A SIMPLE METHOD ON EQUIPMENT SELECTION METHODOLOGY OF VAPOR COMPRESSION REFRIGERANT ELECTRIC VEHICLE AIR-CONDITIONING SYSTEM

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ABSTRACT: This paper presents a simple method on equipment selection of vapor compression refrigerant, electric vehicle air-conditioning system i.e. electric compressor and electronic expansion valve (EEV). This method utilized validated compartment cooling load model to identify maximum cooling capacity of selected vehicle specifications. The maximum cooling capacity determined the appropriate sizes of the compressor and electronic expansion valve by matching the predicted maximum cooling capacity with data published by the manufacturer. By using this method, the predicted maximum cooling capacity of a 1.6L Proton Wira Aeroback passenger car was estimated at 2.9 kW. The results show that the appropriate electric compressor and EEV for the air-conditioning system are from high voltage brushless DC variable speed hermetic compressor, type SIERRA06-0982Y3 and Danfoss EEV type ETS 6 – 14 respectively.

KEYWORDS: *Vehicle Air-Conditioning System, Equipment Selection Method, Compartment Cooling Load Model, Electric Compressor, Electronic Expansion Valve*

1.0 INTRODUCTION

In the case of electric vehicles (EVs), one of the major successful factors of these vehicles in future is it must meet the consumer needs of city driving and longer distances for holiday outings, etc. One of these needs is the thermal comfort which is to be provided by the air-conditioning (A/C) systems that runs on battery. The A/C cooling load is the most significant auxiliary loads [1, 2], reported second largest of energy consumption after power train [3]. Thus, its operation becomes critical for full EVs due to limited battery storage capacity, limited battery charging station and longer time taken to charge the battery compared to fuel conventional internal combustion engine powered vehicles. The battery is not only used to run the electric motor to run the EV, but also to run the A/C system, as well as other accessories thus reducing the driving range of the EVs. Therefore, the correct size of component selection i.e. compressor and expansion valve in the early stage of system development are significant in producing efficient vehicle air-conditioning (VAC) system.

Senawi [4] stated that accurate prediction of design cooling load is important for equipment sizing. Farrington and Rugh [5] added that the size of the A/C system is related to the peak thermal load in the vehicle, which is generally related to the maximum temperature the compartment will reach while soaking in the Sun. Zheng et al. [6] and Li and Sun [7] stressed that the first challenge in the proper sizing of a VAC system is to accurately determine the compartment cooling load. In addition, Li and Sun [7] mentioned that the determination of cooling load and understanding of their variations are critical for the efficient design of the VAC system. Several reported studies here have produced a good agreement that through design maximum cooling load, adequate cooling capacity shall be supplied by the system can be calculated, enabling correct size of components of VAC system.

Previous studies have reported research in cooling load model [8,9,10,11,12] but so far however, there has been almost none detailed discussion about component selection process in the public domain mainly due to commercial confidentiality. Therefore, it is the intent of this paper to introduce a simple method in equipment selection for vapor compression refrigerant, VAC system that could be used as a basis in component selection. For an exercise, the selection of electric compressor and EEV, aimed to be used for future energy-efficient electric vehicle A/C system are discussed in this paper.

2.0 RESEARCH METHODOLOGY

The capacities of the electric compressor and EEV for the VAC system are selected according to possible maximum cooling capacity imposed to the vehicle cabin compartment. Figure 1 illustrates the cooling capacity calculation methodology in a diagrammatic form. For simplification, the maximum cooling capacity is determined from the hourly cooling capacity profile with the basis of front windscreen facing four different orientations i.e. North, East, South and West. In addition, compressed Singapore weather data of six typical days of the year as highlighted by Senawi [4] is used as weather input data. Designed cabin temperature and humidity ratio were set at 24°C and 50% respectively.

