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Modelling Of An Automotive Multi-Evaporator Air-Conditioning System

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Modelling of an automotive multi-evaporator air-conditioning system

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ABSTRACT

An automotive multi-evaporator air conditioning system, which is composed of two evaporators and a secondary fluid cooler, was modeled using the LMS Imagine.Lab Amesim® 1D software. The present study focuses on understanding the dynamic coupling of the several loop components such as the three evaporators having different cooling capacities. This kind of multi-evaporator air-conditioning system has a number of technological barriers that must be overcome. Understanding the behavior of their respective expansion devices and the choice of these latter is also essential to control properly the transient phase and ensure an optimal operation of the air-conditioning system. In order to study the behavior of the loop, step disturbances were simulated on an operating point at medium and high load. The impact of these disturbances on the stability of the supplied cooled air temperature is analyzed for two types of expansion valve. Initial results show that the thermostatic expansion valves can cause instabilities. Furthermore, the electronic expansion valves have to be regulated with an advanced control in order to use their full potential and to try to achieve desired results.

1. INTRODUCTION

Over the last decade, vehicle electrification has increased to meet the demands of reducing fuel consumption and greenhouse gas emissions. With the arrival of plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) with significant autonomy, battery cooling becomes a necessity in driving mode to ensure their durability and ability to charge rapidly. For these vehicles, the air-conditioning system may be composed of two evaporators (for front and rear passengers) in order to afford cooled air in the cabin and a chiller or a built-in battery evaporator to cool down the traction battery. A chiller is a glycol water-to-refrigerant evaporator which enables heat to be transferred between a secondary loop and the air conditioning loop.

Air-conditioning systems composed of an evaporator and a chiller are already available in series production vehicles such as the Tesla Model S and, more recently, the Volkswagen Golf GTE. They raise the question about how to regulate properly the system with two evaporators having different cooling capacities. Thus, expansion valve becomes a key component. While the first mentioned model is a pure electric vehicle with significant autonomy, the second one is a plug-in hybrid vehicle whose battery has a much lower capacity. The cooling requirements are therefore not identical. It can explain the choice of a chiller having a greater cooling capacity in the first case. Moreover, while a thermostatic expansion valve (TXV) regulates the quantity of refrigerant going through the chiller of the Tesla, Volkswagen made the choice of an orifice tube. However, according to the authors, no explanation has been so far mentioned in the literature about the choice of the expansion valve. The effect of battery cooling by means of a chiller on the automotive air-conditioning loop has been already proved by simulation in the Dymola® environment (Krüger et al., 2012). The simulation results for several driving cycles, refrigerants and ambient conditions emphasize the thermal discomfort caused by the use of the chiller loop. However, no global control strategy able to regulate properly the system has been presented.

Concerning high-end vehicles with one or more passenger ranks or vehicles intended for passenger transport with a large cabin volume, the presence of two evaporators is necessary to provide thermal comfort to the rear seats. Hybridization of this type of vehicle is also relevant. Recently, a first study of an air-conditioning system model with three evaporators was carried out (Shojaei et al., 2015). After the validation of their component models, a standard cabin pull-down test was performed to test the performances of their air conditioning system. From a control point of view, a simple proportional integrator (PI) control on the temperature of air blown at the front evaporator outlet was used to regulate the speed of the compressor.

Moreover, a first driving cycle dedicated to the air-conditioning systems will soon be set up while the regulation in terms of CO_2 and pollutants emissions becomes increasingly restrictive. These result in car manufacturers innovating in order to make air-conditioning system as efficient as possible. Recent technologies such as solenoid valves and electronic expansion valves (EXV) offer opportunities to elaborate global control strategies. Recent studies show already the benefits of robust regulations on the performance and stability of the system. An optimization of the control strategy was studied for several operating points (Varchmin et al., 2015). The nonlinearity of the system makes the control development a significant challenge. In the building sector (Elliott and Rasmussen, 2013), the benefits of a supervisory controller to regulate the multi-evaporator air-conditioning system was developed. Although this type of decentralized model seems to be robust and applicable to the car, it requires the use of sensors and components currently too costly and subject to a less restrictive environment than in automotive.

