DOI: 10.2428/ecea.2020.27(1-2)4 ECOL CHEM ENG A. 2020;27(1-2)

Jan GRYGIERZEC[1*] and Sebastian WERLE[2]

CRITICAL ANALYSIS OF THE FUNCTIONING OF TEST BENCHES DEDICATED TO TESTING HEAT PUMPS IN ELECTRIC VEHICLES

KRYTYCZNA ANALIZA FUNKCJONOWANIA STANOWISK BADAWCZYCH PRZEZNACZONYCH DO BADANIA POMP CIEPŁA W POJAZDACH ELEKTRYCZNYCH

Abstract: Changes in the automotive industry to bring more electric and hybrid cars to market have a significant impact on the type of heating and cooling systems for vehicles. The work done so far in this area shows the considerable impact of these systems on vehicle coverage. This is due, among other things, to the fact that air conditioning systems in electric and hybrid cars have additional tasks, such as keeping the battery temperature at the right temperature. Studies also show that heating and cooling systems based on heat pump systems have the highest efficiency. The development of such systems, however, depends on a properly planned test phase under widely varying boundary conditions. Such research allows to limit the negative impact of heating and cooling systems on the range of electric cars under real operating conditions and can contribute significantly to the popularity of electric vehicles. The aim of this work is to develop a test bench concept for testing heat pumps used in electric vehicles. The impact of the assumed boundary conditions on individual system components is presented. On the basis of two examples of test stands, a critical assessment of the effectiveness of the applied methodology was made. Differences in individual systems were indicated, and the own concept of the test bench for testing heat pumps for variable input parameters was presented.

Keywords: heat pump, air conditioning, test bench, electric vehicle

Introduction

Climate change has a significant impact on the vehicle market worldwide. Car manufacturers are reducing the number of vehicles powered by combustion engine bruises by introducing alternative powertrain systems in these places. With the development of social economy and improvement of environmental requirements,

---

[1] Faculty of Energy and Environmental Engineering, Konarskiego 18, 44-100 Gliwice, Poland, email: grygierzec.jan@gmail.com

[2] Department of Thermal Technology, Konarskiego 22, 44-100 Gliwice, Poland, email: sebastian.werle@polsl.pl

* Corresponding author: grygierzec.jan@gmail.com

battery electric vehicles (BEV) are considered as a potential substitute for conventional internal combustion engine automobile [1, 2]. Currently, it is assumed that electric vehicles are a solution for sustainable transport for passenger vehicles and light transport vehicles. It is estimated that the increasing number of such vehicles will have a significant impact on pollution levels in large urban agglomerations. However, due to current power generation technologies, it is often the case that emissions are transferred to power generation locations. It is a mix that can indirectly lead to a high level of total CO_2 emission, caused by the electric energy production process required for the operation/use of an electric vehicle [3].

For this reason, the critical aspect of electric vehicles is the use of energy, which results directly in the range of one battery charge. An additional problem of electric vehicles is heating the cabin, currently used solutions are based on heat pumps. These two aspects contribute to the complexity of heat pump systems in electric vehicles and differences in measurement results during validation under laboratory conditions and real measurements during driving. An additional problem of electric vehicles is heating the cabin, currently used solutions are based on heat pumps. These two aspects contribute to the complexity of heat pump systems in electric vehicles and differences in measurement results during validation under laboratory conditions and actual measurements while driving. The design stage of appropriate heat pump systems is carried out by adequately selected parameters together with the verification of the system functionality. However, electric vehicles have additional functionalities based on heat pumps. Systems of this type maintain appropriate temperature of battery operation, take heat from the inverter, electric motor and other systems. A heat pump with such complex functions in the design, validation and testing stages of an electric vehicle can be subjected to various conditions that often differ from the extreme saturation caused when driving an electric vehicle. Complicated functionality of heat pump systems should significantly affect the validation process. The article presents test stands for testing heat pumps in electric vehicles together with the advantages and disadvantages of each solution.

Electric vehicle

Climate change and related international policy objectives influence solutions to reduce oil consumption. Such solutions are often based on electric motors based on intelligent control. The most apparent direction of development is the transformation of global transport into electric vehicles. This transformation will affect the entire supply chain, forcing changes in technology, materials and implementation approaches. Governments around the world intend to adopt electric vehicles to build a sustainable transportation system [4] and have set goals to promote electric vehicle acceptance [5] however, the change with the use of hybrid vehicles with different technological variants. Manufacturers introduce different types of solutions like are shown in Table 1, by applying electric motors in different configurations. These types of activities allow for the development of electrification and the transformation of combustion vehicle technology into a challenge-based electric vehicle technology.