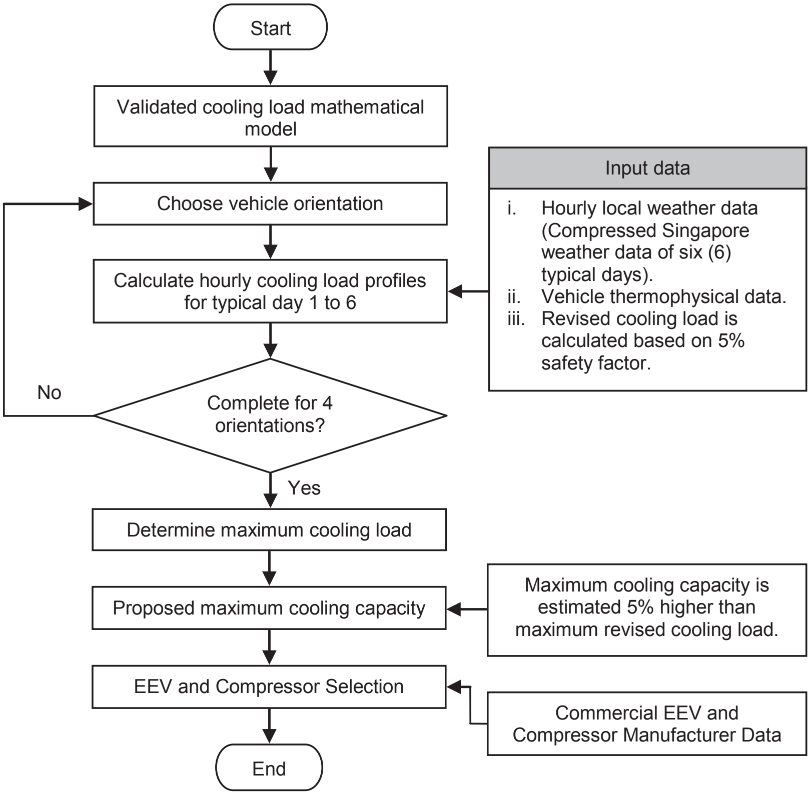


Figure 1: A flow chart of electric compressor and EEV selections

Since the accuracy of cooling load calculation highly depends on the assumption being made, a 5% heat is added to the sensible and latent heats due to probable error in load estimation (safety factor), as proposed by Arora [13]. In addition to probable heat loss, design maximum cooling capacity was 5% higher than design maximum cooling load. Then, the selection of the EEV and compressor are determined by matching/mapping the maximum cooling capacity with the available data published by the compressor and EEV manufacturers.

2.1 Cooling Load Mathematical Model

The hourly vehicle compartment cooling load calculation procedures is shown in Figure 2. Details of the validated cooling load mathematical model were explained by Sukri et al. [14].

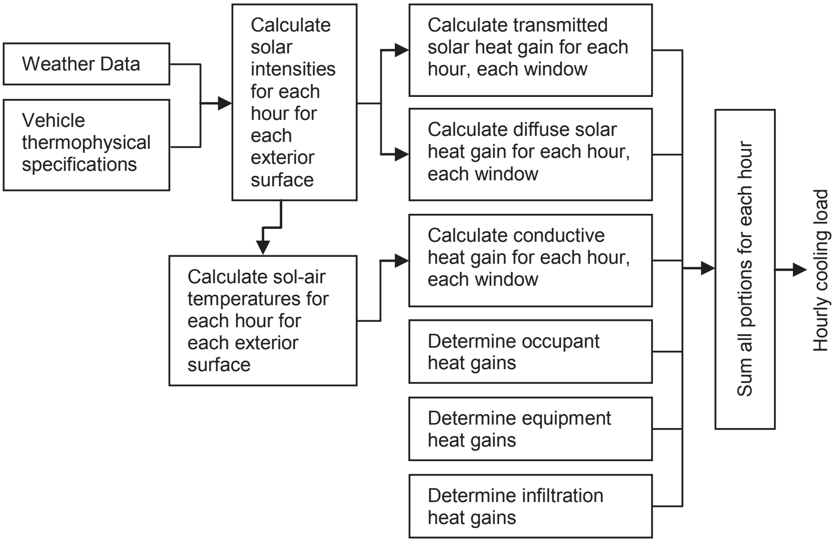


Figure 2: Simplified hourly vehicle compartment cooling load calculation procedures [14]