In order to control properly the transient phase and ensure an optimal operation of the air-conditioning system, a model of a multi-evaporator air-conditioning system composed of two evaporators and a chiller was therefore conducted. The impact of disturbances was studied such as opening a valve or the change in the temperature set point. The use of a TXV will be compared to the EXV. The drawbacks of TXV's and the potential capacity of EXV's will be discussed.

2. METHODOLOGY

This study aims to model the air conditioning system and the battery subcooling system for a PHEV. The first approach consisted in starting with an existing vehicle. Its air conditioning system, which was already composed of two evaporators, provided the basis for the study. Several components such as the heat exchangers (condenser and the two evaporators) and the TXV were already known and modeled. The second approach was about the electrification of the system. A conventional compressor was replaced by an electric compressor which was sized in order to supply the needed cooling capacities. A chiller is also added to extract the thermal power dissipated by the traction battery. The chiller was modeled using existing data from another project and will be sized in the future. Finally, an electric pump provides a flow of glycol water through the chiller loop.

Figure 1 shows a schematic multi-evaporator air conditioning system. All the components previously cited are illustrated. Solenoid valves are added to manage independently the opening and closing of each evaporator loop. The respective component characteristics are mentioned in Table 1 hereunder. As several components were not already characterized with the new refrigerant R1234yf, the whole system is modeled with the R134a refrigerant

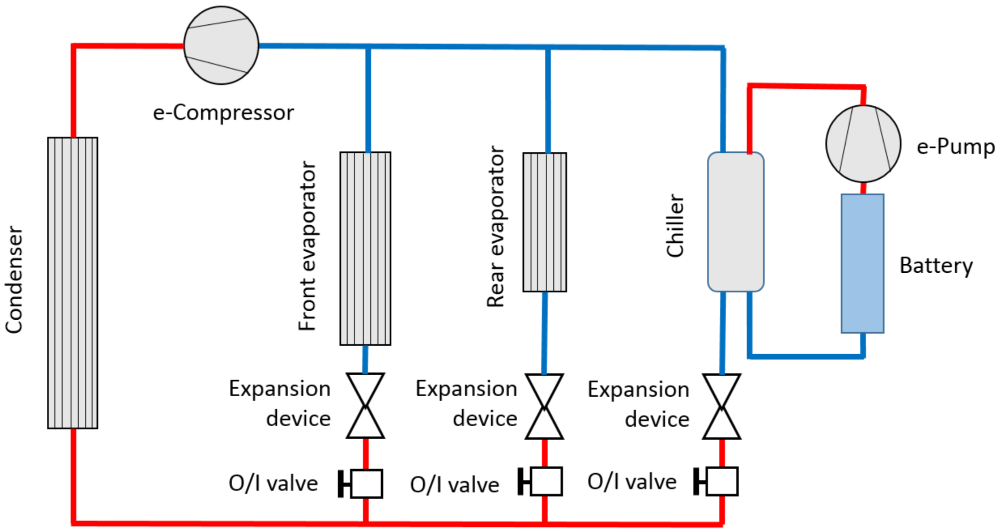

Figure 1: Schematic of the modeled a multi-evaporator air conditioning system

Table 1: Component technical characteristics of the modeled air conditioning system

Component specifications	**Units**	**Value**
Compressor displacement	cc	34
Rated capacity of the condenser	kW	18
Rated capacity of the front evaporator	kW	7
Rated capacity of the rear evaporator	kW	3
Rated Capacity of the chiller	kW	5
Rated Capacity of the front TXV	kW	7
Rated Capacity of the rear TXV	kW	3.5
Rated Capacity of the chiller TXV	kW	3.5

3. NUMERICAL MODEL

The study was performed using the LMS Imagine.Lab Amesim® 1D software. This graphical user interface is able to represent mathematically the physical behavior of every components thanks to the bond-graph formalism (Dauphin-Tanguy, 2000). Bond-graph theory is based on the notion of causality. It means that each flow type element is followed by an effort type element and reciprocally. In thermodynamics, the effort is a temperature and the flow is an entropy flow. Their multiplication is always equal to the exchanged power. Unlike block diagrams and signal-flow graphs, where the flow of information is unidirectional, the physical exchange is bidirectional. Furthermore, bond graphs are easily applied to multi-energy domains and can mix different libraries such as thermos-hydro, mechanical, electrical, etc.