Table 1

Types of vehicle drive trains

Type	Combustion engine/emission	External recharge	Comments
Fuel vehicle	YES	NO	Without electric engine
Non-plug-in hybrid	YES	NO	—
Parallel plug-in hybrid [PHEV]	YES	YES	—
Series plug-in hybrid [PHEV]	YES	YES	Combustion engine for charge purpose only
Battery electric [BEV]	NO	YES	No tail pipe emission

The way to full electrification is connected with the development of technologies separately for each type of vehicles with an electric motor. All innovations are expected in space:

- battery management [6],
- power supply [7],
- charging infrastructure [8].

A key element in battery management is also maintaining the right temperature. New solutions must also meet the assumptions and standards known from current vehicles. Another important aspect is the awareness of changes taking place at manufacturers of components for the automotive industry. All components must be based on new assumptions to consistently increase the chances for a greater range of electric vehicles while maintaining the safety and comfort of travellers. The range of the EV vehicle is generally related to elements divided into classes of influencing factors: vehicle construction, driver, external environment. Studies on this subject show that each of these classes depends on the variability of direct or indirect parameters [9–12]. Some of these parameters depend on the vehicle, battery, gearbox, weight, amount of space in the vehicle. This type of parameters are invariable, however, some of the parameters that affect the range depending on the battery charge status, driver's behaviour[13], traffic flow [14] of the battery management system, weather conditions [15].

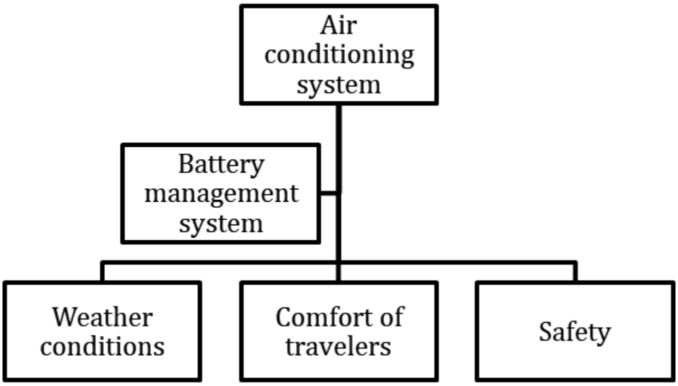

Fig. 1. Summary of factors influencing the efficiency of the cooling system in an electric vehicle

Heat pump

The air-conditioning system in electric vehicles in more and more cases is responsible not only for heating and cooling but also for keeping the battery at the right temperature or for heat recovery from the inverter. However, the basic task of such aźsystem is to maintain temperature and humidity in the passenger cabin at appropriate levels in all climatic conditions. It maintains proper air recirculation and prevents stagnation of used air, with increased levels of CO_2 from passengers as well as volatile organic compounds and other particulate pollutants. This system, based on the operation of a heat pump, significantly increases energy consumption. AC can be considered as the main accessory which extracts the largest quantity of power when it is operating [16–18]. Heat pump systems appear in electric vehicles as a solution that uses the same thermodynamic principle; however, due to the fast-growing automotive market with different technologies and additional solutions. The number of vehicles and configurations, together with the clear competitiveness on international markets, introduce various types of facilities and fast-track solutions. The positive temperature coefficient heater (PTC) for air conditioning of electric vehicles will cause drive range attenuation of 50–60 %, which greatly hinders the application and promotion of electric vehicles [19]. Researchers [20] have also carried out research indicating that electric vehicles can be equipped with economical vapor injection molding (EVI) technology that improves sparkle at low temperatures with the same outlet air temperature, thus increasing the thermal capacity of the system by 76 %. Wang et al. [21] conducted research to analyse the degree of overheating for different evaporation temperature values and different cone density temperatures. The results of the research indicated that the values (COP) of the coefficient of performance and thermal capacity of the system for the refrigerant R134a is 1.39–4.06 % and 0.53–4.08 % higher than R1234yf, respectively. Navarro et al. [22], carried out research on systems based on R1234yf, which had a COP 19 % higher than systems based on R134a refrigerant, with slight fluctuations at higher condensing temperatures.