3.0 HOURLY COOLING CAPACITY PROFILE

By using vehicle compartment cooling load model as proposed by Sukri et at. [14], the effect of vehicle orientation on the hourly cooling capacity profile of a passenger car similar to 1.6 Proton Wira Aeroback specifications is investigated. Details of the cooling load model and thermophysical data of the passenger car can be found at Sukri et al. [14]. The cooling load profile enables prediction of maximum cooling capacity to be supplied for equipment selection. Besides cabin temperature of 24°C and relative humidity of 50%, the other designed conditions are four (4) passengers include a driver, dark in vehicle surface color and vehicle speed of 110 km/h.

Figure 3 to 6 show the hourly cooling capacity profile for Singapore six typical days with front windscreen facing North, East, South and West respectively. The cooling capacity is low in the early morning hours, gradually increases up to a maximum between 12 noon to 1 pm and then slowly decreases to around its initial value. The highest cooling capacity typically occurs between 12.00 noon to 1 pm. Figure 3 to 6 also show that the hourly cooling capacity profiles for all four orientations are almost identical. This is due to the fact that all exterior surfaces of right and left doors and windows, front and rear wind screens, floor and roof still contribute to conductive/convective heat loads although the orientation is changed. Therefore, the weakest exterior surfaces, which are exposed to direct solar radiation at critical hours, will lead to the highest cooling capacity required by the cabin compartment. Critical hour is identified as hour where ambient dry bulb temperature, direct solar radiation and diffuse sky radiation incident on a horizontal surface are high.

From Figure 3 to 6, the highest required cooling capacity is 2.896 kW (2.9 kW round up), which occurs when the front windscreen is facing South occurs at 1.00 pm.

