Une approche Monte Carlo pour l'analyse de sensibilité d'un système de pompe à chaleur automobile au R1234yf

A Monte Carlo Approach for Sensitivity Analysis of an Automotive R1234yf Heat Pump System

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Résumé
Cette étude analyse les incertitudes de mesure liées aux paramètres d'entrée d'un modèle de système de pompe à chaleur pour véhicule électrique. Un modèle thermique unidimensionnel, développé sous AMESIM et dont les composants ont été préalablement corrélés à des données expérimentales, sert de base à l'évaluation. Des variations contrôlées sont appliquées à des paramètres tels que la masse de fluide frigorigène, les paramètres de contrôle et la vitesse de l'air. Leurs effets sur le COP et la consommation d'énergie, en régime permanent, sont quantifiés pour un système fonctionnant au R1234yf. Les comportements du modèle avec régulation PID sont comparés. Les résultats visent à démontrer l'utilité de la méthode de Monte Carlo pour optimiser le dimensionnement et les stratégies de contrôle, afin d'assurer des performances robustes dans les véhicules électriques.

Abstract -
This study analyzes the uncertainties in measurements linked to the input parameters of an automotive heat pump system model. A 1D thermal model developed in AMESIM with components formerly correlated with experimental data, serves as the basis of the evaluation. Controlled variations are applied to parameters such as refrigerant mass, subcooling target and air speed. Their effects on COP and power consumption, in steady-state cabin heating mode, are qualitatively summarized for an R1234yf system. Model behaviors with PID regulation are compared. The results aim to demonstrate the utility of the Monte Carlo method to optimize sizing and control strategies for robust performance in electric vehicles.

Abbreviations

COP Coefficient of Performance
EV Electric Vehicle
EXV Expansion Valve
PID Proportional Integral Derivative control

1. Introduction

Automotive heat pump systems are a rising trend in the EV market owing to the increased efficiency of the system translating into EV autonomy gains. This is especially because thermal energy used for cabin comfort can significantly affect the total energy consumption of EVs and hence directly influence the range of the vehicle [1]. Heat pumps used in EVs fall under the

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category of variable temperature lift, subcritical vapor compression refrigerant systems. This is necessary owing to the different ambient temperatures at which an EV is required to operate while serving a range of cabin and battery temperatures. At very low ambient temperatures, present EV heat pumps struggle to maintain their advantage and require supplementary PTC heaters to meet the heating demands of the vehicle.[2]

In EVs, heat pumps are principally designed to serve two major thermal loads: the battery and the cabin while interacting with the ambient [3]. Therefore, these systems need to run in multiple operating modes and can have multiple heat-rejecting and heat-absorbing exchangers in action throughout the driving period of the vehicle in order to meet the varying thermal demands in the car. This causes the system to have more than one feedback control loop operating upon different components in the heat pump system simultaneously depending on the operating mode [4][5]. This in turn increases the difficulty of deciphering the influence of each individual sizing and operating parameter on the overall performance parameters of the heat pump system model. Besides this, depending on the refrigerant used the control loop calibration parameters would vary depending on the difference in the required operating pressures. This is especially true for R1234yf, the widely used industrial drop-in substitute to the former R134a automotive heat-pumps in Europe [6][7][8].

At the lowest level, the refrigerant line of an automobile heat pump system alone has a minimum of two control loops for a simple heat pump configuration of a single condenser and single evaporator. The compressor speed is usually controlled to attain a target condenser air exit temperature whereas the expansion valve or the metering device is controlled to maintain a specific degree of refrigerant subcooling/superheating at the condenser or evaporator respectively. Since the heat pump systems in automobiles generally include the use of an accumulator in between the evaporator exit and the compressor inlet, the expansion device is generally controlled for a certain degree of subcooling of the refrigerant at the exit of the condenser. In addition, further control loops are implemented in the system for the control of air flow rate over the condenser and the evaporator.

