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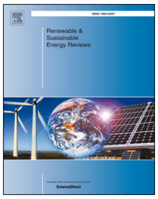

The solutions to electric vehicle air conditioning systems: A review

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ABSTRACT

The air conditioning (AC) system provides cool, heating and ventilation in the cabin of the electric vehicles (EVs). It is necessary to control the interior thermal environments of the vehicle and ensure safety in visibility. Because AC systems are electrically powered, vehicle range is reduced drastically when the AC system is operating. EVs present a particular challenge to the development of more efficient AC systems for automotive applications. In this paper, the state of the art for various AC system solutions to EVs was critically reviewed. The investigations of alternative solutions are continuing along many parallel routes, e.g. vapor compression refrigeration-dedicated heater AC systems, reversible vapor compression heat pump AC systems, non-vapor compression AC systems and integrated thermal management system combined AC and battery pack. The characteristics and particular applications of each solution have been extensively discussed. Finally, a comparison listing the various pros and cons of the different available solutions was presented.

1. Introduction

Recently, electric vehicles (EVs) have earned considerable attention as a promising solution to global greenhouse gas emissions [1–3]. There is a great potential to substitute EVs for internal combustion engine vehicles (ICEVs) in the coming years. The EVs include hybrid electric vehicles (HEVs, including full hybrid, mild hybrid, plug-in hybrid), pure electric vehicles (PEVs) and fuel cell electric vehicle (FCEVs). EVs discharge little air pollutants at the place where they are operated. They also typically generate less noise pollution than the ICEVs. From the energy aspect, electricity as an energy vector for vehicle propulsion offers the feasibility to replace oil with a diversity of elementary energy sources. This could ensure security of energy supply and a wide use of renewable energy sources. Furthermore, EVs will be more intelligent to improve traffic safety and road utilization, and will have a great impact on energy, environment and transportation as well as hi-tech promotion, new industry creation and economic development [4].

The air temperature and humidity in the cabin are the two crucial factors of the comfort perceived by passengers [5]. How comfortable the cabin environment is to the driver is also an influential factor of driving safety [6–8]. The AC system provides cool, heating and ventilation to the cabin of the EVs, which is necessary to control the interior thermal environments (including temperature, relative humidity and air velocity) of the vehicle and ensure safety in visibility (defogging and deicing) [9]. Besides, the batteries of the EVs are worked within a limited temperature window. Thermal management of the battery pack is necessary to prevent premature aging and subsequent loss of capacity. The AC system is the only heat sink/source that allows a sufficient cooling/heating at high/low ambient temperatures. Also, the integrated thermal management system combined interior environment and battery pack is a great challenge for the AC system. Therefore, it is essential to find an innovative AC solution to the EVs [10].

The AC systems present the highest power consumption of the auxiliary components of the EVs [11]. The exclusive available energy for EVs propulsion is the electricity stored in the battery pack, so any additional power consumption implies a reduction of the driving range. Generally, AC systems cause about 30–40% average decrease in driving range depending on the size of AC and the driving cycle for EVs [12,13]. Pino et al. [14] numerically found that an increment of hydrogen consumption is between 3% and 12.1% when the AC system is operated in a FCEV. The driving range must be improved to boost EVs use by reducing battery power consumption, which requires the development of a highly efficient AC system. Thus, the AC system is crucial to the development of EVs.

The AC system solutions as well as integrated thermal management systems combined AC and battery pack to EVs are critically reviewed in this paper. The review is divided into four main parts that each have sub-sections and covers all of the main AC system solutions to EVs presented in the literature. In the first part, AC systems of conventional vehicles are described. In the second part, a review of AC systems based on vapor compression cycle of EVs is presented. This section is divided into three subsections, i.e. vapor compression refrigeration - dedicated

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Nomenclature

AC	Air conditioning
AMRR	Active magnetic regenerator refrigerator
BV	Bypass valve
COP	Coefficients of performance
DH	Dedicated heater
DB	Dry bulb temperature
EH	Electric heating
EVs	Electric vehicles
ERV	Energy recovery ventilator
ECOP	Equivalent COP
EVI	Economized vapor injection
EXVs	Expansion valves
4wV	Four-way valve
FCEVs	Fuel cell electric vehicle
FH	Fuel Heating
GWP	Global warming potential
HX	Heat exchanger
HP	Heat pump
HEVs	Hybrid electric vehicles
ITM	Integrated thermal management
ICEVs	Internal combustion engine vehicles
ME	Magnetic effect
ODP	Ozone depletion potential
PCM	Phase change material
PHEVs	Plug-in hybrid electric vehicles
PEVs	Pure electric vehicles
PTC	Positive temperature coefficient
RV	Refrigerant valve
TES	Thermal Energy storage
TE	Thermoelectric
3wV	Three-way valve
TEWI	Total equivalent warming impact
VC	Vapor compression
WB	Wet bulb temperature
WHD	Waste heat driven