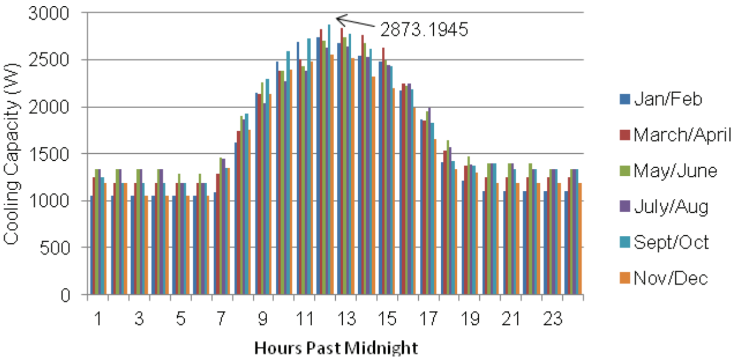


Figure 3: Cooling capacity profile during front windscreen facing North

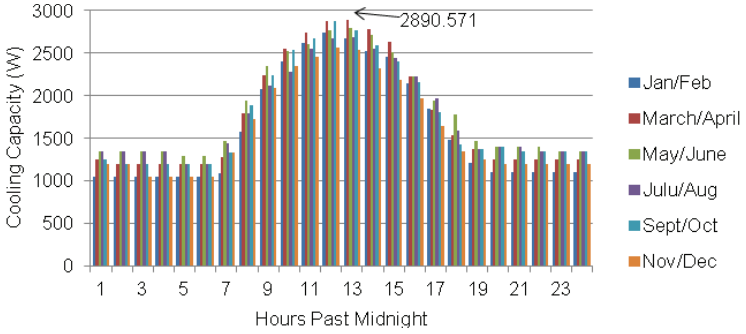


Figure 4: Cooling capacity profile during front windscreen facing East

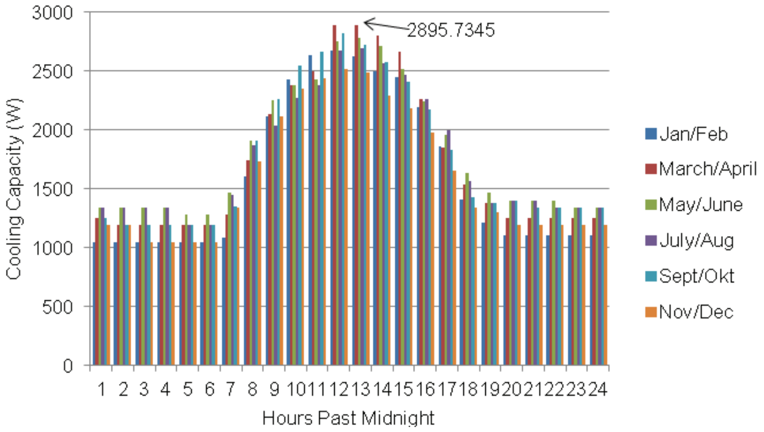


Figure 5: Cooling capacity profile during front windscreen facing South

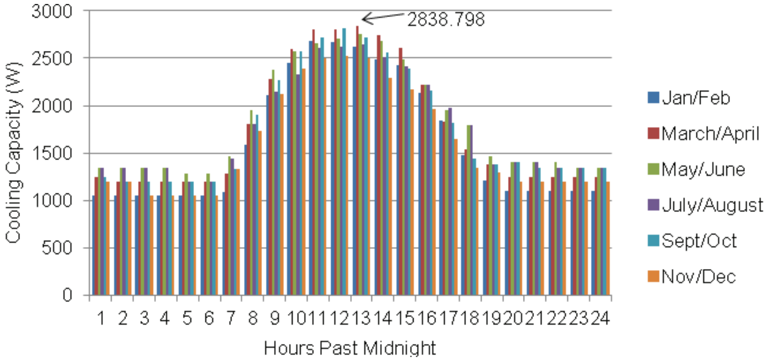


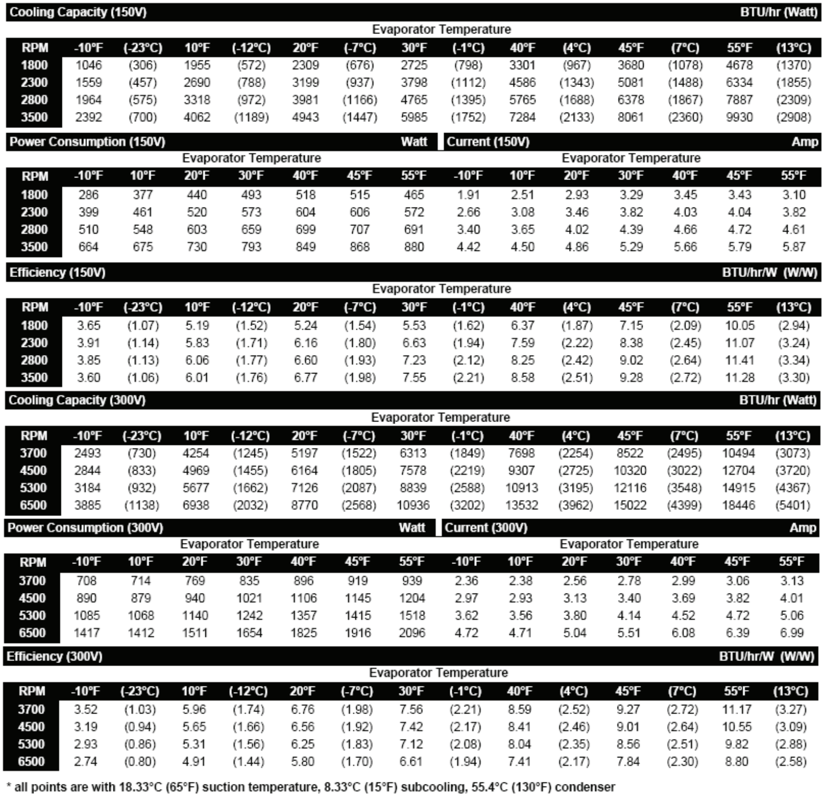
Figure 6: Cooling capacity profile during front windscreen facing West