Table 2

Properties of refrigerants

Properties	R134a	R1234yf
Formula	CH_2FCF_3	$CF_3CF = CH_2$
Chemical Abstracts Service number	811-97-2	754-12-1
Molecular mass	102	114
ODP	0	0
GWP100	1300	< 1
Safety classification	A1	A2L
Critical temperature [^oC]	374.21	367.85
Critical pressure [MPa]	4.06	3.38
Density of liquid [kg/m^3]	1206.00 (at 25 ^oC)	1091.91 (at 0 ^oC)
Density of saturated steam [kg/m^3]	8.288 (at 15 ^oC)	37.920 (at 25 ^oC)

Zhao and others [23], carried out performance tests on automotive air conditioning using a condenser with a microchannel flow parallel to R134a and R1234yf. The study indicated that R1234yf has a reduced charge of about 5% compared to R134a. At the same time, the cooling capacity and the COP of the R1234yf utilization system were lower due to different thermo-physical characteristics. Qi [24] presented a study that R134a has better heat transfer and flow parameters compared to R1234yf. The test concerned heat exchange and flow in an evaporator with a laminated plate. The results concerned the thermo-physical properties regardless of the refrigerant pressure at the expansion valve inlet.

Studies show that there are clear differences between the solutions, and there is no concept that is based on the ideal model. There is no indication of a refrigerant with clearly better parameters in current models. Solutions in electric vehicles have additional functions that use the capabilities of the heat pump, influencing the overall energy consumption of the battery. The process of validation of air-conditioning systems is based on a statement in which each step follows the result of the previous one. This is part of the whole vehicle validation process. Under such conditions, the key element is to carry out appropriate measurements, as previously presented, based on solutions without taking into account today's complexity of systems. The design of heat pump systems together with their full functionality with all possibilities is often based on results deviating from the real levels in the final design phase.

Heat pump test bench

Test benches for heat pumps are often based on refrigerants R134a, R1234yf and R744. Still, while the combinations between the refrigerants and the layout of the bench itself can be variable, the results are based on simulated laboratory conditions. The system heat exchangers for R1234yf and R134a are commonly used microchannel heat exchangers, but for the refrigerant R744, they are microchannel designs with a smaller duct diameter due to the higher operating pressure. Such a station consists of an accumulator with an internal heat exchanger which is located on the suction line. In the laboratory conditions, the data are taken from the sensors and then exported to the calculation programs, and the system becomes stable during this time; the results are close to expected. The results are taken during the stabilized state of operation with a sampling frequency; these results are averaged. Internal and external performance is evaluated using external and internal chambers. This efficiency is equal to the multiplication of the flowing mass and the enthalpy difference at the inlet and outlet of the heat exchangers. The energy balance level is the ratio of the capacity on the airside and the refrigerant side for the external and internal heat exchangers. During the validation process, simulation and laboratory measurements, the results significantly influence the technology used in the product. Each of these elements should be monitored under actual conditions. The difficulty in designing heat pump systems is the relatively large number of variables related to environmental conditions; however, the air conditioning system with additional functions is assumed to have full functionality under difficult conditions to maintain appropriate conditions in the passenger compartment. The test stands for heat pumps presented below represent systems with a high degree of external conditions. However, they do not include:

– climatic conditions caused by the installation of the system in the vehicle (places more or less exposed to temperature changes),

– the impact of other devices installed in the vehicle in close proximity,

– airflow while driving,

– the effect of additional air conditioning system functions on the efficiency of the system.

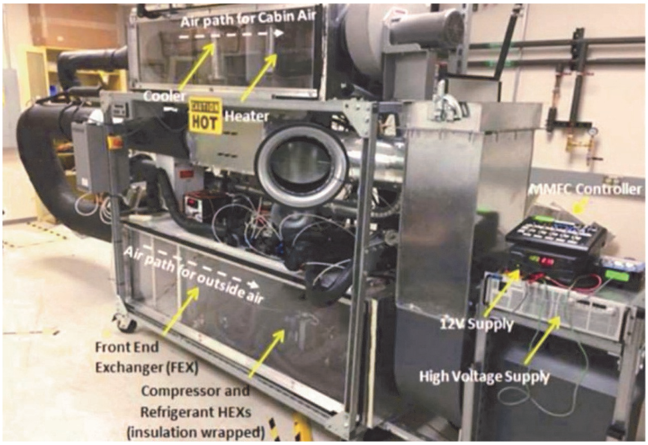

Fig. 2. Heat pump in situ test bench [25]

