Cooling of a battery pack of a car, working on renewable energy

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Abstract. The aim of the work is to choose a method of a solar car battery cooling. The student engineering team of Peter the Great Petersburg Polytechnic University designs the car. The analysis of the electrical circuit of the battery is carried out, the heat release is estimated due to three factors. According to the conditions of reliable operation of the battery, it is necessary to maintain its temperature range below 45°C, which requires cooling. The paper analyzes the possibilities of liquid, air-cooling, compares the free and forced methods of convective heat transfer. For the normal operating mode of the electric vehicle, environmental temperature at the level up to 38°C, a criterion thermal engineering calculation of the forced air-cooling of the corridor assembly of 405 battery cells providing the required heat dissipation is performed. It is shown that relatively high values of the heat transfer coefficient are provided under turbulent flow conditions characterized by Reynolds criteria above 10^3. On the basis of an analysis of the steady-state stationary heat-removal regime, it was concluded that an air flow provides a temperature gradient, sufficient for cooling the lithium-ion battery of a Solar Car «Polytech Solar».

1 Introduction

The potential of solar energy, as the largest and most accessible to humanity, has always attracted the attention of the scientific community. In recent years, the use of solar energy has been widely spread [1]. At the same time, the idea of designing the car that can overcome long distances using only solar energy is extremely evolving [2, 3].

Solar car racing [4–6] competitions are held each year. The goal of one of them – «American Solar Challenge 2018» – is to overcome the distance of 2866 kilometers in the minimum time. According to the rules, it is allowed to start the race with a full battery charge, but along the way it can only be charged by solar energy.

Within a student engineering project «Polytech Solar» of Peter the Great St. Petersburg Polytechnic University a solar electric car is constructed that is powered by a storage battery which is charged by a solar photovoltaic panel [7], Figure 1.

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Fig. 1. Electric vehicle «Polytech Solar».

The design [8, 9], as well as the technical parameters [10] of the car are determined by the regulations of the competition, as well as the intention of minimizing aerodynamic losses [11–14].

The battery pack is assembled from cells of 18650 [15] size in an amount of 405 pcs, see Figure 2. It is arranged in the form of a corridor beam, see Figure 3.

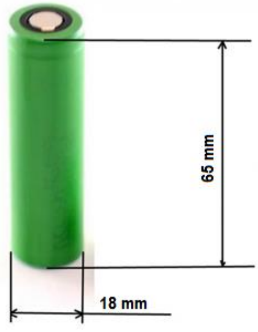

Fig. 2. 18650 battery cell.

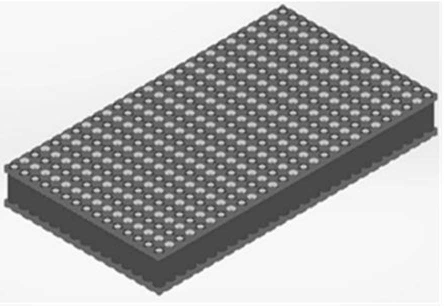

Fig. 3. The Battery Pack.

Because of charging and discharging, the cells are heated. A significant temperature increase adversely affects the battery characteristics, and can lead to its capacity degradation [17, 18] and even to destruction [19], which explains the need for cooling [20, 21].

2 Methods

2.1 Heat dissipation analysis

Battery power losses during charge and discharge occur due to internal resistance and concentration losses due to transport of species [22, 23]. In addition, the energy of electrochemical reactions within the cells is converted into heat during discharge, but it is less than 1% of the total thermal losses [24], thus it is not taken into account in the calculations.

Thermal power losses of one cell:

$$Q = I^2 \cdot R_{in} \quad (1)$$

where

I — current flowing through the cell,

R_{in} — cell internal resistance,

R_{in} value is determined using the empirical model proposed in the paper [25]. The maximum current passing through the cell is 4 A. It is limited by an electronic battery protection system. The choice of this value is due to the values of the peak current consumption of the motor and the thermal losses in the wires. The rated maximum discharge current of the cell is 10 A.

The maximum thermal power loss for one cell under such conditions is 0.81 W, for all 405 cells — 328 W.

