MagnetoCaloric Refrigeration for Efficient Electric Air Conditioning

Final Report Summary - ICE (MagnetoCaloric Refrigeration for Efficient Electric Air Conditioning)

Executive Summary:
The proposal is focused on the development of an Efficient air conditioning and heating system based on a MagnetoCaloric heat pumps and a new system architecture to fulfill the thermal comfort and energy requirements of Fully Electric Vehicles (FEVs).

The system is based on the Magneto Caloric refrigeration to realize innovative automotive heat pump able to assure the on board thermal comfort and on the integration of the on board thermal systems to improve the thermal management and the overall vehicle energy efficiency.

Besides the advances on Magneto Caloric Refrigeration technology, the other main innovations developed within in ICE are:

- A new electrical Heat Pump using the Magnetocaloric refrigeration principle. The unit will be based on the most advanced technologies and materials assuring very high efficiency levels.
- Innovative and efficient heat exchangers to assure the maximum benefit and efficiency from the magnetocaloric heat pump. A quite high heat exchange efficiency ($h > 30000$ W/m$^2$K) between a solid (the magnetic material) and a liquid coolant (e.g. water glycol) at high frequency (> 10 Hz) is required to
achieve the target efficiency and a compact system package.

- A heating and cooling distribution system able to deliver locally the thermal power and allowing to minimize the energy demand in agreement with the real thermal load and the number of occupants
- An integrated Thermal System providing the temperature control of all the on board systems and using the rejected heat as heat source for the magnetocaloric heat pump and the exceeding cooling power to keep the battery temperature below critical level.

At the end of the project, the main achieved results are:
- A complete, detailed and reliable numerical model of the system (including vehicle, thermal power distribution and magnetocaloric unit)
- The realization of a thermal power distribution system able to locally guarantee the thermal comfort, minimizing the energy demand. This system is based on the distribution of a water/glycol mixture as thermal vector
- The development of specific heat exchangers for the cooling and heating system
- The realization and onboard installation of the magnetocaloric unit.

The thermal power produced with the magnetocaloric unit is not in line with the expectations, being the refrigeration load required by a Light Commercial Truck still high for this tested prototype at reasonable cost and size. Some modifications are also required on secondary circuit like heat exchangers to fit with the new requirements of this technology. At mid-term, an optimization of the thermal loops, on the magnetocaloric materials and higher frequencies will increase the cooling capacity.

Project Context and Objectives:
The project is focused on the development of an Efficient air conditioning and heating system based on a MagnetoCaloric heat pumps and a new system architecture to fulfil the thermal comfort and energy requirements of Fully Electric Vehicles (FEVs).
A conventional vehicle uses the engine waste heat to assure the cabin heating and window de-icing and de-fogging requiring from 5 kW to 10 kW, while a mechanically driven (powered by the engine by means of a conveyor belt and pulley) vapour compression cycle guarantees the cabin cooling and dehumidification, absorbing up to 3 kW and generating up to 5 kW of cooling power.
On a FEV the amount of available heat is limited and at low temperature (e.g.2-3 kW @ 40 °C) and to operate a conventional automotive air conditioning (A/C) system a relevant amount of energy is required having a significant impact on vehicle autonomy.
For these reasons specific approach and solution should be identified and adopted to guarantee heating and air conditioning on a FEV.
Within the ICE a new air conditioning and heat pump system will be developed and prototyped based Magneto Caloric heat pump, on the redesign of the cabin air conditioning and of its control strategies to use is the most efficient way the available thermal power and adjusting the system operation depending on the number of cabin occupants assuring a good perceived comfort and the highest safety level (de fogging and de icing).
The Magneto Caloric heat pump has been widely investigated in the past years and within the project will be developed at industrial prototype level for automotive application realising a real new generation of heat pump equipment able to replace the vapour compression system not only in FEV but also in all the other vehicle applications. The system major features are
- high efficiency level (average COP > 5), twice as a conventional vapour compression cycle
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• compact packaging
• electrically driven
• reversible heat pump with high efficiency also at low ambient temperature (heat source)
• no refrigerant (no GHG emissions, no leakages, ...) and low working pressures (<2 bars),
• does not demand any specific training for the assemblers

The scenario of the FEV is moving rapidly towards their progressive diffusion with focus on urban area. In their framework two vehicle’s type will be required: very small passenger cars with two or three places and small buses (10 to 30 places) allowing to guarantee a green public transport mean or private shuttles (e.g. from parking to commercial centres).
In this context a small bus has been selected as a demonstrator vehicle this because:
• Represents the most challenging application for an air conditioning system due to the quite high heat cooling and heating requirement
• is commercially available and in use (real use data available)
• has a real exploitation potential in the short–medium term period

