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Polymer Heat Exchangers for Electric Bus Battery Thermal Management Systems

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Executive Summary

Legislation influence and raising environmental awareness lead to significant growth in demand for zero-emission buses [1]. Among the newly registered eco-friendly public transportation vehicles the electric buses have the largest market share. Public Transport Operators are looking for the vehicles being able to meet the transportation system requirements with the lowest possible cost of ownership. Batteries used in the electric buses are the most expensive component both in terms of buying and their replacement. In order to maximize the battery lifespan it is crucial to maintain the proper temperature of the electrochemical cells. The crucial part responsible for transfering the heat between cells and the coolant is a heat exchanger. The standard method applied for a cold plate design is to use metal alloys, however due to research it may be not the most advantageous solution.

Based on the research works conducted by Solaris Bus & Coach S.A., the specific polymers being able to replace metal alloys for heat exchangers purposes were selected. In this paper the authors will present the results of study allowing the usage of polymer materials for lightweight and cost-effective cold plates.

1. Introduction

1.1 The importance of proper battery cell temperature

Batteries are one of the most complex components of modern electric bus. Behaviour and durability of the energy storage system is highly dependant on several crucial parameters, such as depth of discharge range and charging/discharging current among them, but cell temperature being the most significant one. Based on the researches conducted on lithium-ion batteries cell temperature negatively affects both cycling aging, as well as calendaric aging.

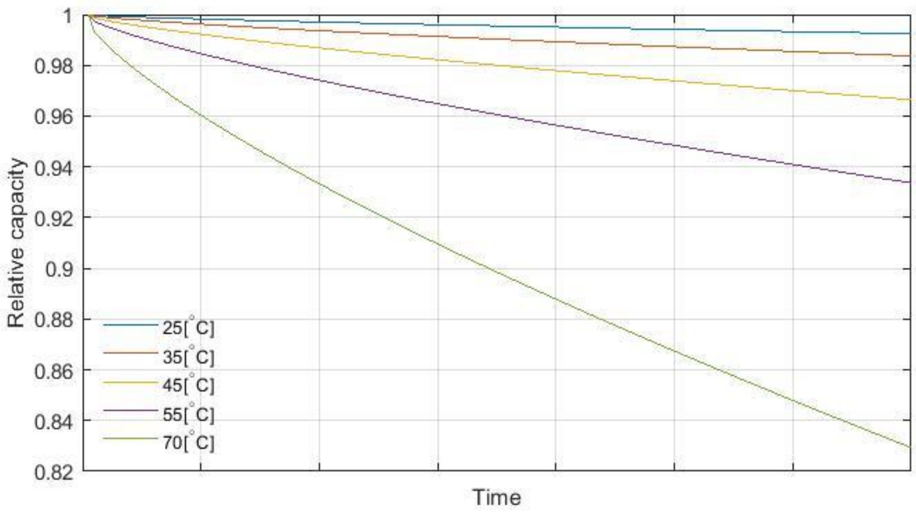

Figure 1: Impact of the cell temperature on aging process [2]

Overheating of battery systems is a serious threat not only in terms of technical reliability and efficiency, but is also increasing electric bus total costs of ownership. Batteries are not only a major part in battery electric buses capital expenditures, but additionally the lithium-ion battery systems replacements over time stand for significant fraction of maintenance costs.

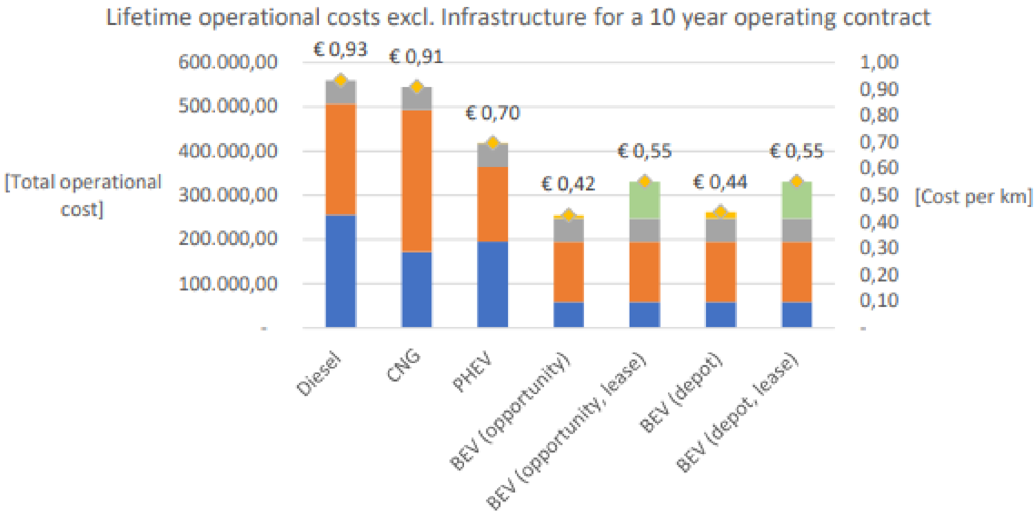

Figure 2: Estimated different propulsions bus operational costs [3]