2.2 Initial data for calculation of battery cooling

The battery pack contains n = 15 along the beam width and m = 27 cells along the length. Length of one cylindrical cell is l = 0.065 m, diameter d = 0.018 m. The longitudinal and transverse steps between the cells are equal and are s = 0.06 m. Total heat exchange surface area F without taking into account the side walls is:

$$F = \pi \cdot d \cdot l \cdot (n - 1) \cdot m = 1.39 \text{ m}^2. \quad (2)$$

The calculation is carried out at the maximum ambient temperature — 38°C and the maximum acceptable temperature of the battery — 45°C.

2.3 Analysis of cooling methods

The heat transfer coefficient at free convection between a lithium-ion cell of 18650 size and air does not exceed [26]

$\alpha = 5 \text{ W/(m}^2 \cdot \text{K)}$.

This value at a quite high temperature difference of the battery and the cooling airflow in 20°C provides heat dissipation of:

$$Q = \alpha \cdot F \cdot \Delta t = 139 \text{ W}. \quad (3)$$

First, this amount of heat dissipation is not sufficient for the given conditions.

Secondly, when the cells inside the battery are densely packed under conditions of natural air circulation, stagnant areas with an increased air temperature form, which contribute to the deterioration of heat transfer. Liquid cooling is preferable for systems with more powerful loads, but for specified conditions it is redundant.

Forced air cooling using a fan is most appropriate in these conditions. The air flow is directed through the most compressed cross-section along the battery pack [27].

The side walls, as well as the upper and lower planes ("cover" and "bottom") are isolated from the environment in such a way that the air flow passes only between the cells. There is no circulation between the first and last rows of cells and the side walls.

In this calculation, some assumptions were made:

1. The internal heat dissipation and heat flow rate stays constant throughout the heat exchange surface.
2. Specific heat capacity does not depend on the air temperature.
3. Since the air flow speed is less than 70 m/s and the Mach number is less than 0.2, the incompressible gas model can be used so enthalpy of the air flow does not depend on the air pressure change, and equals to:

$$\int dh = c_p \cdot \Delta t_{air}, \tag{4}$$

where c_p is specific heat capacity and Δt_{air} is the difference between inlet and outlet air flow temperatures.

Based on (4) equation and the assumptions, the heat flow rate between the battery pack and the air flow in steady state is provided by the internal heat dissipation and is equal to:

$$Q_v = Q_\alpha = G \cdot c_p \cdot \Delta t_{air}. \tag{5}$$

3 Results and Discussion

The diagram of the temperature distribution over the heat exchange surface is shown in Figure 4.

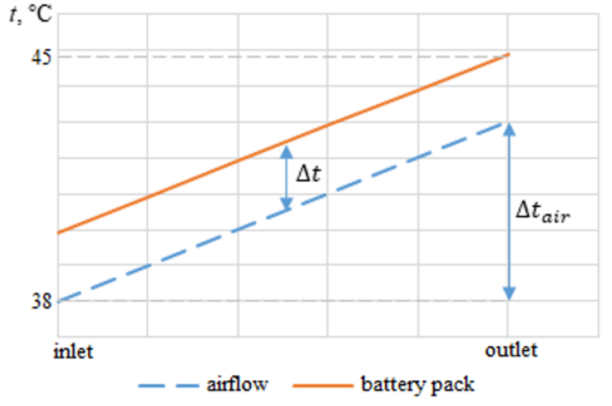

Fig. 4. The heat exchange surface temperature distribution.

The maximum battery temperature in steady state conditions is the sum of the ambient temperature, the difference between inlet and outlet air flow temperatures Δt_{air} and the difference between battery pack and air flow temperatures Δt.

Δt_{air} is set in the first approximation to determine the air flow rate that is sufficient to warm up the air to the temperature t_{air}^{outlet}, that is:

$$t_{air}^{outlet} < t_{bat}^{max} - \Delta t, \tag{6}$$

where t_{bat}^{max} is maximum battery temperature.