Research stands are based on prototype materials and components at the production level. They often support the laboratory testing stage; however, during the design work, the simulation conditions are limited due to the possibilities of the test bench. The

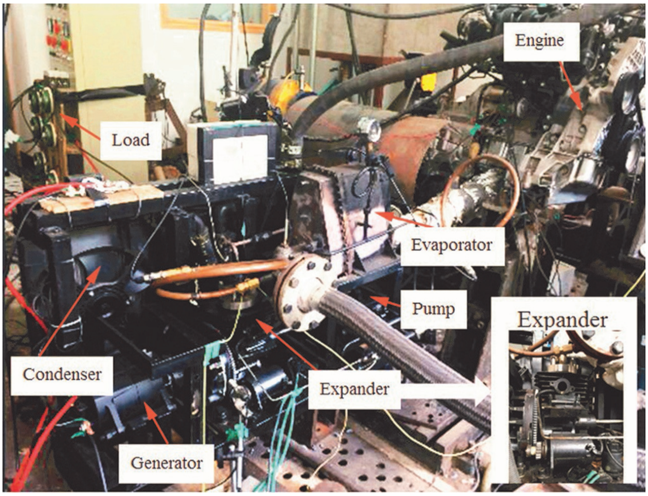

Fig. 3. Heat pump in situ test bench [26]

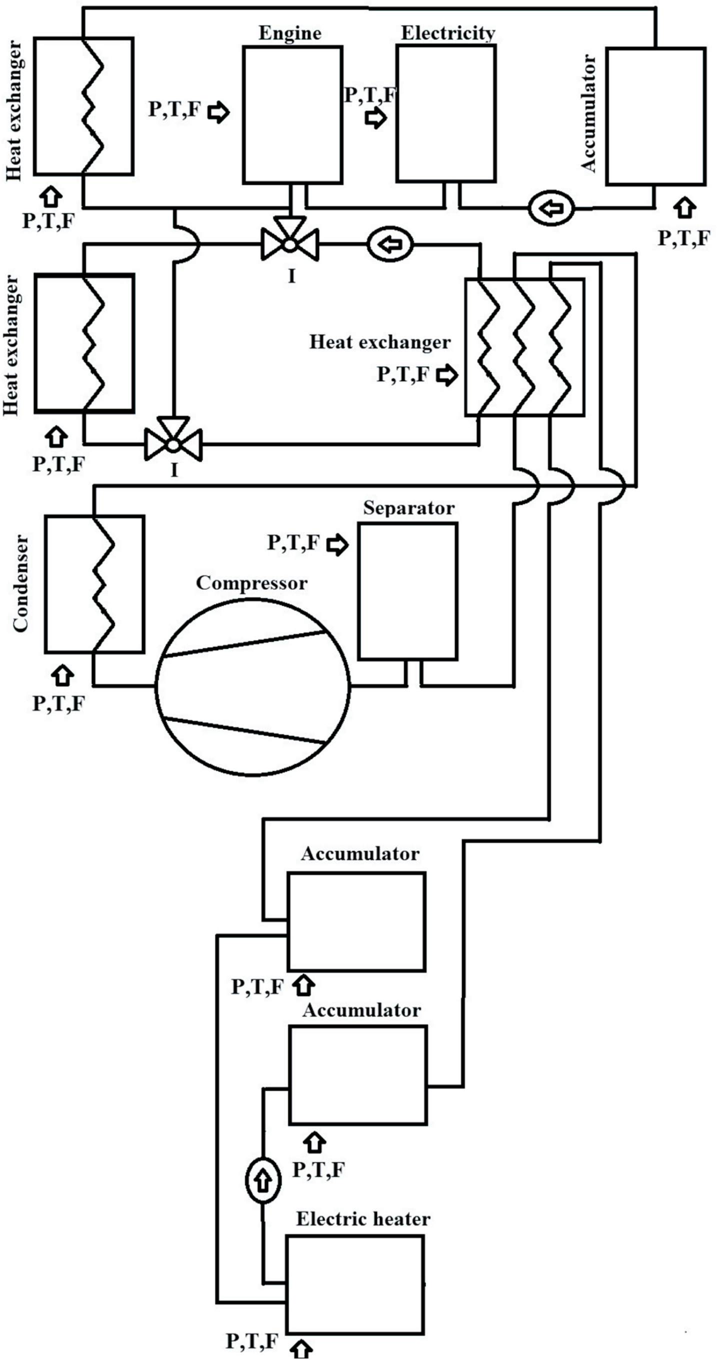

Fig. 4. Concept of built-in measuring station for testing heat pumps based on Mitsubishi i-MIEV (I three-way valve)

