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Thermal management of a battery electric vehicle system utilizing air conditioning

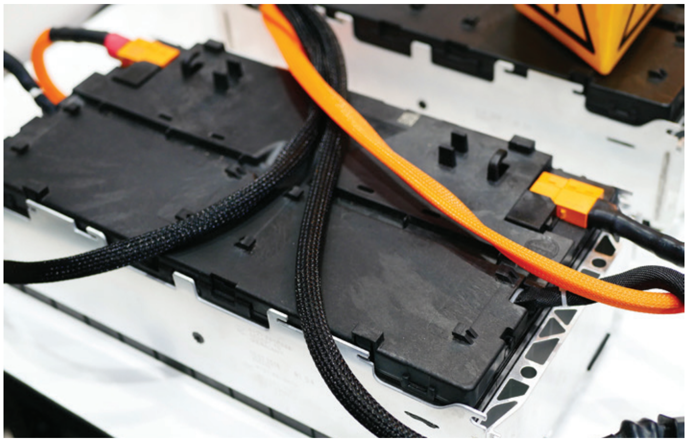
Executive summary

The ability to quickly and accurately model air conditioning (AC) systems is of increasing interest to the automotive industry due to the growing trend towards electric vehicles (EVs), plug in hybrid electric vehicles (PHEVs) and vehicle autonomy. While AC systems have been used for over 85 year to cool vehicle cabins, extra requirements are being placed on the heating ventilation and air conditioning (HVAC) systems [1]. This is due primarily to battery technology along with motors, inverters and computing resources, all of which require advanced thermal management solutions. These systems are highly complex though and take a large amount of time and effort to design and can be extremely costly if incorrectly specified. A tool is therefore required to aid in the development of these systems from the very early design phase all the way through to project completion. In this white paper, several of these techniques will briefly be described along with the technology and methods behind them that are required to successfully design a system using 1D thermo-fluid system simulation.

Battery electric vehicle cooling

Most current generation electric vehicles store the batteries under the floor, primarily under the rear seats. This provides a large relatively flat and unobstructed space while also keeping the center of gravity of the vehicle as low as possible. This provides a challenge though as the battery needs to be thermally regulated to between 20°C and 40°C while being tightly packaged. A number of vehicle manufacturers have decided to forgo battery thermal management, but this results in the temperature changing very slowly as the battery is quite dense. While this initially may appear beneficial in hotter climates it can result in the battery never cooling down and the opposite scenario occuring in colder climates. It can also result in extreme temperature gradients and localized hot spots. If the battery is too cold it temporarily loses capacity, but if it gets too hot it can permanently damage it while also limiting power output and input in an attempt to prevent damage.

AC systems can be leveraged to overcome these problems by providing a solution that both cools and heats the cabin and the battery simultaneously. This does however create addition thermal management requirements, packaging constraints, increased system control and complexity. By using an AC system, it increases the power draw from the batteries by approximately three kW, thus increasing electrical consumption of the vehicle, however this can vary based on the system design and usage [2]. A second generation Nissan Leaf draws 16 kW while cruising at 60 mph, so a three kW increase in load represents a 19 percent increase in power draw [3]. This results in the range being reduced from 65.3 miles on a full charge to 52.8 miles. While this is a



concern for internal combustion engine (ICE) operation, particularly due to emissions, miles per gallon (MPG) and the environment. The majority of users would rather be cool and range reductions can easily be mitigated by increasing the size of the gas tank which has minimal cost to OEM's. This is not the case with EVs though which need to maximize battery range to overcome many customers' range anxiety. In additon to this battery electric vehicles cannot be 're-fuelled' as quickly, hence this becomes a bigger concern to the end user along with the battery requiring cooling/ heating which isn't a concern for ICE vehicles. All of these requirements cause concern for system designers and engineers that can be quickly and easily addressed using Simcenter Flomaster™ software.

Air conditioning systems

While it has been established that AC systems can provide an optimal solution to cooling both the cabin and battery, it is important to understand how these systems work before applying them to a battery electric vehicle (BEV) system.