Assuming that Δt will be less than 2°C, the outlet air temperature is set as 43°C and Δt_{air} is set as 5°C, so using the (7) equation the air flow rate is:

$$G = \frac{Q_v}{c_p \cdot \Delta t_{air}} = 6.53 \cdot 10^{-2}\ \text{kg/s}; \tag{7}$$

Δt can be found through Newton's law of cooling

$$Q_\alpha = \alpha \cdot F \cdot \Delta t, \tag{8}$$

where α is heat transfer coefficient.

To calculate α, the flow regime is determined and the criterion equation of convective heat transfer is solved.

Area of the most compressed beam cross-section:

$$f = (s - d) \cdot l \cdot (n - 1) = 5.46 \cdot 10^{-3} \text{ m}^2. \tag{9}$$

Air flow velocity:

$$w = G / (\rho \cdot f) = 10.6 \text{ m/s}, \tag{10}$$

where $\rho = 1.128 \text{ kg/m}^3$ — air density at 40°C [28, 29] and
Reynolds criterion:

$$\text{Re} = w \cdot d / \nu = 1.12 \cdot 10^4, \tag{11}$$

where
d — the diameter of the cell, for smooth-tube beams is adopted as the characteristic dimension,
ν — coefficient of kinematic viscosity of air, $\nu = 1.7 \cdot 10^{-5} \text{ m}^2/s$.

In the range of developed turbulent flow

$$\text{Re} = 10^4 ... 10^5$$

for corridor bundles of tubes with a number of rows greater than three, the dependence is:

$$\text{Nu} = 0.27 \cdot \text{Re}^{0.63} \cdot \text{Pr}^{0.33} = 85.4, \tag{12}$$

where
Nu — dimensionless heat transfer coefficient,
Pr — Prandtl number, for air at temperature 40°C [28, 29] and atmospheric pressure:

$$\text{Pr} = 0.699.$$

The analysis of the results of the heat transfer studies makes it possible to draw the following conclusions:

1. There is a shortage of data on the heat transfer of compressed corridor beams.
2. The most extensive studies were performed by the group A.A. Zhukauskas. In their experiments, 27 types of beams of smooth cells of different configurations were used in the range Re = $(1…2 \cdot 10^6)$ and Pr = (0.7…500). These studies made it possible to determine and clarify the effect of layout features, ripple on heat transfer, hydraulic resistance, and beam efficiency.
3. Various authors recommend that as a characteristic speed:

– average speed for the most constrained section;
– speed in the narrow section of the beam;
– average rate in the transverse compressed (narrow) beam section, calculated through the difference between the width of the channel and the product of the outer diameter of the cell by the number of cells in the row;
– speed along the narrowest cross-section of the considered beam row.

As the determining velocity for the possibility of comparing the results, we adopted the velocity in the smallest cross-section of the beam.

Coefficient of heat transfer:

$$\alpha = \mathrm{Nu}\cdot\lambda/d = 133\ \mathrm{W/(m^2\cdot K)}. \quad (13)$$

The difference between battery pack and air flow temperatures is

$$\Delta t = \frac{Q}{\alpha\cdot F} = 1.8°\mathrm{C}\,. \quad (14)$$

Estimated maximum temperature of the battery pack is:

$$t_{bat}^{max} = t_{amb} + \Delta t_{air} + \Delta t = 44.8°\mathrm{C}. \quad (15)$$

Considering that the maximum battery temperature must not exceed 45°C according to the conditions of reliable operation of the battery, fan with air flow rate of

$$G = 6.53\cdot10^{-2}\ \mathrm{kg/c}$$

will ensure sufficient cooling of the lithium-ion battery.

4 Conclusions

(1) The heat transfer coefficient is obtained for forced air cooling of the battery pack of the specified parameters.

(2) Based on the calculation results, a fan with an air flow rate of $6.53\cdot10^{-2}$ kg/s is chosen. At steady-state heat transfer and at the most powerful continuous battery operating conditions it is able to maintain the maximum battery pack temperature, which is sufficient for the reliability of cooling lithium-ion battery.

(3) When calculating air cooling, it must be taken into account that relatively high values of the heat transfer coefficient can be achieved with the turbulent air flow regime, with the values of the Reynolds criterion of $\mathrm{Re}>10^4$.