1.2 Technical criteria desirable for a heat exchanger design

In order to select proper heat exchanger material key parameters crucial for correct operation were selected. Major criterium for analysed materials is thermal conductivity rate [4]. This value is especially high for conventional metal alloys. High thermal conductivity allow to rapidly transfer the heat from heat exchangers making it the crucial factor for the battery cold plate. Additionally the thermal contact conductance (Equation 1), the parameter describing energy transfer on contact surface between two materials [5], was analysed for chosen polymers.

$$q = \frac{T_a - T_c}{\frac{\Delta x_1}{k_1 * A} + \frac{1}{h_3 * A} + \frac{\Delta x_2}{k_2 * A}} \quad (1)$$

The massive challenge for battery systems design teams is to utilize effective method of increasing two components contact pressure, as well as maximize surface area of contact. The easiest, but not the most effective way to achieve this, it to use heat sink compounds or special thermopads. The drawback of this solution is growth of material and manufacturing cost, as well as keeping the dielectrical insulation on desirable level.

1.3 Analysis of automotive battery homologation requirements

In order to introduce the new generation of batteries for electric vehicles it is necessary to conduct and pass all demanded homologation testing. The mechanical safety testing is described complexly by UN-ECE R100.02 norm. The battery system, including the heat exchangers installed inside the pack have to successfully pass all of the evaluation phases. The most challenging for polymer exchangers are mechanical shock and fire resistance tests.

Electric buses are categorised by Consolidated Resolution on the Construction of Vehicles (R.E.3) as M3 vehicle type (Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes). To pass the testing the rapid deceleration and flame exposure of the battery is done. After the shock/flammability phase the battery needs to show no damage signs for at least one hour (for mechanical shock) or 3 hours (for flammability test) of observation.

Table 1: Basic thermal parameters of few analysed materials [6]

	M3 Mechanical Shock Testing
Maximum longitudinal acceleration (g)	12
Maximum transverse acceleration (g)	10
Maximum acceleration timespan (ms)	30

Additionally the flammability tests can be found in extended form in Regulation No 118 of UN-ECE. For polymer materials additional norm UL 94 Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances testing.

2. Usability of polymer heat exchangers

2.1 Advantages of adopting the polymers for heat exchangers design

Polymers compared to the metal alloys have several key benefits from both an engineering and economical point of view – lower gravimetric density and more effective series manufacturing are one of those factors. Although, when comparing sheer parameters describing as Young's modulus or ultimate tensile strength the metal are superior to polymers, but for heat exchangers these values are not the most crucial ones.

Table 2: Basic mechanical parameters of few analysed materials

	7075-T6 Aluminium	304 Stainless Steel	HDPE
Young modulus (GPa)	70	210	0.7
Yield stress (MPa)	500	240	25
Ultimate tensile strength (MPa)	570	590	35
Fracture toughness ($MPa \cdot m^{1/2}$)	28	50	3.5
Thermal expansion (10^{-6}/K)	33	17	225

Based on the conducted analysis of heat exchangers design the most suitable solutions for mass production are injection (for most complex shapes) and plastic extrustion for cold plates with cross-section not changeable on one of the axis. The investments needed to establish polymer manufacturing line is much higher compared to classic metal machining methods (mostly due to the need of designing and manufacturing the die forms). Fortunately the fused filament fabrication (FFF), as well as other additive manufacturing methods allow rapid creation of prototypes, on which it is possible to evaluate the design and implement necessary upgrades.

Additive manufacturing is also an interesting option for small volume manufacturing. In terms of cost-effectivness it seems like a optimal choice for pilot projects – there is no need to prepare special tooling. Higher manufacturing cycle time of components made by various 3D printing and lower dimensional tolerance compared to previously mentioned methods[7] still can be an valuable alternative.

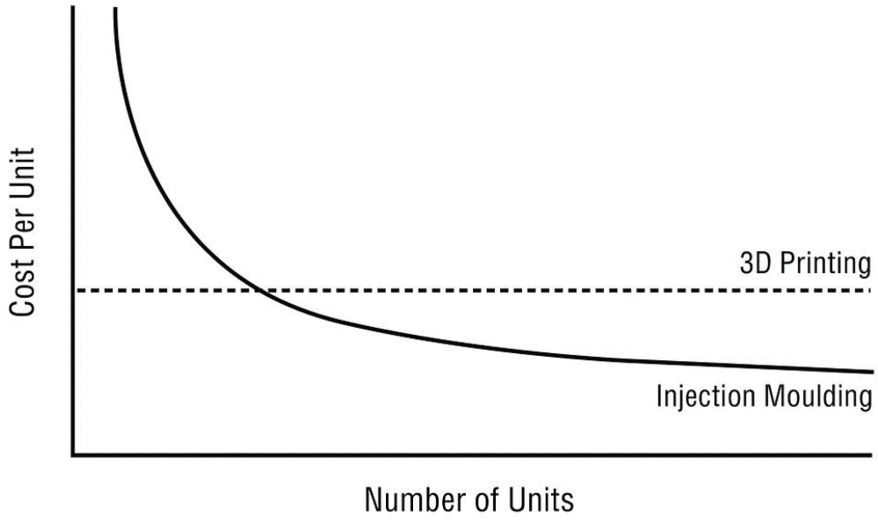

Figure 3: Generalised cost curve of 3D printing versus injection-moulding [8]

2.2 Polymers suitable for thermal management purposes

The research on selecting the matching materials for electric bus thermal management system components was performed. Based on the parameters chosen in the previous chapter the polymers with sufficient thermodynamic characterictics were analysed. During the reseach both popular thermoplastics, as well as high-performance plastics where evaluated.