A complete multi-evaporator air-conditioning system is modeled in Figure 2. This model is presented with three currently used expansion valve (TXV). The mass air flow going through the condenser can be regulated in function of the vehicle speed and the fan speed. The e-compressor is supplied with a high voltage source and can be regulated in function of different criteria such as the blown air temperature at the front and rear evaporators. In Figure 2, the three evaporators in parallel are framed to be distinguished from each other. The battery cooling loop includes an e-pump which supplies the desired mass flow rates to dissipate the thermal power out of the battery by the means of a chiller. This mass flow rate has to be sufficiently high to avoid a large temperature gradient between battery cells over time without compromising the cabin comfort.

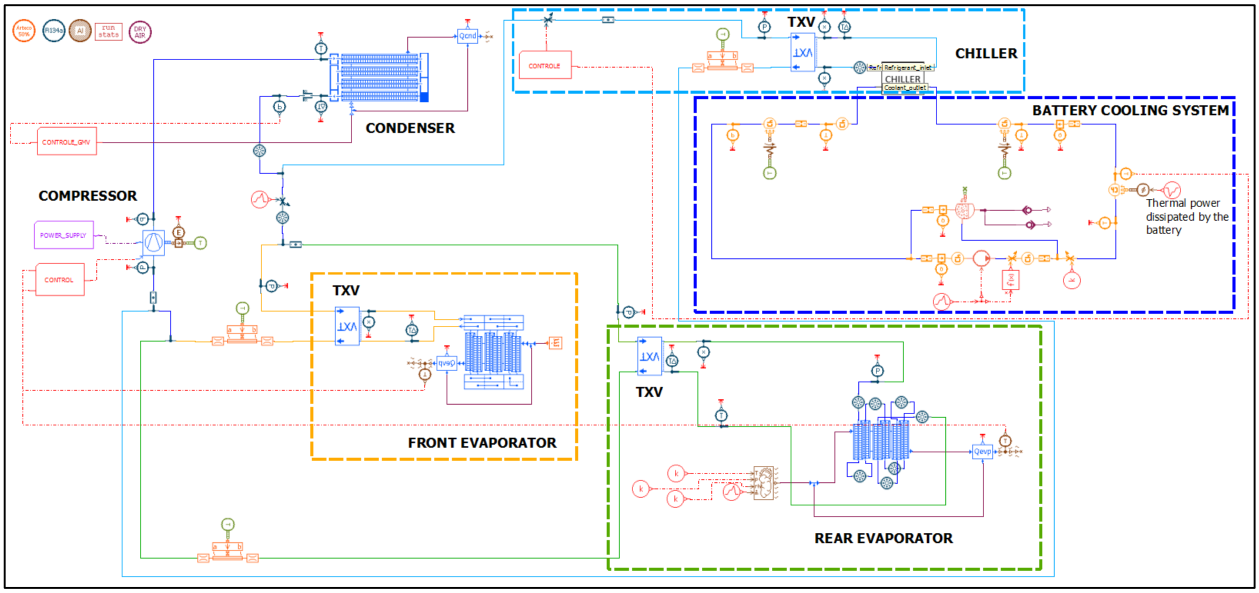

Figure 2: Multi-evaporator air-conditioning system model

3.1 Heat exchangers model

Heat exchangers models take into account the involved transient aspects thanks to the ability to represent the physical behaviors of the condenser and the evaporator (El-Bakkali and Olivier, 2004). In the case of the condenser, every pass is considered as a generic duct model which is defined by its length, hydraulic diameter and cross-section area on both refrigerant- and air-sides. The fins are defined by the fin efficiency related to its geometry parameters and also by the finned/total area ratio. Using the finite volume method, we can consider a duct as an assembly of small capacitive fluid elements where we can suppose that the thermodynamic properties are uniform. These elements are connected to each other by virtual resistive elements. The capacitive elements can accumulate mass and energy and exchange heat with air through the wall elements that can equally accumulate energy. The pressure drop and the refrigerant density are computed within the set of virtual elements. Similarly to the condenser, every plate (U-channel) of the evaporator is represented by two generic ducts.