laboratory stand is used to measure energy consumption and thermal performance. The set consists of airflow simulators in the cabin. Outside the vehicle, the system has a resistance heater to heat the refrigerant and to simulate heat from the vehicle. Besides, heat drawn from the battery of an electric vehicle is simulated. To obtain conditions similar to the real ones, the stand has a model of the drive system, thermal and efficiency and a model of the energy storage system and thermal cabin.

The system presented in Fig. 3 is based on a system of collecting data from pressure, temperature, speed, backpressure and power output sensors. Temperature sensors perform the measurement in points together with pressure sensors with a high-frequency measurement. The backpressure measured on the recuperator and the medium outlet is measured using overpressure sensors. The output power meter measures the power output from the generator.

The element affecting each stage of the validation process is the appropriate collection of measurement data; however, laboratory measurements with increased accuracy simulate only part of the operating conditions of the heat pump system.

The concept of the test stand is based on measurements made in the natural environment. It is a validation stage in which some of the measurements can be carried out under laboratory conditions, using temperature chambers, ventilators with proper flow and temperature and humidity. It is possible to perform tests in real conditions due to the full functionality of the solution. The heat pump system is tested in the vehicle using the full functionality of all components, together with the possibility of pressure, temperature and flow (P, T, F) measurements. This kind of measurements allows to accurately reflect the conditions associated with the impact of all environmental conditions in an electric vehicle. The design process often has the characteristics of innovative solutions, with the use of such a solution, there is a possibility of testing new solutions already on the finished concept of the vehicle.

Conclusion

The development of electro-mobility creates new challenges in the transport industry; air conditioning systems are changing their existing application, entering into vehicle thermal energy management systems. The direction of development and the increasing range of purely electric vehicles must be taken into account in the basic principles of an air conditioning system. The clear impact of air conditioning systems based on heat pumps on the range of the vehicle increases the emphasis on solutions with increased efficiency. The basic indicator of heat pump technology is its functionality with low energy consumption. To achieve the highest possible efficiency, this article presents the concept of a test stands at the design stage with an innovative character in the vehicle body. This solution increases the accuracy of the results and the possibility of simulating an increased number of operating conditions.

Bibliography

[1] Granovskii M, Dincer I, Rosen MA. Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles. J Power Sources. 2006;159(2):1186-93. DOI: 10.1016/j.jpowsour.2005.11.086.

[2] Yang F, Xie Y, Deng Y, Yuan C. Predictive modelling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation. Nat Commun. 2018;9:2429. DOI: 10.1038/s41467-018-04826-0.

[3] Varga BO, Mariasiu F. Indirect environment-related effects of electric car vehicles use. Environ Eng Manage. 2018;17:1591-9. DOI: 10.30638/eemj.2018.158.

[4] Nie Y, Ghamami M, Zockaie A, Xiao F. Optimization of incentive polices for plug-in electric vehicles. Transportation Res Part B: Methodological 84. 2016:103-23. DOI: 10.1016/j.trb.2015.12.011.

[5] Mock P, Yang Z. Driving electrification: a global comparison of fiscal incentive policy for electric vehicles. Experim Physiol. 2013;98(98):1244-6. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.8471&rep=rep1&type=pdf

[6] Lu L, Han X, Li J, Hua J, Ouyang M. A review on the key issues for lithium-ion battery management in electric vehicles. J Power Sources. 2013;226(3):272-88. DOI: 10.1016/j.jpowsour.2012.10.060.

[7] Guo Y, Wang L, Liao C. Modelling and analysis of conducted electromagnetic interference in electric vehicle power supply system. Progress Electromagnetics Res. 2013;139:193-209. DOI: 10.2528/PIER13031101.

[8] Morrow K, Karner D, Francfort J. Plug-In Hybrid Electric Vehicle Charging Infrastructure Review. INL/EXT-08-15058. Idaho National Laboratory, U.S. Department of Energy, 2008. http://www.electrictechnologycenter.com/pdf/phevInfrastructureReport08.pdf.

[9] Bi J, Wanga Y, Shaoa S, Cheng Y. Residual range estimation for battery electric vehicle based on radial basis T function neural network. Measurement. 2018;128:197-203. DOI: 10.1016/j.measurement.2018.06.054.