3.1 The Compressor Selection

The selected compressor unit is from high voltage brushless DC variable speed hermetic compressor, type SIERRA06-0982Y3 as shown in Figure 7. According to manufacturer technical data as in Table 1, this compressor is able to produce cooling capacity between 967 W to 5401 W at evaporating temperature of 4 to 13°C, compressor input voltage of 150 to 300V and compressor speed of 1800 to 6500 rpm respectively [15]. This compressor is selected due to the fact that the designed maximum cooling capacity of 2896 W is in the compressor output range. In addition, higher capacity of this compressor can be matched with higher cabin cooling capacity than maximum designed value (if occurs), in the case of lower setting cabin temperature than 24°C, more than 4 passengers in the cabin, extreme ambient conditions and higher vehicle speed than 110 km/h.

Figure 7: A SIERRA06-0982Y3 high voltage brushless DC variable speed hermetic compressor [15]

Table 1: SIERRA06-0982Y3 compressor data sheet [16]



Cooling Capacity (150V)														BTU/hr (Watt)
	Evaporator Temperature													
RPM	-10°F	(-23°C)	10°F	(-12°C)	20°F	(-7°C)	30°F	(-1°C)	40°F	(4°C)	45°F	(7°C)	55°F	(13°C)
1800	1046	(306)	1955	(572)	2309	(676)	2725	(798)	3301	(967)	3680	(1078)	4678	(1370)
2300	1559	(457)	2690	(788)	3199	(937)	3798	(1112)	4586	(1343)	5081	(1488)	6334	(1855)
2800	1964	(575)	3318	(972)	3981	(1166)	4765	(1395)	5765	(1688)	6378	(1867)	7887	(2309)
3500	2392	(700)	4062	(1189)	4943	(1447)	5985	(1752)	7284	(2133)	8061	(2360)	9930	(2908)

Power Consumption (150V)							Watt	Current (150V)						Amp
	Evaporator Temperature							Evaporator Temperature						
RPM	-10°F	10°F	20°F	30°F	40°F	45°F	55°F	-10°F	10°F	20°F	30°F	40°F	45°F	55°F
1800	286	377	440	493	518	515	465	1.91	2.51	2.93	3.29	3.45	3.43	3.10
2300	399	461	520	573	604	606	572	2.66	3.08	3.46	3.82	4.03	4.04	3.82
2800	510	548	603	659	699	707	691	3.40	3.65	4.02	4.39	4.66	4.72	4.61
3500	664	675	730	793	849	868	880	4.42	4.50	4.86	5.29	5.66	5.79	5.87

Efficiency (150V)														BTU/hr/W (W/W)
	Evaporator Temperature													
RPM	-10°F	(-23°C)	10°F	(-12°C)	20°F	(-7°C)	30°F	(-1°C)	40°F	(4°C)	45°F	(7°C)	55°F	(13°C)
1800	3.65	(1.07)	5.19	(1.52)	5.24	(1.54)	5.53	(1.62)	6.37	(1.87)	7.15	(2.09)	10.05	(2.94)
2300	3.91	(1.14)	5.83	(1.71)	6.16	(1.80)	6.63	(1.94)	7.59	(2.22)	8.38	(2.45)	11.07	(3.24)
2800	3.85	(1.13)	6.06	(1.77)	6.60	(1.93)	7.23	(2.12)	8.25	(2.42)	9.02	(2.64)	11.41	(3.34)
3500	3.60	(1.06)	6.01	(1.76)	6.77	(1.98)	7.55	(2.21)	8.58	(2.51)	9.28	(2.72)	11.28	(3.30)