3.2 Compressor model

The electric compressor model is based on the concept of volumetric, isentropic and mechanical efficiencies maps according to the compressor speed and the compression ratio. These maps are built with a set of preselected operation points from experimental measurements in steady state. They provide the state of the working fluid at the inlet and outlet of the compressor as well as its mass flow rate. The electrical efficiency of the compressor, which is the ratio between the mechanical power and the electrical power, is assumed equal to one. The compressor speed is regulated by a PI-type control signal, which is function of the real-time calculated error on the blown air temperature target at the outlet of the evaporator.

3.3 Expansion valve models

A TXV is an expansion valve that regulates the mass flow rate in function of the force balance between the bulb pressure, the evaporator outlet pressure and the spring pressure. Specifically, the resultant force makes the valve pin move downward or upward. In the case of an EXV, an electromagnetic actuator adjusts precisely the displacement of the valve pin according to an external regulation.

TXV's are modeled using manufacturer's 4-quadrant valve diagrams. These two dimensional graphs provide the relation of the opening rate of the valve in function of the mass flow rate and refrigerant conditions at the evaporator outlet (pressure, temperature and superheat). A relation between the equivalent cross-section area and the evaporator outlet conditions is established thanks to the parameters identification of a power curve. A pressure drop component then calculates the mass flow rate, which is function of these equivalent cross-section area and the enthalpy at the inlet and the outlet of the pressure drop component. A time constant is used to represent the dynamic behavior of the bulb. EXV's are modeled using the same pressure drop component previously described. The maximal cross-section area value is assumed to be equal to the one calculated from the TXV's identification. The expansion valve is regulated by a PI-type control signal that is function of the real-time calculated error on the superheat target. Depending on the error value, the cross-section area is adapted.

3.4 Chiller and battery cooling loop model

The chiller is an evaporator that produces chilled glycol water. It is made of several plates stamped to each other. It aims to sub cool the traction battery via the air-conditioning system when the specific radiator is no longer able to maintain the battery under a critical temperature. A secondary fluid, most often glycol water, flows through the channels of a plate which is thermally in contact with each battery cells. The battery inertia is not taken into account. An electric pump provides the mass flow rate and its speed is regulated by a controller in function of the desired mass flow rate.

