of the electronic components. For example if the coolant temperature rises by 5 °C, the front size of cooling radiator will be reduced by 25%.

In the future, the evaporative cooling by using FC72 will be a very interesting solution allowing to cool directly by immersion the electronic components particularly the power chip.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Cpe: Specific heat of ethylene glycol-water
Cpf: Specific heat of fluorinert
Delta T: Tc - Ta
Db: Dynamic boiling rate = Pl/Pt
EV: Electric Vehicle
FC72: New coolant called « Fluorinert FC72 » a trade-mark of the « 3M » company
h: Global heat exchange of radiator
IC: Internal Combustion
L: Latent heat of Fluorinert
m: Mass flow rate evaporated of Fluorinert FC72
P: Heat flux of radiator
Pl: Heat flux in the liquid phase of radiator
Pt: Total heat flux of radiator
qe: Mass flow rate of ethylene glycol-water
qf: Mass flow rate of Fluorinert
qv: Coolant flow rate per pass
S: Front surface of radiator
Tc: Coolant temperature
Ta: Ambient temperature
Tfi: Fluorinert temperature at the inlet of radiator
Tfo: Fluorinert temperature at the outlet of radiator
Tei: Ethylene glycol-water temperature at the inlet of radiator
Teo: Ethylene glycol-water temperature at the outlet of radiator
Ua: Air frontal velocity of cooling radiator

APPENDIX 1

HEAT PERFORMANCE TEST BENCH