Cooling Capacity (300V)														BTU/hr (Watt)
	Evaporator Temperature													
RPM	-10°F	(-23°C)	10°F	(-12°C)	20°F	(-7°C)	30°F	(-1°C)	40°F	(4°C)	45°F	(7°C)	55°F	(13°C)
3700	2493	(730)	4254	(1245)	5197	(1522)	6313	(1849)	7698	(2254)	8522	(2495)	10494	(3073)
4500	2844	(833)	4969	(1455)	6164	(1805)	7578	(2219)	9307	(2725)	10320	(3022)	12704	(3720)
5300	3184	(932)	5677	(1662)	7126	(2087)	8839	(2588)	10913	(3195)	12116	(3548)	14915	(4367)
6500	3885	(1138)	6938	(2032)	8770	(2568)	10936	(3202)	13532	(3962)	15022	(4399)	18446	(5401)

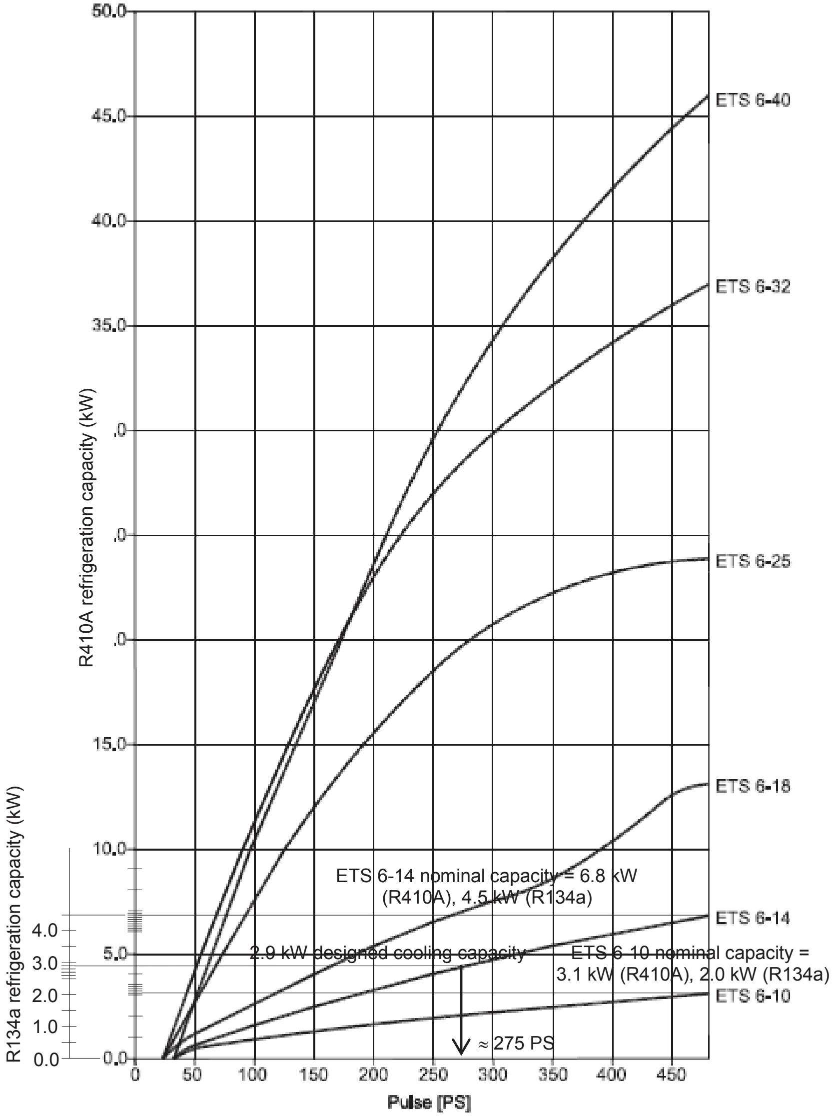
Power Consumption (300V)							Watt	Current (300V)						Amp
	Evaporator Temperature							Evaporator Temperature						
RPM	-10°F	10°F	20°F	30°F	40°F	45°F	55°F	-10°F	10°F	20°F	30°F	40°F	45°F	55°F
3700	708	714	769	835	896	919	939	2.36	2.38	2.56	2.78	2.99	3.06	3.13
4500	890	879	940	1021	1106	1145	1204	2.97	2.93	3.13	3.40	3.69	3.82	4.01
5300	1085	1068	1140	1242	1357	1415	1518	3.62	3.56	3.80	4.14	4.52	4.72	5.06
6500	1417	1412	1511	1654	1825	1916	2096	4.72	4.71	5.04	5.51	6.08	6.39	6.99