Table 3: Basic thermal parameters of few analysed materials

	PPSU	PPS	PA6.6	LDPE
Density (kg/m^3)	1290	1430	1120	920
Specific heat capacity (J/g*K)	1.0	1.0	2.2	2.2
Thermal conductivity (W/m*K)	0.35	0.3	0.26	0.3

Polyphenyl sulfone (PPSU) and polyphenylene sulfide (PPS) were found to be meeting the requirements needed for the polymer heat exchangers. These materials combine decent thermal conductivity, good mechanical shock resistance and dimensional stability. Additionally, due to the desirable dielectric property, there is no need to use additional layer of electrical insulation. The electroinsulating layer between battery cell and heat exchanger usually negatively affects the ability to transfer the heat to the coolant, therefore it is advantageous not to utilize it in the battery. PPSU and PPS are eligible to be molded or extruded. Thermal expansion factor of materials is comparable to steel alloys used as battery frame material. Therefore the strain between the frame and the heat exchanger is decreased and the risk of cold plate mechanical failure is significantly lower.

2.3 Comparision of polymer and conventional metal heat exchangers

The polymer heat exchangers have a few technical drawbacks when compared to conventional metal alloy counterparts. With specific design of the cold plate the negative effects regarding battery behaviour can be avoided [9]. Lower thermal conductivity value of the polymers could be overcame by proper heat exchanger shape. During the design phase of battery equipped with polymer heat exchangers it is necessary to take into consideration the heat distortion temperature in order not to cause deformation of the heat exchanger material.

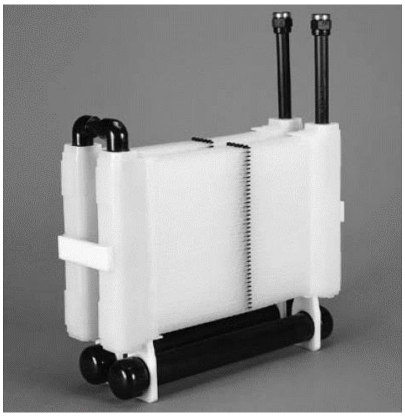

Figure 4: Example of polymer heat exchanger with high surface/volume ratio [10]

The usage of polymer heat exchangers have multiple advantages over conventionally used metal alloys for cold plate purposes. The lower gravimetric density and cost-effectivnes are among most important general superiorities. For automotive purposes and especially for electric vehicle battery design the described polymers offer also dielectric property, good cracking resistance, desirable chemical protection against compounds used for battery cells and flame and smoke resistance.

3. Future of the polymer heat exchangers

The polymer chemistry is a very fast developing branch of science and engineering. The development of the polymer additives is able to change the specific material parameters vastly [11]. The selection of the proper additives mixture results in obtaining dielectrical material with relatively high thermal conductivity. The well-known and reliable plastic manufacturing techniques, including injection and extrustion, will allow to create lightweight and affordable solutions for battery thermal management systems. The demand for electric public transportation vehicles is still rapidly emerging.

Based on the conducted research and Solaris Bus & Coach S.A. experience in providing state-of-the-art public transport vehicles the polymer heat exchangers seems like a possible solution for creating lightweight and cost-efficent battery thermal management system. The accurate market analysis of the future polymer development may lead to finding new materials fitting even better into the idea of creating polymer cold plates for automotive solutions.

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Presenter Biography

Dariusz Adamczyk – graduated from Poznan University of Technology at Faculty of Mechanical Engineering and Management. Since 2018 student at Faculty of Transport Engineering.

In Solaris Bus & Coach since 2015. Currently works as a Junior Design Engineer in Advanced Technologies Team.

Bartosz Patkowski – received the M.Eng. degree in Automatic Control and Robotics Engineering from Poznan University of Technology in 2017.

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Michał Sierszyński - graduated from Poznan University of Technology and from Poznan Universityof Economics and Business - Project Management studies. He is currently a PhD student at AGH University of Science and Technology.

He has joined Solaris in 2004. Since 2012 an Advanced Technology Manager in Development Department.

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PhD Eng. Dariusz Michalak – after graduating from the Faculty of Machines and Transportation at Poznan University of Technology, from 1993 until 1998 Michalak worked as researcher and teacher in the Institute of Machines and Motor Vehicles. He obtained his PhD at the Poznan University of Technology.

Joined Solaris in 1998. On August 2012 appointed to the Solaris Management Board.