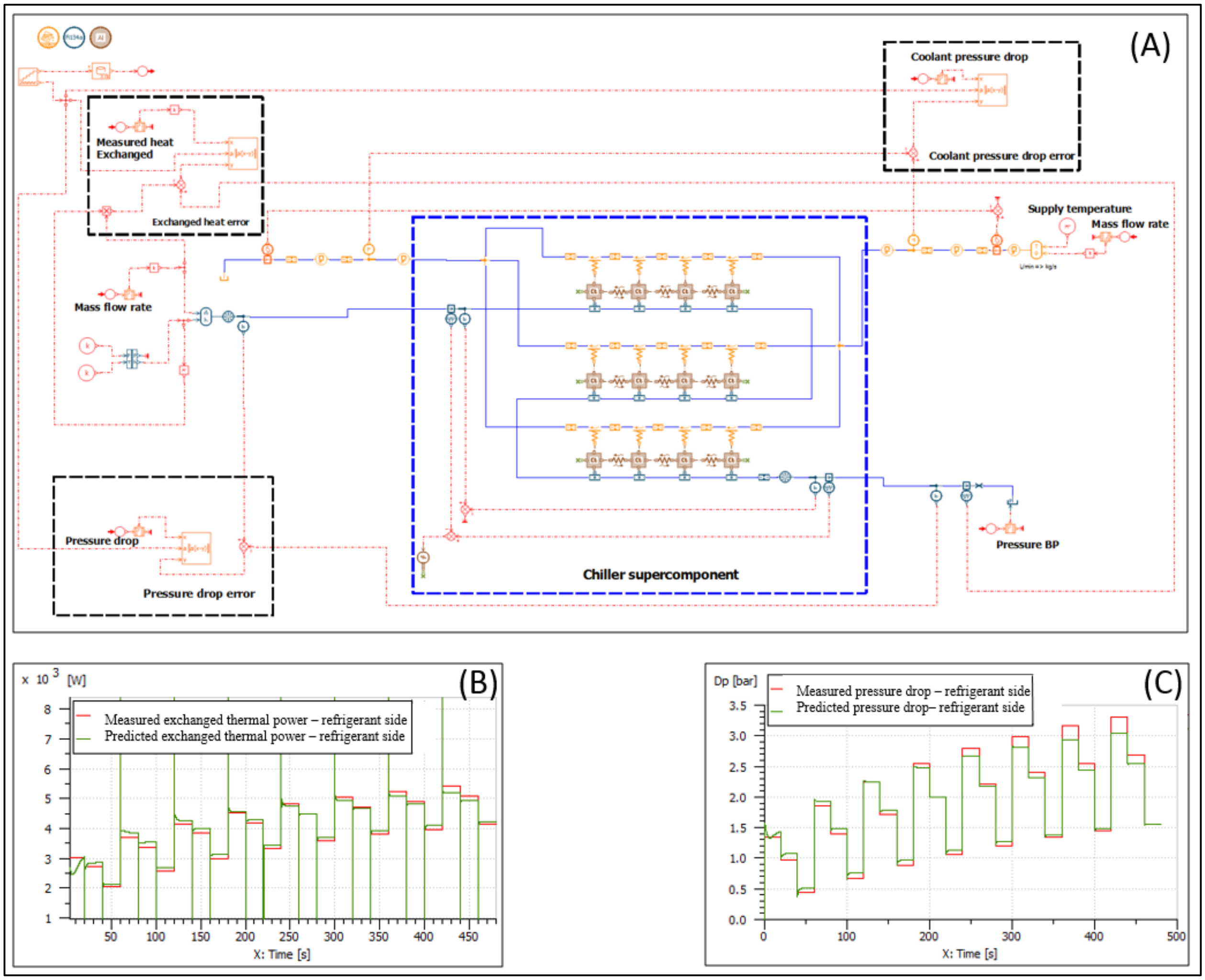

Figure 3: Physical chiller model and calibration results

The chiller is physically modeled with the finite volume method in order to obtain more representative results in the transient state than a lumped model available in steady state. Since the quantity of heat exchanged between two fluids through several plates of a same pass is equivalent to the quantity of heat exchanged through one plate, the chiller is modelled in a set of ducts representing each pass. As it is shown in the Figure 3 (A), this chiller has 3 passes and each pass is discretized in four mass elements. This discretization is a good compromise between performance and computation time. This model has the particularity of mixing two different theoretical domains: hydraulic and thermodynamic domains.

The chiller was calibrated with the help of experimental measurements under steady state conditions and its specific geometry. Measured and predicted exchanged thermal power are illustrated in Figure 3 (B). The maximal calculated error on the thermal power exchanged is about 300W (6%). Regarding the refrigerant side pressure drop (see Figure 3 (C)), the maximal calculated error is about 3,3 bar (10%).

4. RESULTS AND DISCUSSION

In order to study the ability of different types of expansion valve to maintain thermal comfort in the cabin, the air-conditioning system was subject to various disturbances. Although the occupant comfort cannot be simply equated with a change in temperature of blown air at the evaporator outlet, its evolution over time gives a good indication about the loop stability.

The multi-evaporator air-conditioning system was simulated for two configurations (three TXV's and three EXV's) and two operating points (low and high loads) with partial air recycling. The first configuration corresponds to the one represented in Figure 2 where three TXV's regulate the refrigerant flow rate through their respective evaporator. The compressor speed is regulated by a PI controller on the temperature set point of the blown air at the front evaporator. Consequently, rear passengers have to deal with the loop behavior according to the selected temperature set point at the front evaporator. In the second configuration, three EXV's replace the common expansion valves and are regulated to maintain a superheat equal to 3K. Their characteristics are shown in Table 2. The initial conditions for both operating points are presented in Table 3.

Table 2: Electronic expansion valves characteristics

	Units	**EXV (front)**	**EXV (rear)**	**EXV (chiller)**
Maximal cross-section area	mm²	1.95	2.2	1.11

Table 3: Initial conditions for two operating points

	Units	**Low load**	**High load**
Ambient air temperature	°C	30	30
Ambient air relative humidity	%	60	60
Ambient air pressure	hPa	1013	1013
Air velocity through the condenser	m/s	4	4
Air temperature at the front evaporator inlet	°C	25	25
Relative humidity at the front evaporator inlet	%	50	50
Airflow at the front evaporator inlet	kg/h	300	500
Air temperature at the rear evaporator inlet	°C	20	20
Relative humidity at the rear evaporator inlet	%	40	40
Air flow rate at the rear evaporator inlet	kg/h	200	400
Thermal power dissipated by the battery	W	500	1000
Temperature target of blown air at the front evaporator	°C	5	5

Figure 4 shows the evolution of the temperature of the blown air at the rear evaporator when the air-conditioning system has to face a sudden activation of a solenoid valve in the chiller loop. To simulate this valve activation (closing and opening), a step disturbance was generated. Four configurations are represented and compared to one another:

- 3 TXV’s & low load,
- 3 TXV’s & high load,
- 3 EXV’s & low load,
- 3 EXV’s & high load.