Air conditioning refers to the treatment of air across an adverse temperature gradient. Meaning that heat is transferred from a colder location to a hotter location. As heat would naturally flow in the opposite direction, energy is required in the form of work to overcome this. A refrigerator is a good example of this as it transports the heat from the interior to the external environment. Four major components are required to achieve the reverse rankine cycle used in air conditioning systems. These are the evaporator to remove heat from one environment, the condenser which deposits it to another and the thermal expansion valve (TXV) and compressor to reduce and increase system pressures. The process takes advantage of highly compressible refrigerants to achieve the cycle which are leveraged due to the high thermal energy available during phase change. This allows for heat exchange with minimal temperature change making the thermal range of operation much lower on the system components. It also allows for heat extraction from low temperature sources and with a low temperature differential between environments.

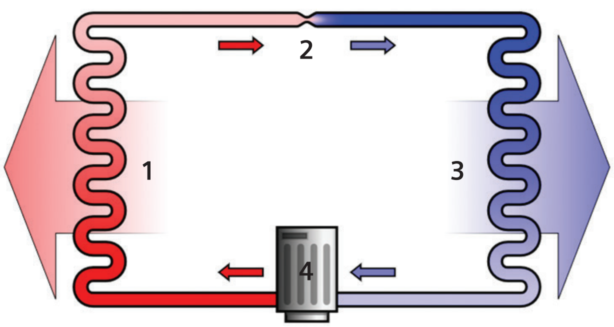


Figure 1: Simple four component air conditioning close loop.

Potential solutions

There are a number of possible methods to effectively cool the battery and cabin simultaneously in an electric vehicle. The first is the most traditional method where a minimum of two heat exchangers are used, the first heat exchanger is used to cool the cabin in the same manner as in an ICE vehicle. A second evaporator is added to the system in parallel which is usually of the plate frame variety, this interfaces with intermediatery cooling fluid which is pumped around the battery. This system can be extended to include multiple cabin or battery heat exchangers, which is typically done in larger more luxury vehicles for multi zone cooling.

The second method of combined AC cabin and battery cooling is to directly cool the battery using the working fluid of the AC system. While this system can more effectively thermally regulate the battery, it isn't without its risks. Due to the cooling fluid directly interfacing with the battery, it can lead to hot or cold spots. The cold spots are directly at the inlet to the battery as the sub zero fluid directly interfaces with the battery pouches, while hot spots can occur at the exit of the battery when the temperature differencial between the working fluid and battery is lower. This depends on the temperatures and flow rate of the working fluid and the battery configuration. While the mean temperature of the battery may be satifactory, the battery can still be sustaining damage. Just as in the previous solution, multiple heat exchangers could be used for the battery or the cabin to provide multi zone temperatures or regulate multiple batteries.

Both of these systems provide a solution to battery cooling which can heat or cool the battery and cabin independently. The only major drawbacks to this are the increased system costs, control complexity and additional maintainance required. These are all minor compared to many systems on ICE vehicles.

The final potential solution is to cool the cabin only and to take the rejected air and pass that over the battery. Figure 2 shows how the cabin air can be re used to cool the battery before being exhausted to the atmosphere.

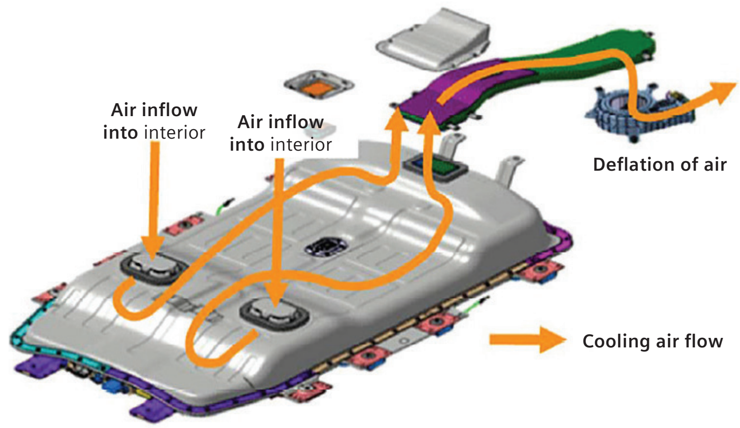


Figure 2: Air flow from the cabin being used to cool the battery [4].