The thermal system in EVs is essentially a system of systems which can be further subdivided into the heat pump system (refrigerant loops), the coolant circuits and the air circuits. What seems necessary while creating the digital twin or simulating such a complex system of systems is the need to identify the right set of input parameters that affect the desired output parameters of an isolated but coupled nonlinear subsystem. While thermophysical approaches are the classical way of identifying white-box (pure-physics) model parameters in order of sensitivity for heat pump systems; the method is heavily dependent on experimental tests or on the physical equations identified which are specific to the type of heat pump technology and the refrigerant used [9]. Besides, the sensitivity study of a heat pump system fully driven by multiple PID control loops is scarce in literature. This requires more intensive computational power and consumes more time both simulating and experimentally while sweeping all the minimum required operating points [10]. The objective of this work is to consider the use of the Monte Carlo method to help shortlist the input parameters that influence the desired outputs of an industrial grey-box heat pump subsystem especially when isolated from a larger model.

Although Monte-Carlo methods are well known in energy systems, HVAC design and building performance modeling, it is very rarely applied to an automotive thermal management context with active control loops. One other physics relevant study in the EV automotive sector is that on the impact of heat pumps and EV on the disruption of low voltage feeders although this is considerably distant from the present study's scope [11]. The intention of this study is to explore the utility of Monte Carlo method in helping understand the sensitivity of isolated physical subsystems in complex automotive thermal systems. The complexity of the system is evident in its nature of being a highly non-linear coupled system; at a model level, it requires a clear distinction of correlation parameters, passive parameters (i.e., geometrical data & controller gain values), and active parameters such as air mass flowrates.

2. Objective

The objective of this work is to vary the input parameters of an R1234yf automotive heat pump system model in cabin heating mode to simulate uncertainty in input and control measurements to understand the propagation of error and the corresponding variations in the key performance indicators of the model. The study would also help verify the utility of the Monte-Carlo method in the global sensitivity analysis of non-linear controlled systems like that of heat pump models with multiple control loops.