In further researches, it is advisable to perform pressure loss calculation, as well as numerical simulation in CFD-systems, and full-scale tests to compare the experimental results with the calculated.

References

1. V. Butuzov. Thermal Engineering, **10**, 78–88 (2018)
2. R. Zaripov. Science and Technology of Kazakhstan, **3–4**, 36–45 (2017)
3. D. Vandishev, I. Goldina. Youth and science, **12** (2016)
4. E. Betancur, G. Osorio-Gómez, J. Rivera. Sustainability, **9 (10)**, 1576 (2017)
5. S. Tamura. Reinforced Plastics, **60 (3)**, 160–163 (2016)
6. M. Elshafei, A. Al-Qutub, A. Abdul-Wahid. *Proc. of the 13th Int. Multi-Conf. on Systems Signals and Devices,* 751–756 (2016)
7. M. Giannouli, P. Yianoulis. Sol. Energy, **86 (1)**, 441–451 (2012)
8. G. Minak, C. Fragassa, F. Vannucchi de Camargo. Int. Conf. on Sustainable Design and Manufacturing, 847–856 (2017)
9. E. Betancur, R. Mejia-Gutierrez, G. Osorio-Gomez, A. Arbelaez. Int. Joint Conf. on Mechanics, Design Engineering and Advanced Manufacturing, 25–32 (2016)

10. J. Kock, N. Rensburg, S. Kruger, R. Laubscher. ASME Int. Mechanical Engineering Congress and Exposition, IMECE2014-38053 (2014)
11. N. Vinnichenko, A. Uvarov, I. Znamenskaya, H. Ay, T. Wang. Sol. Energy, **103**, 183–190 (2014)
12. S. Paterson, C. Perera, P. Vijayaratnam, G. Doig. *Proc. of the Institution of Mechanical Engineering, part d: J. of Automobile Engineering*, **230 (14)**, 1972–1986 (2016)
13. G. Doig, C. Beves. Int. J. Veh. Engineering, **66 (2)**, 143–167 (2014)
14. W. Kin, S. Kruger, N. Rensburg, L. Pretorius. ASME Intern. Mechanical Engineering Congress and Exposition, IMECE2013-65760 (2013)
15. N. Spinner, K. Hinnant, R. Mazurick, A. Brandon, S. Rose-Pehrsson, S. Tuttle. J. of Power Sources, **312**, 1–11 (2016)
16. F. Leng, C. Tan, M. Pecht. Scientific Reports, **5**, 12967 (2015)
17. A. Zhoujian, J. Li, D. Yong, D. Chao, L. Xuejia. J. of Therm. Science, **26(5)**, 391–412 (2017)
18. D. Tarasova, A. Staritcyna, D. Nemova, K. Andreev. MATEC Web of Conf. **53**, 01007 (2016)
19. M. Fedorov, E. Makarova, T. Titova. Magazine of Civil Engineering, **71(3)**, 3–9 (2017)
20. S. Arora. J. of Power Sources, **400**, 621–640 (2018)
21. D. Chalise, K. Shah, R. Prasher, A. Jain. J. of Electrochemical Energy Conversion and Storage, **15 (1)**, JEECS-17-1051 (2018)
22. S. Galushin. Russian Electrical Engineering, **88(12)**, 800–804 (2017)
23. X. Ye, Y. Zhao, Z. Quan. Intern. J. of Energy Research, **42 (2)**, 648–655 (2018)
24. P. Bhatia. *Thermal analysis of lithium-ion battery packs and thermal management solutions* (2013)
25. A. Borisevich. Modern technics and technology, **5** (2014)
26. S. Khateeb. J. of Power Sources, **128(2)**, 292 (2004)
27. T. Wang, K. Tseng, J. Zhao, Z. Wei. Applied Energy, **134**, 229–238 (2014)
28. L. Saw, A. Tay, L. Zhang. *31st SEMI-THERM Symposium*, 298–302 (2015)
29. R. Rangappa, S. Rajoo. Intern. J. of Energy and Environmental Engineering, **10** (2018)