The results from simulation show that the air-conditioning system becomes unstable just after the activation of the chiller loop. Indeed, a peak in temperature of the blown air at the rear evaporator is suddenly reached and a maximal difference of 5K is noticed. The amplitude of this peak is much larger at the opening of the valve than at the closing and increases with the load. At low load, it takes approximately 60 seconds to the air-conditioning system to recover the initial temperature of the blown air. The peak in temperature at the opening of the valve is due to the sudden need in cooling capacity to cool down the battery, which is not immediately provided by the compressor. Consequently, it can cause thermal discomfort in the cabin. At the opposite, when the valve closes, the speed of the compressor becomes too high which makes the temperature of the blown air lower that the set point.

Furthermore, for the configuration with 3 TXV’s at high load, the temperature of the blown air becomes unstable just after the disturbance. This phenomenon is certainly due to varying refrigerant flow rate which leads to superheat hunting of the TXV. Indeed, the TXV opens and closes in an attempt to maintain a constant operating condition. Superheat hunting is an intrinsic behavior of the TXV and can be increased with the oversizing or a wrong setting of the TXV. A set of TXV’s setting should be studied to evaluate their impact on the stability of the system.

Moreover, the results also shows that a basic PI control of the EXV’s superheat is not sufficient to decrease the peak in temperature. The PI parameters was identified by the trial and error approach but do not seem to be efficient for this operating point. This “single-input single output” (SISO) control type is not well suited for complex system. Therefore, a global control strategy, such as a “multi-input multi-output” (MIMO) control type using gain scheduling adaptive PI, has to be established. This control should take into account the cooling capacity required in the cabin for the front and the rear passengers while regulating the compressor speed and the opening rate of the EXV’s and solenoid valves, for example. Although the advantage of an EXV about the decrease of the peak is not demonstrated for this disturbance, it is not subject to superheat hunting.

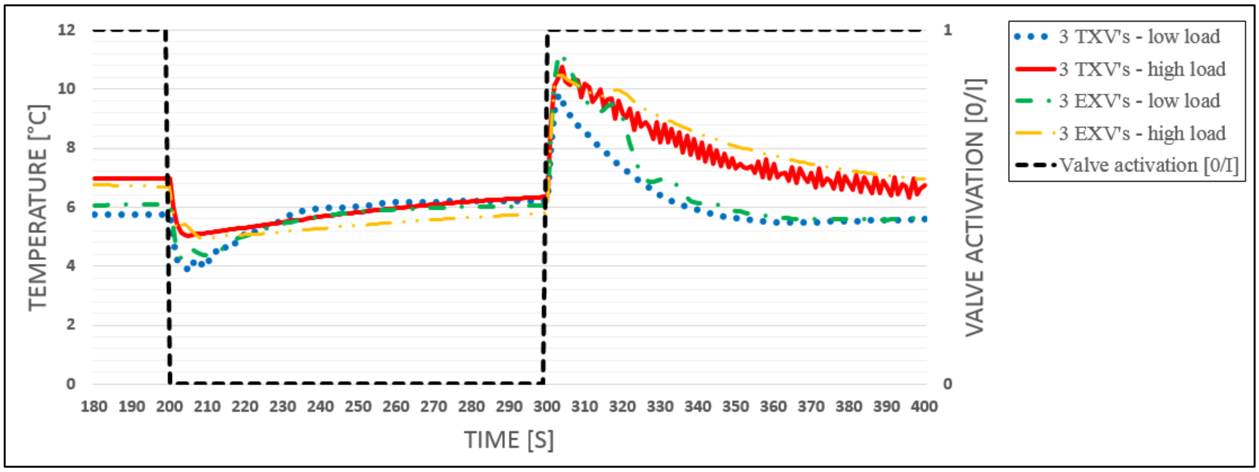

Figure 4: Temperature evolution of the blown air at the rear evaporator when the system is subject to the activation of the chiller valve (0/1)

Figure 5 shows the temperature evolution of the blown air at the rear evaporator when the air-conditioning system is subject to a sudden change in temperature set point of the front evaporator: from 5°C to 7°C and then, from 7°C to 5 °C.