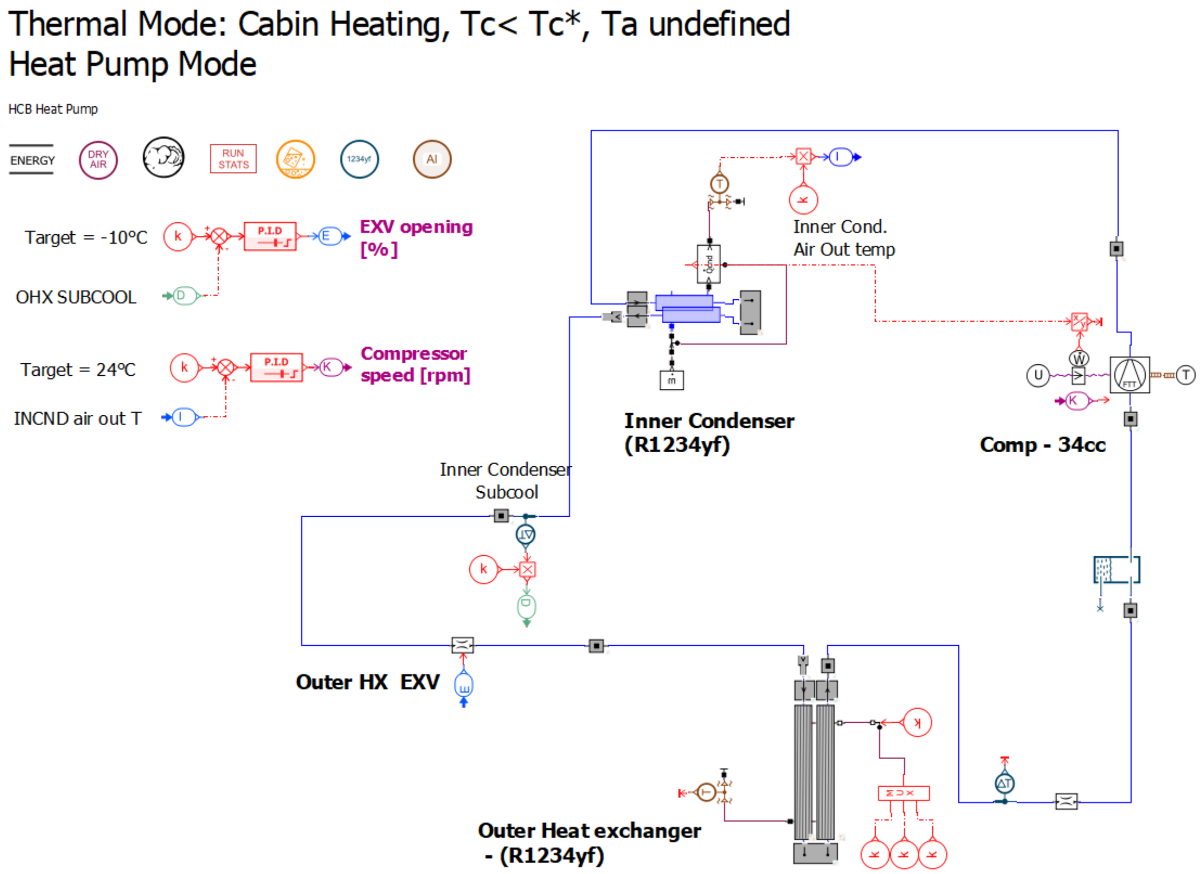

Figure 1: Schematic Diagram of the 1D Heat Pump Model in AMESIM

3. Methodology

The important foundation for the validity of the application of Monte Carlo method is that the component grey-box or black-box models used for the simulated the heat pump subsystem are well correlated with their experimental results. Besides this, it is necessary that all the significant components of the actual subsystem are well integrated into the model.

In order to carry out this study, a grey-box heat pump subsystem model representing the cabin heating mode of a commercially marketed EV was taken. The circuit was developed as a

1D model in Simcenter AMESIM software for the purpose of simulations. The individual components in the circuit, namely the outer heat exchanger (functioning as an evaporator in this thermal mode), inner condenser, compressor and expansion valve were previously identified grey-box models and tuned to ensure correlation with their experimental data. The compressor model was a finite-time-thermodynamic model correlated for an electrically driven scroll-type compressor of 34 cm^3 capacity. Pressure drop along the low-pressure gas line between the outer heat exchanger and the accumulator was modelled as an orifice pressure drop. Apart from this, the refrigerant tubing between the components were not modelled since their pressure drop is considered minimal and thus simplify the model. The simulation was run for an ambient temperature of -20 degree Celsius. This temperature also served as the initialization temperature of the circuit components and the refrigerant. The mean operating point was selected based on a validated running point in the vehicle. In order to assess the steady state performance of the heat pump, the air flow into the cabin condenser was continuously maintained at -8 degree Celsius at its inlet and the mass flow & relative humidity were maintained constant. Similarly, the air speed and relative humidity at the entry of the front-end module of the outer heat exchanger was also held constant while the ambient air temperature was set to be the temperature of the air entering the evaporator.

Input Parameter	*Unit*	*Mean Value*	*Standard Deviation*	*Results Series Number*
Ambient Temperature	°C	-20	2	8
Refrigerant Mass	Kg	0.5	0.05	3
Target Subcool	°C	-10	1	1
Target Condenser Air Outlet Temperature (TCAOT)	°C	24	2.4	2
Sensor Bias	%	100	10	6 (TCAOT),7(Subcool)
Cabin Air Mass Flow Rate	Kg/h	380	38	4
Evaporator Air Velocity	m/s	2	0.2	5

Table 1: *Input Parameter Distribution for Monte Carlo Analysis*

Each simulation was run for 2000 seconds in order to ensure that the system had arrived at its steady state. In order to implement the Monte Carlo uncertainty analysis, for each run, the model's selected input parameters were varied one at a time with a Gaussian distribution standard deviation of 10% of the mean value of the operating point (refer Table 1). 100 Latin hypercube sampled points were generated and simulated for using the same seed number for each input parameter studied. The overall key performance indicators for EV heat pump model are the heat rejected by the condenser and the COP of the system. COP in this system is defined as the heat power rejected by the condenser divided by the power consumed by the compressor in the system. The power consumed by the controllers and the EXV for varying the metering area is neglected in this calculation as they are considered negligible. Apart from this, other indicators are also studied such as the compressor discharge temperature and the mass flow rate in the system. Together, these serve also as a set of comparison parameters to compare other heat pump systems running on different refrigerants or of different geometric dimensions.