This is a viable solution as the vehicle occupants' comfortable temperature level and battery optimal operating point are very similar. BEV batteries typically operate optimally at approximately 20°C and 40°C. The European Pharmacopoeia defines the comfortable range for humans as being between 15 and 25°C [5]. This is inline with battery optimal thermal condition. While this solution has several major advantages, mainly that it requires less components, hence reduced cost and maintenance, there are multiple engineering challenges that also need to be addressed. The first is that humans have different perceived comfort levels, this could result in the battery being kept below its optimal range of operation, individuals may also choose to not operate the air conditioining system as they believe it will increase range if they are not aware of this solution. This first issue isn't detrimental to battery longevity as the battery wont be perminantely damaged by being operated too cold, in addition to this the temperature isn't extreme so most people probably wouldn't notice the difference in range. The second concern is much more important as the battery could overheat without cooling, but in these conditions most people would start the air condtioning system.

The next thing to consider with this solution is that many people prefer the air not to be blown at their faces directly, this solution requires a high air flow rate to cool the battery and cabin simultaneously so a bypass should ideally be used. Finally this solution is susceptible to fowling or dust ingress which could restrict or completely block airflow over time leading to localized overheating and the potential for cell combustion.

Case study

A case study has been created to demonstrate how a twin heat exchanger model with a separate battery thermal management loop can be modeled using the vapor cycle capabilities of Simcenter Flomaster. This has been leveraged to create a full BEV thermal system solution. Figure 3 shows how a simple system can be built up into a full EV thermal management solution, this comprises of the cabin loop (red) interacting with the AC system (blue). The AC system also interacts with the battery cooling solution (green). Finally, the motor and inverter cooling system is shown in brown.

Each of these systems have several modes of operation, the first of these is the cabin loop (red), by controlling the three way valves air can either be recirculated or fresh air can be drawn into the circuit. A fan drives the air and then a second three-way valve controls the airflow path where it can interact with either the AC system or a heater core.

The AC system (blue) uses a condenser, which is positioned at the front of the vehicle, and with the ambient conditions and airflow representing the vehicle moving at highway speed. Two flow paths enable the working fluid to be sent to the cabin evaporator or the battery evaporator. The TXVs provide feedback from the evaporators to control their position. This enables the system to respond to different operating points such as the ones described for the cabin loop. The system uses a tube and fin heat exchanger for the cabin loop while the battery loop evaporator utilizes a plate frame evaporator. This allows the water/ glycol solution to pass through it properly, which is used to thermally manage the battery and minimize, hot spots or temperature spikes. The working fluid is then combined together from the two streams after which it is compressed back up to the high side operating point. The AC Circuit Manager component controls the whole system by specifying R134a as the working fluid and setting the low side pressure.

The battery cooling loop (green) interfaces with the AC system to provide cooling to the battery. It also has two other paths available where it can receive heat from the front of the vehicle from the motor and inverter loop or, like the cabin, do nothing and simply recirculate the fluid if the battery is at the desired operating point. These valves can also be controlled to do a combination of these if only a small amount of heating or cooling is required to maintain an optimal operating point.

The final major fluids system is for cooling the power electronics; this is primarily for the electric drive motor and the inverter/ transformer. As this system uses the same fluid as the battery cooling loop these two systems are connected through the fluid reservoir system that allows for fluid expansion and simpler maintenance and "topping up". This is a relatively simple system but due to the heat exchanger stack at the front of the vehicle, the cooling heat exchanger in this loop is what is used to heat the battery if it requires it. By carefully considering the heat exchanger stack at the front of the vehicle heat can be effectively moved around the various systems and repurposed where possible.

By analyzing how all of these systems combine and interact to create a complete thermal management solution the best possible layout for a BEV can be achieved while waste can be minimized, hence reducing costs. This results in vehicle range being maximized by reducing further electrical draw in the form of heaters and coolers and operating the motor, inverter and batteries at their optimal operating conditions.

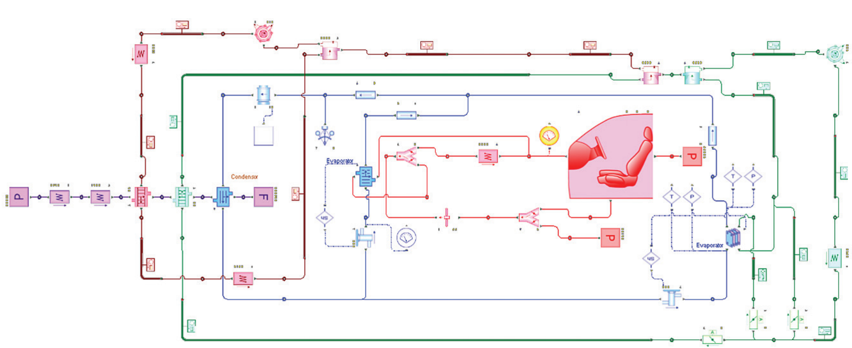


Figure 3: Full BEV system model.

