MEASUREMENT OF AIR COOLING CHARACTERISTICS FOR THE SEVERAL SURFACE TYPES OF Li-ION BATTERY

Andrey A. Byelyayev[1]***, Dmitrij V. Fedorchenko***[1]***,***
Manap A. Khazhmuradov[1]*[*]***; Oleksandr A. Lukhanin***[1]***,***
Oleksiy A. Lukhanin[1]***, Sergey O. Martynov***[1]***, Yegor V. Rudychev***[1]***,***
Eugen O. Sporov[1]***, Upendra S. Rohatgi***[2]

[1]*National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine;*
[2]*Brookhaven National Laboratory, USA*

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The system of air cooling for Li-Ion batteries is considered. Experimental setup included thermal chamber and Li-Ion battery cell simulators with temperature sensors. We investigated static and dynamic cooling regimes for several types of cooling surfaces, for different gaps between the simulators and flow rates. Experimental results are compared to the data of computer modelling using SolidWorks Flow Simulation software. The cooling efficiencies of the various surfaces for static and transient heat emission modes are compared.

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1. INTRODUCTION

Reliable Li-ion battery operation depends on a number of factors [1]. One of the crucial requirements is restricted operation temperature regime. A battery average temperature must fall within 25...35°C temperature range with deviation from average temperature less than of 2...3°C. Thus, real-world application of Li-Ion batteries demands an efficient cooling system. Now the liquid cooling is generally used for high-capacitance Li-Ion batteries of electric vehicles. Although liquid cooling is very efficient there are some drawbacks inherent in it. Typical liquid cooling set-up requires a relatively complex ducting, water pump and radiator. As a consequence system maintenance becomes more complicated and its reliability decreases.

The more robust and reliable alternative is air cooling. But practical application of this technology for electric vehicles faces essential difficulties. The main problem is low air thermal capacity compared to any liquid coolant and low air thermal conductivity. This substantially decreases the cooling efficiency. To compensate the loss of the efficiency one can use complex cooling surfaces that ensure high heat transfer from battery to cooling air flow.

In our work we study the efficiency of Li-Ion battery air cooling for various flow parameters, cooling channel geometries and cooling surfaces. First, we present and discuss the results of computer simulation of battery cooling. Next we describe the experimental setup used for measurements. The results of experimental measurements are finally presented and compared to the results of computational fluid dynamics (CFD) calculations.

2. COMPUTER SIMULATION

For computer simulation we have use commercial CFD software, especially SolidWorks 2011 with SolidWorks Flow Simulation module. The simulation process included development of the corresponding solid model followed by flow simulation setup. On that second stage we specified model materials, boundary and initial conditions and heat sources.

The main goal of cooling system simulation was heat exchange augmentation. The straightforward solution - heat exchange surface extension through the installation of additional elements in the air channel has its shortcomings. The placement of additional elements in the air channel increases aerodynamic drag and pressure drop. Cooling system needs more powerful air supply and thereafter provides lower service performance. Thus, the geometry of additional elements should ensure high heat transfer rate without significant air drag increase.

We considered two cooling surface types: twisted ribbons and open pyramids. As reference for comparison we used smooth cooling surfaces considered in the previous paper [3]. Fig. 1 and Fig. 2 show solid models developed using SolidWorks software and Tab. 1 holds model parameters used during simulation.

We chose these two types of surfaces as rather suitable for manufacturing and consequent experimental studies. Open pyramids provide both convection cooling and also additional cooling effect due

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[*] Corresponding author E-mail address: khazm@kipt.kharkov.ua

to air mixing. The twisted ribbons provide solely the air mixing without convective cooling. Thus twisted ribbons are insensitive to the material of construction, even plastic is permissible. Twisted ribbons expectedly provide relatively low air drag. So the main purpose of simulation was to compare the cooling efficiencies while keeping the pressure drop as low as possible to reduce required pumping power.