For this type of disturbances, the advantage of the EXV is clearly demonstrated. Indeed, at high load, the peak in temperature is much lower than the configuration using 3 TXV’s. EXV’s contribute to maintain the system in the desired conditions and reject disturbances. However, when the load is low and with the same PI parameters, the system with three EXV's is less efficient than with three TXV's. It confirms the need to use EXV's with a robust global control strategy.

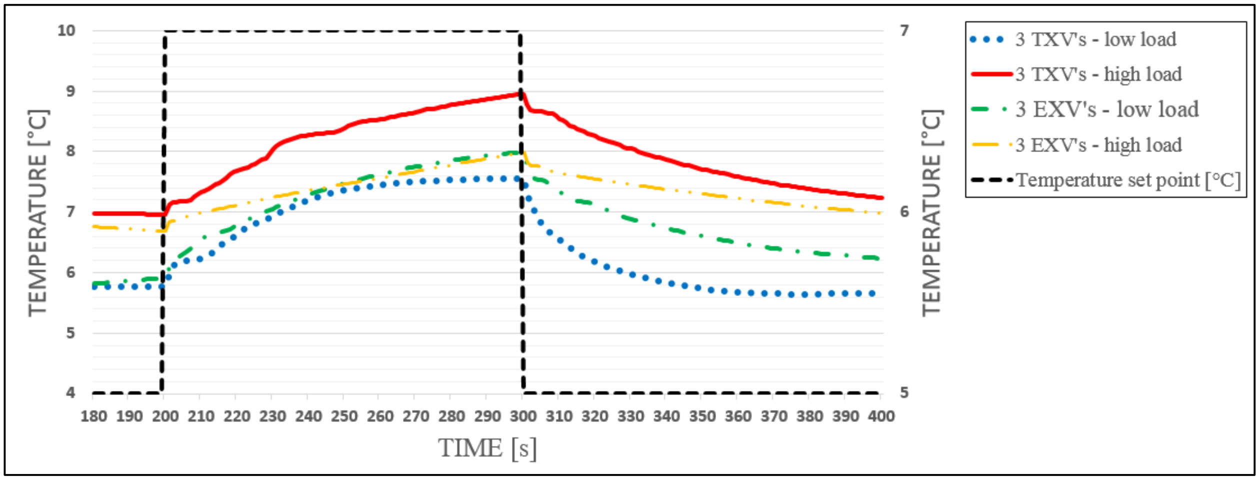

Figure 5: Temperature evolution of the blown air at the rear evaporator when the system is subject to a change in temperature target

5. CONCLUSION

A model of a multi-evaporator air-conditioning system was built using the LMS Imagine.Lab Amesim® 1D software. This model is able to predict the dynamic behavior of the air-conditioning system. It also allows the engineer to design and to check all the components such as the heat exchangers and the expansion valves.

A study about the comparison of two types of expansion valves was carried out in order to evaluate their impact on the stability of the multi-evaporator air-conditioning system. First results confirm the failure of TXV's to maintain a stable temperature of blown air at the evaporator outlet when the system is subject to step disturbances. Moreover, EXV's have to be regulated with a global control strategy to reach their potential. A unique set of PI parameters does not yield good results, since they only fit for one operating point.

In order to be more representative of the system integrated in the car, a thermal model of a cabin must be developed in the near future. The passenger comfort can be then discussed.

An advanced global control will be also created with a view of maintaining passenger comfort during all the operating points. This control, with EXV's, should be able to anticipate the sudden change in cooling load while taking into account all the system constraints such as the maximal accepted pressure. The control should also be designed to filter out several kind of disturbances such as the opening of a solenoid valve.

Finally, a complete thermal model of the traction battery cooling should be realized to predict the thermal power to dissipate in the chiller on a drive cycle in function of the state of charge of the battery.

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