Objectives
Development of an innovative Efficient Air Conditioning System for Electric Vehicles based on Magneto caloric refrigeration and to a new thermal power distribution and microclimate control strategies.
Concept: the system is based on the Magneto Caloric refrigeration to realise innovative automotive heat pump able to assure the on board thermal comfort and on the integration of the on board thermal systems to improve the thermal management and the overall vehicle energy efficiency.
The project major contents are
- Efficient automotive electrical compact heat pump (COP > 5 in cooling mode) based on Magneto Caloric effect using high efficiency magnetic materials, smart design and specific micro channelled heat exchangers.
- Redesign of the vehicle thermal systems to distribute locally the thermal power and to regulate the batteries and electronic temperature also in very hot climate
- Microclimate control system based on thermal comfort and able to limit the thermal power generation only to the really required quantity and to adapt the system to the occupants’ number.
- Sustainable Cost thanks to the innovative technical solutions that will be adopted to develop the heat pump, to the thermal systems resize and their integration
The project results has been validated and demonstrated realising a prototype system on a small electrical bus that will undergo to a series of test, to verify the reliability and effectiveness of the system.
The project includes also a relevant dissemination and exploitation activity to promote the application of the ICE approach not only in the domain of Electrical Vehicles (passenger cars and buses) but in the whole road transport domain as standard air conditioning system.

Project Results:
CRF
The CRF Thermal System Department (TSD) activities in the ICE project are focused on the development of Systems and best practices to use in the most rational way the on board energy, on the development of high efficiency Mobile Air Conditioning (MAC) Systems and control strategies to minimize the fuel consumption associated to the MAC usage and to the analysis of the alternative refrigerant solution to be
consumption associated to the MAC usage and to the analysis of the alternative refrigerant solution to be compliant with the EU F-Gas directive. The activities also focus on the integration of the different vehicle thermal system with the object to reduce the total vehicle fuel consumption and environmental impact. The Research activities performed produces:

- The MCU integration on vehicle following the design performed by CRF
- The sizing of all the subsystems integrated on vehicle (pipes, pumps, fan etc...)
- A new energy saving control strategy for the A/C system based on MRT sensors

Cooltech

In the ICE project, cores competences of Cooltech has been focused on the Magneto Caloric Unit (MCU). All MCU sub systems have been designed and assembled by Cooltech. To implement the magneto caloric technology in a new application field, like automotive, it is necessary to learn and understand the major requirements to be able to provide the right product. In the same way, the users (OEM and car makers) need to understand that this alternative technology requires some changes on the secondary circuit. It is necessary to modify some components in order to have a seamless integration between the MCU and the HVAC system. ICE project is a baseline to define the automotive applications road map for Cooltech. In the same implementation process, Cooltech is involved in MagFreeG project (CIP- EIP Eco-innovation program) for a specific market application.

INSAS

INSAS accomplishes its main task: “System Concept" by creating the mathematical model of the magneto-caloric system (MCS) that is the core of the magnetocaloric heat pump. The conception of the mathematical model of the MCS is a topic of great interest and complexity as the scientific community all over the world agrees.

It is of great interest because magnetic refrigeration offers a solid-state alternative to standard gas-compression-based cooling that would simultaneously eliminate the need for harmful refrigerant gases and reduce energy requirements, and hence carbon dioxide emissions.

It is of a great complexity also because, as an interdisciplinary topic, includes a multi-scale representation of phenomena (micro-scale for magnetocaloric effect; mini-scale for fluid flow channels and macro-scale for the heat transfer) and multi-physics knowledge to put in equation as magnetism, heat transfers, fluid dynamics, materials science and mechanics, all of them coupled and time dependent.

Hence we have conceived the model and made the numerical simulations for:
- 3D magnetic filed architecture and behaviour
- the implementation of the magnetocaloric effect (MCE)
- time dependency of magneto-structural transitions of materials and alloys
- operating temperatures at required magnetic field
- heat transfer in fluid flow coupled with heat transfers in the solid materials;
- heat transfer between the regenerator, the fluid and the heat exchangers.
- cooling power, heating power and power consumption for different user scenarios.
- mechanical constrains for the design of magnetic cooling device, etc.

UPVLC

Within the ICE project, the main interest for UPVLC is to apply and transfer the knowledge on refrigeration and heating systems to the automotive industry. This research activity has materialized mainly in the ICE system concept and sizing as well as in the control system.
Furthermore, a key role as a University partner is to transfer the results both to the students and to the scientific community. As detailed in Deliverable 7.3 UPVLC has disseminated the results in the research community (e.g. events of the IIR working party on magnetic cooling, research journals), the refrigeration industry (CYTEF 2014 congress) and the automotive industry (European Automotive Congresses, ATA workshops on mobile air-conditioning and SAE World Congresses). In total, UPVLC has 2 contributions in research journals and 8 contributions in international congresses.

The developed models are valuable for the automotive industry since they can help better size the heating and cooling systems, not only for electric vehicles but also for vehicles with thermal engines. The models are completely dynamic and can also assist in the control of the heat pumps and the necessary auxiliaries (pumps and fans).