Testing scenarios

As the system is able to be operated in multiple states with various fluid flow paths, a total of 84 unique scenarios have been created. Table 1 shows a small number of these and they were all run using a design of experiments.

Table 1 – Smart sample of possible testing scenarios for the BEV model

Recirculate/ fresh air cabin	AC system/ heater core	Cabin/battery priority	AC/ Heat pump	Battery loop active	Battery heat/ cool/nothing	Power loop active
Recirculation	AC system	Cabin	AC	Yes	Cool	Yes
Fresh air	AC system	Cabin	AC	Yes	Cool	Yes
Recirculation	AC system	Cabin	AC	Yes	Cool	No
Fresh air	AC system	Cabin	AC	Yes	Cool	No
Recirculation	AC system	Cabin	AC	Yes	Heat	Yes
Fresh air	AC system	Cabin	AC	Yes	Heat	Yes
Recirculation	AC system	Cabin	AC	Yes	Heat	No
Fresh air	AC system	Cabin	AC	Yes	Heat	No
Recirculation	AC system	Cabin	AC	Yes	Nothing	Yes
Fresh air	AC system	Cabin	AC	Yes	Nothing	Yes
Recirculation	AC system	Cabin	AC	Yes	Nothing	No
Fresh air	AC system	Cabin	AC	Yes	Nothing	No

In addition to this, three scenarios were selected that represent a minimum load, a mean load, and a maximum system load so that the system could be understood in greater detail. The maximum load case has been highlighted in Table 1, this was run with an ambient temperature of 25°C but with an initial battery and cabin temperature of 40°C.

Results

From the simulation of the model, the correct function of the system has been examined. The AC Circuit Manager has been used to get an overview of system performance. In this model, the coefficient of performance is 3.71 and the heat output is 11.44 kW. This demonstrates a well-optimized high performing system for this application. Further to this the heat, power and efficiencies match up, demonstrating a correct solution to the problem.

Table 2 – System level results

Results	Optimized state point
Coeff. of performance	3.71
Net power input (kW)	2.48
Total heat input (kW)	9.20
Total heat output (kW)	11.44
Total fluid mass (kg)	8.63
Compressor outlet temp (°C)	84.9
TXV outlet temp (°C)	1.51
High side pressure (bar)	15.4
Low side pressure (bar)	3
Mass flow rate (kg/s)	0.05

The only major concern from the system level results is the high system charge mass. For an automotive application, this is approximately four times too great and therefore needs to be further optimized. After further investigation of the system it was determined that the charge mass was concentrated in the condenser as it was used as a combined condenser and receiver drier. For this application, this technique is not required and wastes material. It could only be reduced by a certain amount though so that it did not affect system performance. After careful optimization the charge mass was reduced from 8.6 kg to 2.4 kg with no adverse effects. This was achieved purely through varying the condenser geometry.

The Pressure Enthalpy diagram shows good overall performance but the pressure drop in the condenser is quite high, there is potential for this to be optimized too based on the internal geometry but the external dimensions are limited.

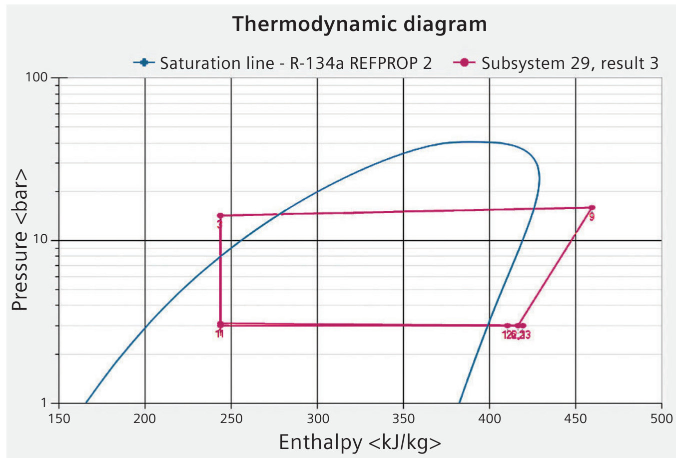


Figure 4: P-h diagram of full BEV AC system.