[10] Kambly K, Bradley TH. Geographical and temporal differences in electric vehicle range due to cabin conditioning energy consumption. J Power Sources. 2015;75:468-75. DOI: 10.1016/j.jpowsour.2014.10.142.

[11] Genikomsakis KN, Mitrentsis G. A computationally efficient simulation model for estimating energy consumption of electric vehicles in the context of route planning applications. Transportaton Res. Part D. Transport Environ. 2017;50:98-118. DOI: 10.1016/j.trd.2016.10.014.

[12] Mruzek M, Gajdáč I, Kučera L, Barta D. Analysis of Parameters Influencing Electric Vehicle Range. Procedia Eng. 2016;134:165-74. DOI: 10.1016/j.proeng.2016.01.056.

[13] Sentoff KM, Aultman-Hall L, Holmén BA. Implications of driving style and road grade for accurate vehicle activity data and emissions estimates. Transportaton Res. Part D. Transport Environ. 2015;35:175-88. DOI: 10.1016/j.trd.2014.11.021.

[14] Wu X, He X, Yu G, Harmandayan A, Wang Y. Energy-optimal speed control for electric vehicles on signalized arterials. IEEE Trans Intell Transp Syst. 2015;16:2786-96. DOI: 10.1109/TITS.2015.2422778.

[15] Yuksel T, Michalek JJ. Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States. Environ Sci Technol. 2015;49:3974-80. DOI: 10.1021/es505621s.

[16] Yeh TJ, Chen YJ, Hwang WY, Lin JL. Incorporating fan control into air-conditioning systems to improve energy efficiency and transient response. Appl Thermal Eng. 2009;29:1955-64. DOI: 10.1016/j.applthermaleng.2008.09.017.

[17] Khayyam H, Nahavandi S, Hu E, Kouzani A, Chonka A, Abawajy J, et al. Intelligent energy management control of vehicle air conditioning via look-ahead system. Appl Thermal Eng. 2011;31:3147-60. DOI: 10.1016/j.applthermaleng.2011.05.023.

[18] Larminie J, Lowry J. Electric Vehicle Technology Explained. 2nd ed. John Wiley and John Lowry; 2012. ISBN: 978-1-119-94273-3.

[19] Rask E. Advanced technology vehicle lab benchmarking -Level 2 (in-depth). US DOE Vehicle Technologies Program Annual Merit Review and Peer 344 Evaluation Meeting 2014. DOI: 10.2172/1220550.

[20] Kwon Ch, Kim MS, Choi Y, Kim MS. Performance evaluation of a vapor injection heat pump system for electric vehicles. Int J Refrig. 2017;74:138-50. DOI: 10.1016/j.ijrefrig.2016.10.004.

[21] Wang H, Zhang S, Kan D. Energy and exergy analysis of R1234yf heat pump system with inner heat exchanger. Chem Eng (China). 2018;46:42-7. DOI: 10.3969/j.issn.1005-9954.2018.05.009.

[22] Navarro-Esbrí J, Mendoza-Miranda JM, Mota-Babiloni A, Barragán-Cervera A, Belman-Flores JM. Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system. Int J Refrig. 2013;36:870-80. DOI: 10.1016/j.ijrefrig.2012.12.014.

[23] Zhao Y, Qi Z, Chen J, Xu B, He B. Experimental analysis of the low-GWP refrigerant R1234yf as a drop-in replacement for R134a in a typical mobile air conditioning system. Proc Institution Mechan Engineers, Part C: J Mechanical Eng Sci. 2012;226(11):2713-25. DOI: 10.1177/0954406211435583.

[24] Qi Z. Experimental study on evaporator performance in mobile air conditioning system using HFO-1234yf as working fluid. Appl Therm Eng. 2013;53:124-30. DOI: 10.1016/j.applthermaleng.2013.01.019.

[25] Lustbader J, Rugh J, Winkler J, Titov G, Chowdhury S, Leitzel L, et al. Total Thermal Management of Battery Electric Vehicles (BEVs). SAE International. 2018. DOI: 10.4271/2018-37-0026.

[26] Gao W, He W, Wei L, Li G, Liu Z. Experimental and Potential Analysis of a Single-Valve Expander for Waste Heat Recovery of a Gasoline Engine. Energies. 2016;9:1001. DOI: 10.3390/en9121001.