heater (VCR-DH) systems, reversible vapor compression heat pump (VC-HP) systems and AC systems using low GWP refrigerants or natural refrigerant. In the third part, the non-vapor compression AC systems, such as thermal energy storage (TES) systems, AC systems using magnetic (ME) or thermoelectric effect (TE), waste heat driven (WHD) systems and so on, are analyzed. In the fourth part, a review focused on integrated thermal management (ITM) system combined AC and battery pack is presented. Finally, a comparison listing the various pros and cons of the different available solutions is presented, suggesting the inherent mechanisms of the AC systems and the information that is needed for proper design of AC systems.

2. AC systems of conventional vehicles

The vapor compression system is dominant in automobile AC systems [15]. **In** Fig. 1, a typical AC system of the conventional ICEVs is outlined. The AC systems usually cool the air in the cabin using the engine driving power to directly drive the A/C compressor. Since the compressor is a belt-driven device coupled to the engine crank shaft, its cycling rate is directly related to the vehicle speed. The losses of the AC system increase with increased vehicle speed, and thus with high compressor cycling. In conventional vehicles, it is well known that around 30 percent of the energy in the fuel burned is converted to mechanical energy. The left significant waste heat is either exhausted out of the tail pipe or moved to the radiator by coolant tubes where it is then dumped to the atmosphere. Thus the AC system warms up the air in the cabin using the waste heat radiated from the engine without the need to burn any additional fuel. The coolant is pumped around the engine block by means of a mechanical or electrical pump, collecting waste heat which is then sent through a heat exchanger (HX), called a heater core. Air is heated as it passes through the heater core and is distributed to the cabin air vents. This process keeps the engine temperature down and heats the cabin up which is ideal in low temperature environments. However in scenarios where the cabin does not require heat (warm ambient conditions), the coolant is diverted to a radiator in the front of the vehicle in order to dissipate heat to the environment and prevent over-heating. This type of vehicle architecture provides more than enough heat for cold weather conditions. However, some ICEVs and HEVs have become so efficient that additional auxiliary electrical heaters are installed to assist with vehicle heating in extremely cold conditions.

In view of convenient substitution, low cost and serviceability, the automobile industry yearns for a direct transition from conventional ICEVs to EVs. Thus the vapor compression system is a preferred alternative for AC systems of EVs. However, the compressor used in the AC system for EVs is an electricity-driven compressor, and thus the speed of electricity-driven compressor can be adjusted independently of the vehicle speed to meet the cooling and heating loads. Also, different heating schemes and sources in order to heat their vehicle cabin are required since the waste heat gained from the motors and battery is far less than the demand of heating for EVs due to their higher efficiency.

3. AC systems based on vapor compression (VC) cycle

3.1. Vapor compression refrigeration - Dedicated heater (VCR-DH) AC systems

This concept is interesting owing to the few variations compared with the conventional ICEVs. The modifications are that the compressor is driven electrically instead of mechanically and heating is achieved by electric or fuel-operated heater instead of hot coolant heater core [9].

The heaters can be divided into two types: direct and indirect heating principles. Direct heating signifies to heat up directly the air to condition the cabin. Indirect heating signifies to heat up over a secondary working fluid (e.g. water, coolant, oil etc.), which transfers the heat to the air and further to the cabin. The combination of different heating concepts is applicable to gain the most comfortable heating behavior of the passenger cabin.

3.1.1. Vapor compression refrigeration - Electric heating (VCR-EH) systems

The electric heaters are commercially available and could thus be an economical feasible option. It requires only one fuel to thoroughly operate the EVs. It is also advantageous for the EVs owing to the characteristics of low-weight, small space, swift response, and environment protection. This concept need not route the high-voltage

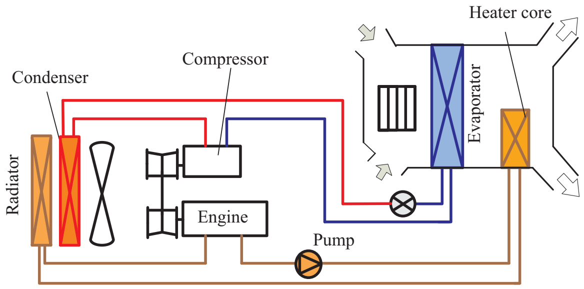

Fig. 1. Typical AC system of the conventional ICEVs.