The P-h diagram clearly shows the expansion process and pressure rise over the compressor. The pressure drop through all of the other components can also be observed. This diagram shows a significantly higher level of superheating after the two heat exchangers with a combined superheat value of 19K.

An investigation into the higher superheat and higher pressure loss through the condenser was conducted. This was due to the TXVs opening more to achieve the desired cooling potential of the cabin and batteries at high system load. This results in a higher system mass flow rate of 0.05 kg/s compared to the 0.035 kg/s in the median use case. The pressure rise over the compressor is therefore reduced from 22 bar to 16 bar.

This happens, as there is a high potential of heat available in the cabin and battery. The scenario that was simulated here was that the vehicle had been parked outside all day and now the vehicle has been started at the end of the day so the ambient conditions are cooler. This results in the cabin having an initial temperature of 40°C and the battery and cooling fluid sitting at 35°C. This stretches the system to its maximum design point so the refrigerant is circulating very quickly to try to cool the system. If the system was operating at a more conservative point, then the AC system would respond in a more typical way. This demonstrates that the same system can operate at different points to determine full system performance at a range of states.

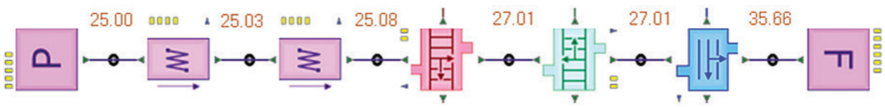


Figure 5: Temperature change through the heat exchanger stack.

Another important consideration is how the air temperature changes through the heat exchanger stack at the front of the vehicle. The first heat exchanger is for the motor and inverter so it is generating heat, the second green HX loop is inactive in this scenario but it would ideally be removing heat. The final heat exchanger is the condenser for the AC system and adds a significant amount of heat to the outlet air. As a systems designer, this stack's layout could potentially be improved by placing the battery loop behind the AC system to provide maximum heating potential. Two points should first be raised, are you likely to run the battery heating and AC systems at the same time? If this were the case, would a heat pump not be more efficient? There is also a packaging consideration at the front of the vehicle. If this was re-configured, would it all still fit in the space provided?

Another way to analyze the system performance is to consider the air leaving the vehicle cabin and the air temperature entering the cabin after the AC system. Given that the air is leaving that cabin at 40°C the inlet air is at 21°C which would cool the cabin down to a much more comfortable level relatively quickly.

The other consideration is the battery temperature. The system loop is initially at 35°C and after travelling through the battery, it reaches 42°C. This flows back into the reservoir system at 26°C however, there isn't a high enough flow to sufficiently cool the battery as the inlet temperature is still at 35°C, this is shown in figure 6.

Given the results, the battery will not significantly cool down as the cabin is being prioritized during the initial startup and cooling procedure. This could indicate a number of things;

The system is undersized to cope with this scenario, this could be intentional to reduce costs and the designer feels that this is an extreme edge case.

The system is designed to prioritize the cabin occupant's comfort over battery life in this scenario.

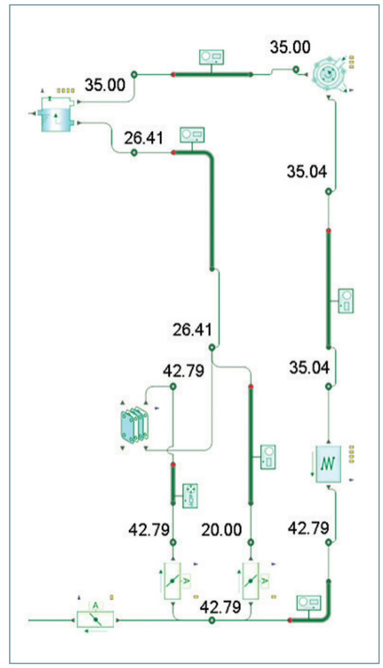


Figure 6: Battery cooling loop temperature results.

The battery is still at a relatively safe operating point with an upper limit of 40°C.

Once the cabin achieves a suitably comfortable temperature then the battery could be cooled faster.

All of these are important system design considerations and simulations like this allow informed decisions to be made about system sizing and performance.