Efficiency (300V)														BTU/hr/W (W/W)
	Evaporator Temperature													
RPM	-10°F	(-23°C)	10°F	(-12°C)	20°F	(-7°C)	30°F	(-1°C)	40°F	(4°C)	45°F	(7°C)	55°F	(13°C)
3700	3.52	(1.03)	5.96	(1.74)	6.76	(1.98)	7.56	(2.21)	8.59	(2.52)	9.27	(2.72)	11.17	(3.27)
4500	3.19	(0.94)	5.65	(1.66)	6.56	(1.92)	7.42	(2.17)	8.41	(2.46)	9.01	(2.64)	10.55	(3.09)
5300	2.93	(0.86)	5.31	(1.56)	6.25	(1.83)	7.12	(2.08)	8.04	(2.35)	8.56	(2.51)	9.82	(2.88)
6500	2.74	(0.80)	4.91	(1.44)	5.80	(1.70)	6.61	(1.94)	7.41	(2.17)	7.84	(2.30)	8.80	(2.58)

* all points are with 18.33°C (65°F) suction temperature, 8.33°C (15°F) subcooling, 55.4°C (130°F) condenser

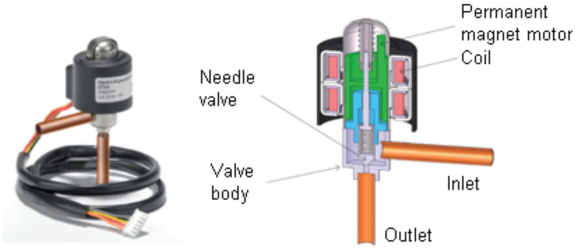
3.2 The Electronic Expansion Valve Selection

According to Figure 8, at 2.9 kW, the pulse of ETS 6 – 14 is around 275 PS. In the case of higher cooling capacity than 2.9 kW as described in section 4.1, the pulse signal can be increased to meet the cooling demand. For refrigerant R134a, this EEV can withstands cooling capacity up to 4.5 kW [17]. Through these reasons, Danfoss EEV, type of ETS 6 – 14 as in Figure 9 is chosen as EEV for the system.



Conditions: $T_e = 5°C$, $T_c = 38°C$, Subcooling = 0°C, Superheat = 0°C

Figure 8: Refrigerant capacity at different number of pulse for Danfoss EEV, model ETS 6



(a) (b)

Figure 9: Danfoss EEV type ETS 6. (a) Actual view (b) cross sectional view [17]

4.0 CONCLUSION

A simple method in equipment selection of vapor compression refrigerant electric vehicle air-conditioning system by using validated cabin compartment cooling load model was proposed and discussed. For designed conditions: cabin temperature of 24°C, relative humidity of 50%, four (4) passengers include a driver, dark in vehicle surface color, vehicle speed of 110 km/h and vehicle thermophysical data similar to 1.6L Proton Wira Aeroback, the designed cooling capacity is estimated around 2.9 kW. Through this analysis, the appropriate electric compressor and EEV are from high voltage brushless DC variable speed hermetic compressor, type SIERRA06-0982Y3 and Danfoss EEV type ETS 6 – 14 respectively. In general, the proposed method can be used for air-conditioning system for equipment selection. However, further analysis i.e. laboratory testing is required to validate the proposed method.