4. Results & Discussion

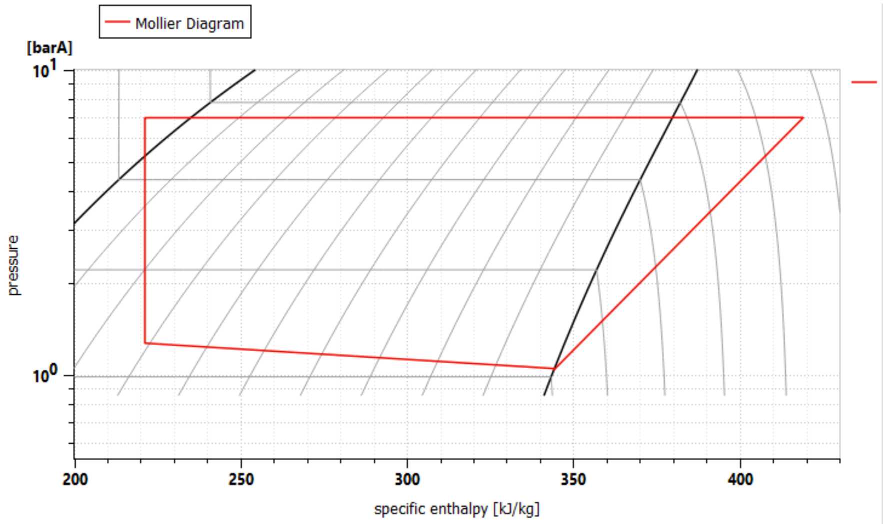

Figure 2: Steady State Mollier Diagram of the System at -20°C Ambient temperature

A pressure-enthalpy trace (Figure 2) of the system at its steady state was plotted to ensure to confirm the steady state nature of the mean operating point selected for the study. The control implemented on the system expansion valve ensures that the system attains a minimum subcooling before exiting the condenser, hence reducing the risk of flash gas formation during the expansion stage. There is also a negligible pressure drop induced by the presence of the accumulator in the system between the evaporator exit and the compressor inlet.

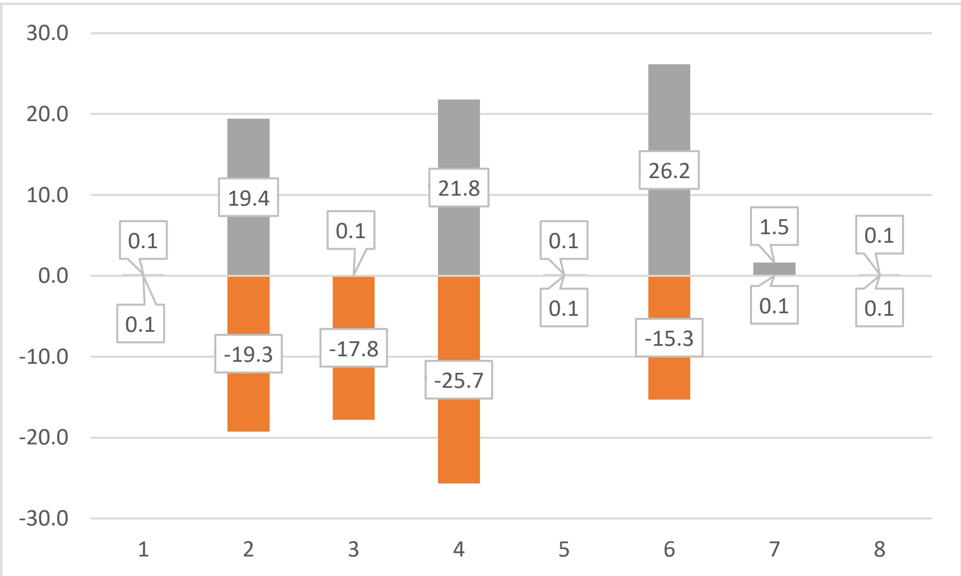

Figure 3: Sensitivity Study – Parameter Variations vs. Heat Rejected by Condenser (% change)