MAHLE

For Mahle Behr France Rouffach, the profit to integrate the ICE project was to start a research phase with new partners on a new technology requiring less power as the present system. MAHLE could share knowledge in heat exchanger technology. Reducing fuel consumption leads to a decrease of CO2 emission which is a usual request of our customer. Participation in the ICE Project enables us to be a major participant in this research.

MAHLE is interested in thermal management with new heat transfer fluid provided by the MCU. New engine with better efficiency, full electrical vehicle, or hybrid cars, take us to go in this direction. The Thermal management in the car has to be the same as today with less consumption.

The technology has to be improved, the heat exchangers developed and provided in the ICE project needs more input power provided by the MCU.

ALTRA

Scope of ICE project was to investigate and develop a possible solution for the last three mentioned auxiliaries systems.

According the very high expected COP on a magneto caloric device electric driven, mostly of the main target seems that could be achieved:

• Efficiency (COP)
• Functionality (Low noise/electric)
• Independent speed from engine revolutions or from other auxiliaries (electrically driven)
• Overnight functionality (LV supply)
• Extended start and stop enabler (LV supply)

While the biggest ICE challenge is to define how and verify if it is possible to achieve the last two target:

• Weight and volume comparable with conventional systems (low speed MCU operation seems to be the main constrain)
• Related TCO comparable with conventional auxiliaries (very new technology are generally expensive)

According the consortium activities main minimal specifications to reach the above mentioned technical targets were define in D 1.4.

If and when these specifications will be achieved, with acceptable MCU related TCO, MCU could be a solution for all CNHI EV HVAC system functionality, while for an extended usage on all the innovative vehicle full performance, similar to belt driven compressed gas solutions, have to be fulfilled.
vehicle full performance, similar to belt driven compressed gas solutions, have to be fulfilled.

According the first performed test it seems, at the state of the art, that the main constrain and limitation for this new technology is the ultralow speed operation that dramatically reduce cooling or heating power vs. weight and volume; for a massive introduction of this very new and promising technology in automotive application, a strong specific power improvement is mandatory as well an important cost reduction.

Potential Impact:

CRF
• System Concept: All the IVECO Daily MINIBUS could be equipped with this kind of architecture that is also suitable for secondary loop solution. In detail: all the systems designed for coolant heating and cooling could transfer the thermal power to the cabin with this kind of solution.
• Refrigeration System Components Design and Realization: The Magneto Caloric technology isn’t ready for the automotive market. The air coolers designed by MAHLE could be useful for any kind of further secondary loops applications.
• Refrigeration unit design and realization: The MCU is not ready for automotive application. The system needs significant improvements in order to become useful for automotive market.
• Control algorithms development: The MRT sensor feedback approach allows to reduce the number of sensors used by the A/C ECU. This approach improves also the cabin comfort reducing the energy power demands. The technology and the strategy are already available for the production.
• On board integration and validation: The MCU is not able to provide the right amount of thermal power. Actually the concept is not ready for automotive market.

Cooltech
• Refrigeration system components design and realization: Requirements are ready for customized and industrial solution with potential suppliers (actually not automotive application).

INSAS
• System Concept: Insas works on the MCU model. The model could be useful for further developments in research and in engineering teaching area in INSA of Strasbourg and also for academia partners.
Refrigeration system design: Specific and general advancement of knowledge for higher education and research. Magneto caloric technology use to meet the new incoming emission regulation. Publications.

UPVLC
• System Concept: UPVLC develops thermal model of the cabin and Overall model of the minibus. The models are physical-based and can be applied to other vehicles in the automotive industry.
• Refrigeration System and Unit Design: UPVLC performs the cabin thermal load analysis. The same modelling approach can help quantify the power requirements for any other application in mobile air-conditioning systems.
• Control System and on-board performance: Simulation of the on-board performance of the reference vapor-compression heat pump and the magnetocaloric unit. The model can be applied for other vehicles since the hydraulic components are the same. Given that the reference system is a vapor-compression heat pump, conventional air-conditioning systems can also be simulated with this tool.

MAHLE
• System Concept:
  - Design heat exchanger for the application. Current MCU power is too low to manage thermal needs in a

...
Design heat exchanger for the application. Current MCU power is too low to manage thermal needs in a car. With an improvement of the power from the MCU, the heat exchanger design must be validate.

- Concept of HVAC: Know how could be used for other application
- On Board integration and validation.

- Analysis of system result: MCU is not ready for automotive application, we need more power. The thermal power is too low to provide the caloric needs.

ALTRA

- System Concept: The system designed is potentially applicable to the Daily line up and Daily minibus.
- On board integration and validation: The MCU is not able to provide the right amount of thermal power. Actually the concept is not ready for automotive market. For a massive introduction of this very new and promising technology in automotive application, a strong specific power improvement is mandatory as well an important cost reduction. At the state of the art MCU is not ready for automotive application, more power is required.

List of Websites:

http://www.ice-project.webs.upv.es/

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