To try to understand this further a study was conducted to investigate the condenser frontal area, the fluid volume and the compressor speed. The results from the compressor speed investigation are shown in figure 7.

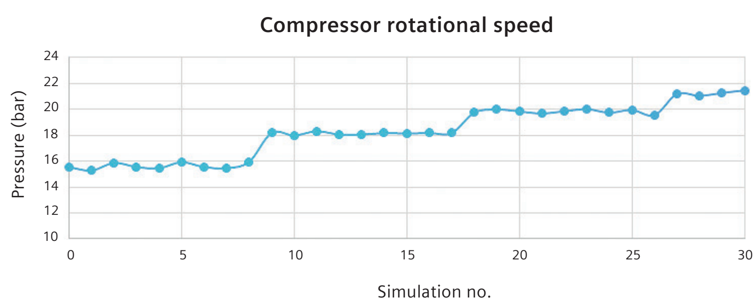


Figure 7: Compressor rotational speed parametric study considering pressure rise.

The compressor speed only impacts the high side pressure and the mass flow rate to a lesser extent. This was due to the TXVs compensating for the higher flow rate so they increased the restriction on the fluid. This resulted in minimal additional heat being removed, but the COP being reduced due to the increased compressor power.

Figure 8 shows the results from the fluid volume and front area investigations. The frontal area had minimal impact on the condenser cooling potential as the overall heat exchanger size wasn't varied which resulted in similar performance. The condenser fluid volume had a positive impact on the system though but this comes at a cost. By increasing the condenser fluid volume, the cost of the component is greatly increased. It is important to note that this is an extreme operating case and is unlikely to happen in most countries, it was conducted to push the system to its limits and understand the boundaries of system operation. It is important to consider what should be prioritized in this situation the battery longevity or passenger comfort, though both could lead to problems in a production system.

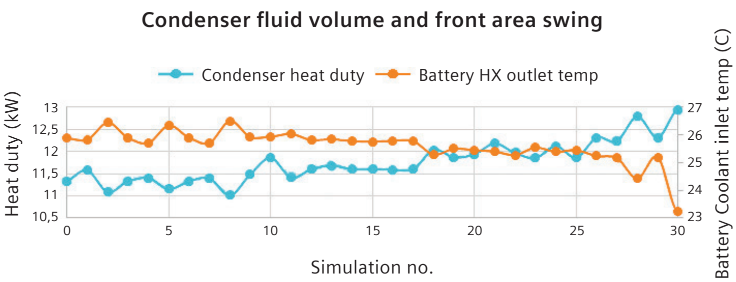


Figure 8: Condenser heat duty parametric study and front area investigation results.

The other significant use case is when the system in operating in a very low load scenario, this is when the cabin AC is on and recirculating a flow of 22°C but no other major systems are active. Under these conditions, the system is massively oversized and it was found that the best solution here is to implement a control strategy to reduce the compressor speed and actively control the TXV positions be de coupling them directly from the evaporator superheat with an intermediate controller. The results from this investigation pushed the high side working pressure from 15 bar to 32 bar, which was the maximum safe operating point of the system. This is interesting as it demonstrates that the system pressures are inversely proportional to the heat input. This is due to the mass flow rate being restricted through the TXVs so that a suitable level of superheating is achieved for the system to operate optimally and without damaging the compressor. This also shows that an accumulator and receiver drier are not necessary as the system self corrects and balances itself.

While it has been demonstrated that the system can operate in this low load condition, it is not the most efficient method to thermally regulating the cabin. It would be far better to turn the AC system off and bring fresh air into the cabin. This could potentially be achieved through sensors and controllers. Additionally, it may be more efficient to run the system for short periods of time in a more efficient region and then switch the system to recirculate the cooled air flow which the AC system is off. It would then be restarted when the cabin air quality drops to a set point.

Conclusion

While there are several possible ways to thermally manage a battery electric vehicle, it is important to understand the positive and negative factors for each. While this paper only considered the most commonly used technique and outlines why this is done, the methods used throughout could easily be applied to other battery thermal management systems. In considering the complete AC system design for this application, a number of issues arose that are critical to ensuring optimal performance. These were addressed quickly and easily using several studies, but could have proven costly later in the design process. The results discussed demonstrate how Simcenter Flomaster's accuracy when simulating these types of systems can add significant value to the design of a BEV or equally any thermal management problem.

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