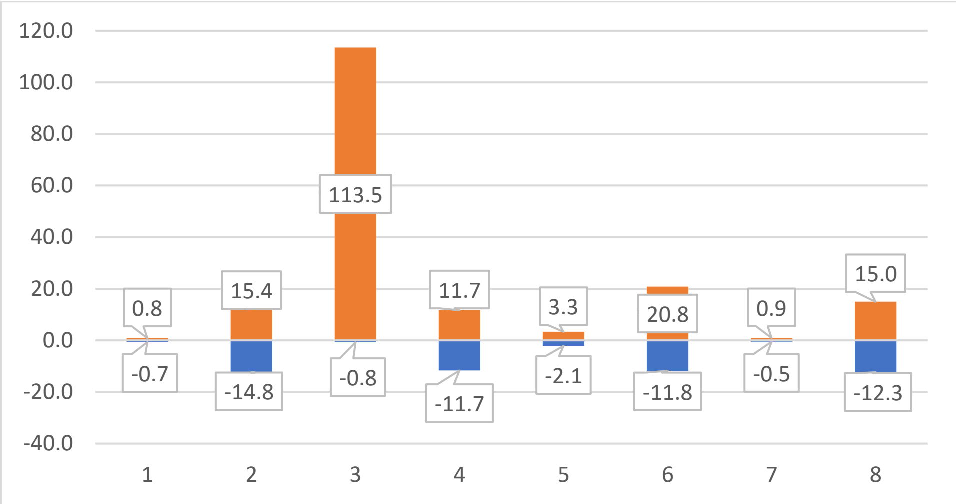

Figure 4: Sensitivity Study - Parameter Variations vs. Compressor Discharge Temperature (% change)

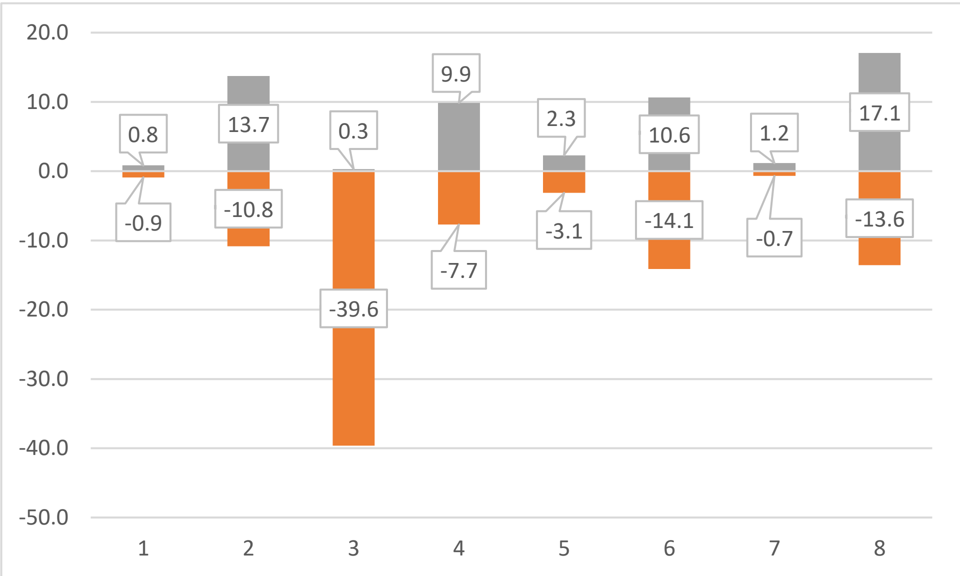

Figure 5: Sensitivity Study - Parameter Variations vs. System COP (% change)

