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Research Paper

Reversible heat pump HVAC system with regenerative heat exchanger for electric vehicles: Analysis of its impact on driving range

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HIGHLIGHTS

- A reversible heat pump air-conditioning system for electric vehicles is modeled.
- The effect of a regenerative heat exchanger is analyzed.
- Impact on driving range of HVAC loads, depending on location and season, is assessed.
- In Italy energy consumption can be as high as 38% of energy required for traction.
- The regenerative heat exchanger lessens the driving range reduction between 2 and 6%.

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ABSTRACT

Besides providing energy for traction, an electric vehicle battery operates on-board auxiliary systems, among which air conditioning features the highest energy consumption and reduces significantly the driving range. Furthermore, electric vehicles heating needs are typically fulfilled through high-consuming resistors. In this respect, heat pumps promise higher energy efficiency and an increase in all-electric range.

This paper analyses a reversible heat pump HVAC system equipped with a regenerative heat exchanger for pre-conditioning and hygrometric comfort improvement, and assesses air-conditioning energy loads and their impact on driving range for a vehicle performing daily commutes in different Italian cities. The dynamic model was set up in a Modelica framework. The overall system integrates component models calibrated against experimental data.

Results confirm that air conditioning, consuming up to 32% of the energy required for traction on a daily commute, highly impacts on the all-electric range, which can decrease to 72 km from a base value of 94 km. In heating mode, replacing a resistor with a heat pump reduces consumption by 17–52% depending on geographical context, which proves to be highly effective in particularly demanding summer conditions lessening the driving range decrease up to 6%.

1. Introduction

Battery electric vehicles (EVs) are progressively emerging in the light-duty passenger market, featuring a stock of 740 thousands in 2015, 60 times more than in 2010 [1]. Remarkable efforts, under the joint support of governments and industry, have been directed towards EVs as a promising alternative to carbon intensive, polluting and oil dependent road transport. However, despite offering low environmental impact and noise pollution along with life-cycle cost savings and enhanced drivability, EVs large-scale adoption and diffusion is still limited by comparatively higher purchase costs and driving range restrictions [2–4].

On-board rechargeable batteries are the sole EVs power source, thus providing for both traction energy needs and auxiliary system requirements. Vehicle heating, ventilation and air-conditioning system (HVAC) features the highest energy consumption among all the accessory loads [5] and therefore may consume a substantial amount of the total energy stored. This results in a driving range reduction, further worsened by energy storage devices limited capacity. Previous studies have modeled the device-level function and energy consumption of HVAC systems as well as the impact on the vehicle driving range [6–11]. All these studies revealed a significant impact on driving range; depending on air conditioner size, driving cycle and external weather conditions,

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the driving range decrease has been estimated in a range between 16% and 36% [6]. This calls for maximizing the efficiency of climate control systems to reduce energy consumption in both cooling and heating modes. Advanced glazing, recirculated air and cabin pre-conditioning have already been regarded as means of improving EVs conventional thermal control systems thus mitigating driving range reductions [6,12,13].

Moreover, thermal comfort loads feature significant variations depending on external climate conditions. Thus, as the geographical context and time of day change, so does the air conditioning load and the driving range in turn. Although of key importance in affecting electric vehicles performance, previous studies estimated the air conditioning load disregarding hourly changes in weather variables, using for instance a daily-mean radiant temperature to describe a summer day for a given city [6] or two different temperatures for summer and winter conditions [14]. Only few studies assessed the dynamic variation of thermal loads as a function of location, season and time of the day to ultimately quantify the effect of geographical and temporal differences on the all-electric range [13,15].

In particular, Kambly & Bradley have carried out a research work aiming to quantitatively assess the extent to which the EV range is affected by cabin comfort conditioning loads and therefore by external weather conditions [13,15]. EV range is shown to vary widely across the geography of the US throughout the time of day from a minimum of 95 km (for midday trips in hot and sunny ambient conditions) to a maximum of 128 km (for early morning trips in moderate ambient conditions). Commutes performed during the middle portion of the day, where temperatures and solar radiation are at their maximum values, feature the highest EV range reduction. Nevertheless, in this study the heating needs are fulfilled by means of a relatively inefficient resistance heater.

This solution is still typically adopted in EVs because of the lack of engine waste heat to recycle [16,17]. In particular, positive temperature coefficient (PTC) heaters are widely used by the industry in EV cabin heating in place of the engine coolant heater core of conventional vehicles [18–21]; however, these systems present limitations related to high costs and energy consumption [22].