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REFERENCES

[1] H. Zhang, L. Dai, G. Xu, Y. Li, W. Chen and W. Tao, "Studies of air-flow and temperature fields inside a passenger compartment for improving thermal comfort and energy saving. Part 1: Test/numerical model and validation". *Applied Thermal Engineering,* Vol. 29, pp. 2022-27, 2009.

[2] S. Kaushik, K. H. Chen, T. Han and B. Khalighi, "Micro-cooling/heating strategy for energy efficient HVAC system". *SAE Technical Paper*, 2011.

[3] M. A. Roscher, W. Leidholdt and J. Trepte, "High Efficiency Energy Management in BEV Applications". *Electrical Power and Energy Systems*, Vol. 37, pp 126-30, 2012.

[4] M. Y. Senawi, *Development of a Building Energy Analysis Package (BEAP) and Its Application to the Analysis of Cool Thermal Energy Storage System,* Ph.D. thesis, Universiti Teknologi Malaysia, 1998.

[5] R. Farrington and J. Rugh. (2000). Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range, Earth Technologies Forum Washington, D.C.

[6] Y. Zheng, B. Mark and H. Youmans, "A simple method to calculate Vehicle Heat Load". *SAE Technical Paper*, 2011.

[7] W. Li and J. Sun, "Numerical Simulation and Analysis of Transport Air Conditioning System Integrated with Passenger Compartment". *Applied Thermal Engineering,* Vol. 50, pp. 37-45, 2013.

[8] D. Kohli, "Mathematical Model for Design Conditions for Cooling Load Calculations". *ASME Transactions*, Vol. 103, pp. 328-34, April 1981.

[9] F. Stancato, H. Onusic, R. A. Antonelli and P. U. Avila, "Experimental and Numerical Analysis of Cooling Loads in a Road Bus". *SAE Technical Paper*, Oct 1992.

[10] F. Stancato and H. Onusic, "Road bus heat loads numerical and experimental evaluation". *SAE Technical Paper*, 1997.

[11] H. Mohamed Kamar, *Computerised Simulation of Automotive Air Conditioning System*, Ph.D. thesis, Universiti Teknologi Malaysia, 2008.

[12] M. A. Fayazbakhsh and M. Bahrami, "Comprehensive Modeling of Vehicle Conditioning Loads Using Heat Balance Method". *SAE Technical Paper*, Aug 2013.

[13] C. P. Arora, *Refrigeration and Air Conditioning*, Third Edition, Singapore: McGraw-Hill, 2009.

[14] M. F. Sukri, M. N. Musa, M. Y. Senawi and H. Nasution, Modeling and Parametric Study of Cooling Loads Characteristics for Automotive Air-Conditioning System, 7th *International Meeting on Advances In Thermofluids*, Swiss-Garden Hotel and Residences, Kuala Lumpur Malaysia, Nov 2014, In Press.

[15] Masterflux. (2013). SIERRA06-0982Y3, MasterFlux., USA. [Online]. Available: http://www.masterflux.com/products/sierra/?pid=51

[16] Masterflux. (2013). SIERRA06-0982Y3 Technical Data Sheet, MasterFlux., USA. [Online]. Available: http://www.masterflux.com/userimages/SIERRA06-0982Y3_Data_Sheet.pdf

[17] Danfoss. (2014). Data sheet-Electric expansion valves Type ETS 6., Danfoss Group, Denmark. [Online]. Available: http://www.ra.danfoss.com/TechnicalInfo/Literature/Manuals/01/DKRCC.PD.VD1.D3.02_ETS6_vs.pdf