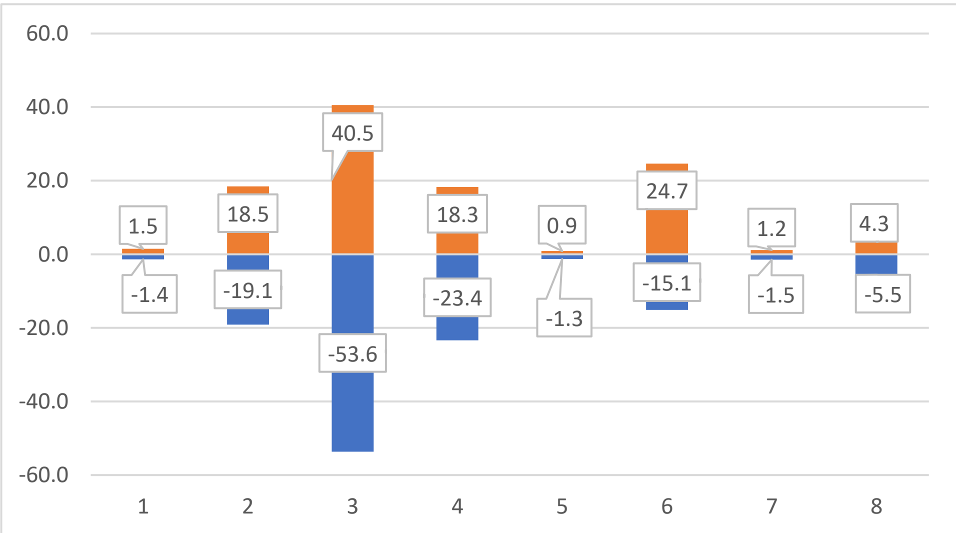

Figure 6: Sensitivity Study - Parameter Variations vs. System Mass flow rate (% change)

At the steady state operating point corresponding to the mean value of the active parameters, the COP was observed to be 2.18 and the discharge temperature of the compressor was 63.85°C. It ensured a constant refrigerant mass flow of 61.72 kg/hr through the circuit and delivered a steady heating power of 3.39 kW at the condenser air side. Of the studied parameters the refrigerant mass charge in the system seems to influence the system outputs significantly when the system is undercharged. But for a value of refrigerant charge beyond the necessary charge, the system COP and heat rejected by the condenser remained the same.

The parameters with the highest variation on the system performance indicators (Figures 3-6) were the cabin condenser air mass flow rate, the ambient temperature and the condenser air outlet temperature control target and its sensor bias value. This indicates that errors in the measurement of these parameters are of higher importance and hence require a lower uncertainty range during the experimental tests.

5. Conclusion

Based on the simulation study done, the Monte Carlo method is verified as an appropriate method for determining the sensitivity of parameters in the automotive heat pump model outputs. Besides this, extending the study for simultaneous multiple input variables variations at a time can potentially help obtain system operating points outside of the defined control loop trajectories that could be optimized for higher system performance indicator values. This could thus help in the fine tuning of the system controls and also in obtaining the Sobol indices for black-box based models of industrial heat-pump subsystems. Similar to conclusions from other studies [12], a potential limitation of the presented approach on local sensitivity could be the dependency of the study to be centered on a previously identified steady state operating point of the subsystem which in the case of EV heat pumps would change significantly for a different mode of operation. Hence the sensitivity results obtained would be specific to the operating mode of the heat pump in cabin heating application.

Applying this method to the geometric parameters of the subsystem would help in the design and optimal the sizing of the subsystem components, provided the component models used in the subsystem are well correlated for geometric variations. During the generation of the sampling points, it is important to additionally impose constraints to eliminate physically impossible operating points of the system.

The method is also useful in correlation studies of grey-box models of the heat pump system in highlighting the propagation effect of constant errors due to uncertainties in measurement of active input parameters upon the output parameters around the given steady state operating point.

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