However, in EVs climate control systems, heat pumps seem a more sustainable and efficient solution, so that heat pump (HP) systems are currently stepping into EVs market [23–25] as a reasonable solution. Several studies have been published demonstrating the feasibility of a reversible heat pump system for electric vehicle air conditioning, pointing to Coefficients of Performance (COP) slightly higher than 2 in heating mode and to electric driving range improvement over the use of PTC by 5–10% at low and mid ambient temperatures [26–33]. However, the dynamic performance of reversible heat pump systems with reference to hourly distributions of climate variables, geographical location and season has not been thoroughly evaluated in the literature, except for Neubauer & Wood [32] who compared, among other things, heat pump systems to conventional PTC heaters.

In this paper, the impact of geographical context, season and time of day on cabin air conditioning energy needs is estimated for an electric vehicle commuting in different Italian cities. The HVAC system is based on a reversible heat pump, also equipped with a regenerative heat exchanger to further improve efficiency and hygrometric conditions both in cooling and heating operating modes. The performance of the proposed heat pump system is compared to that of a conventional PTC resistor to assess the

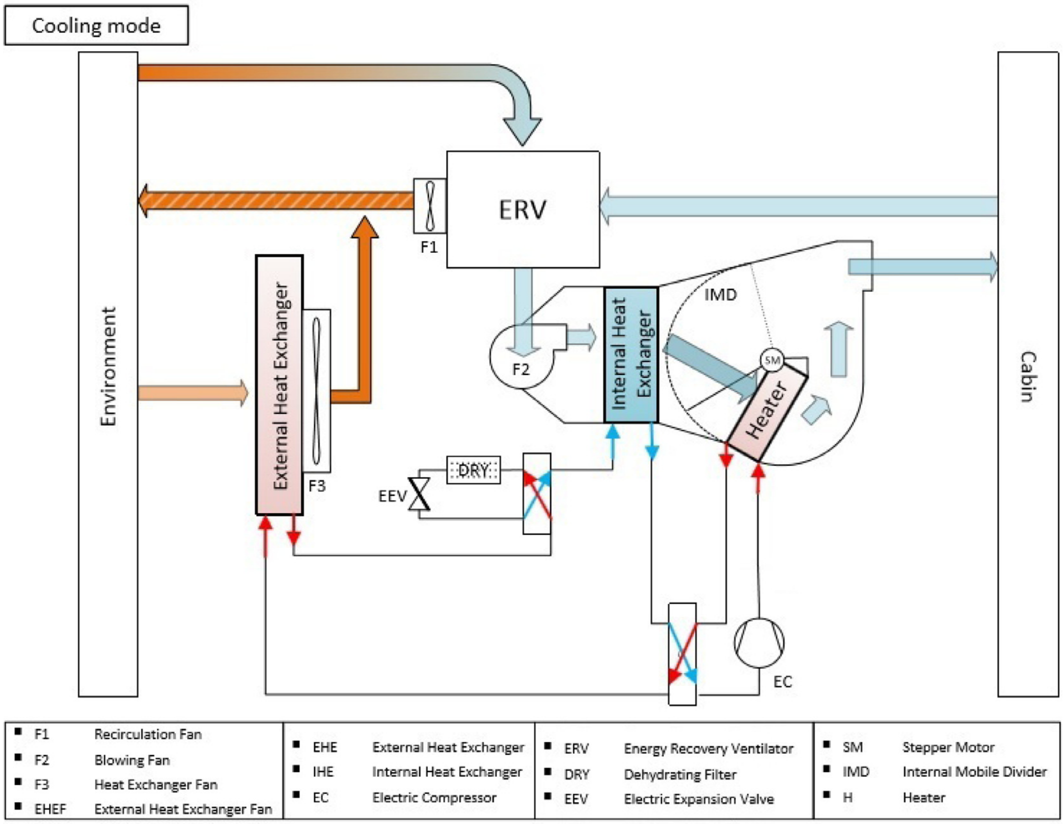

Fig. 1. A/C operation. In cooling mode, the system operates on a refrigeration cycle. Warm air is shown entering the ERV exchanging heat first with air flowing from the cabin and then with the refrigerant by means of internal heat exchangers. With reference to the working fluid side, red and blue arrows show respectively high temperature/high pressure and low temperature/low pressure refrigerant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)