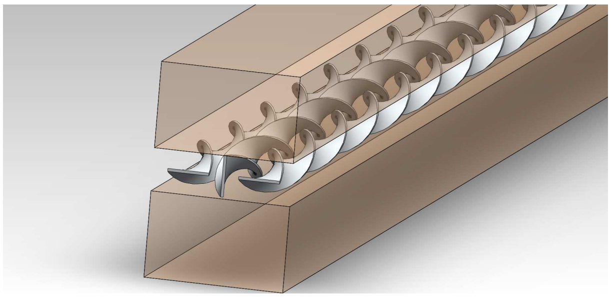

Fig.1. *SolidWorks model for the twisted ribbon surface.*

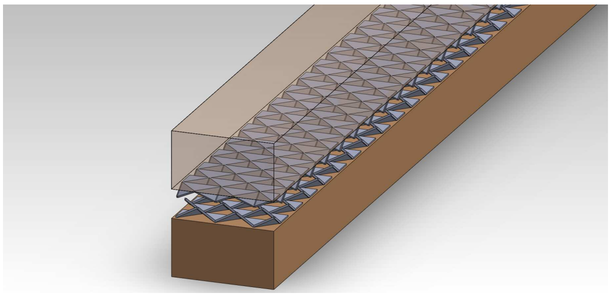

Fig.2. *SolidWorks model for the open pyramids surface.*

Table 1. *Parameters of the model*

Model	**Twisted ribbons**
Width	3 mm
Thickness	0.2 mm
Twist step	10 mm
Row pitch	2.5 mm
Twist direction	alternating
Material	aluminium
Model	**Open pyramids**
Height	1.5 mm
Thickness	0.3 mm
Row pitch	2.5 mm
Span	5 mm
Material	aluminium

We have calculated surface temperature distributions and pressure drops for inlet air flow rates from 1 to $4\,m/s$. The results for plain surfaces were presented and discussed in the previous paper [3]. Comparison of the smooth surfaces, open pyramids and twisted ribbons shows that the later two have almost coincident cooling efficiencies exceeding that for smooth surface (see Fig. 3).

The remarkable fact is twisted ribbons with only air mixing performed as well as open pyramids with both convection and air mixing. Twisted ribbons have significantly lower pressure drop than open pyramids (see Fig. 4) though still higher than that for smooth surfaces. This difference becomes more significant for higher flow rates. The conclusion follows that pure air mixing is more efficient than convecting surface extension. So computer simulation revealed twisted ribbons to be the most optimal cooling surface among the considered for accumulator battery cooling.

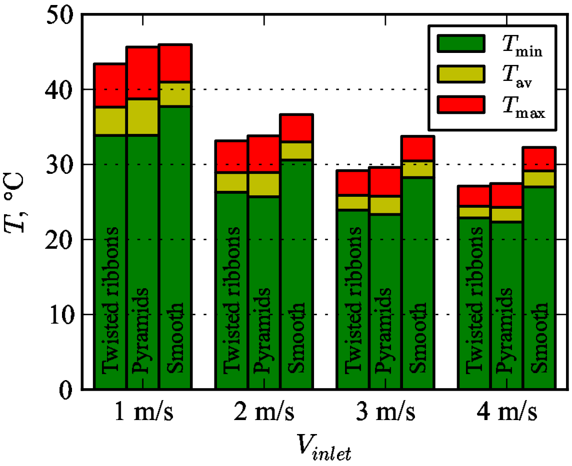

Fig.3. *Surface temperature for different cooling surfaces*

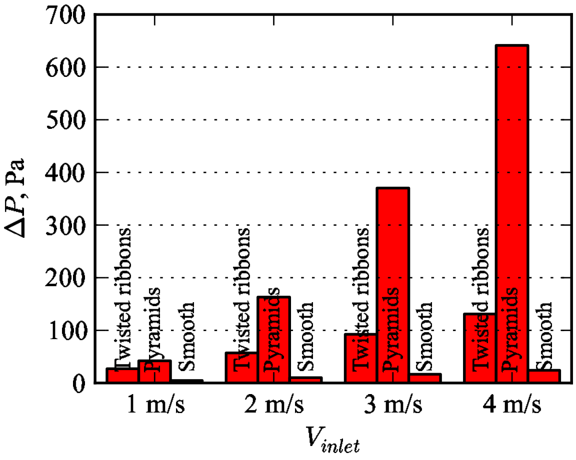

Fig.4. *Pressure drop for different cooling surfaces*

3. EXPERIMENTAL SETUP

The base of our research was specially designed and manufactured calorimeter chamber with air duct (see Fig. 5). The chamber outer surface was covered by heat insulation layer that prevents undesirable heat losses. The calorimeter chamber can hold from 2 to 6 power cells or imitators for air flow cooling studies. The chamber design permits adjustment of gaps between power cells in range 1...5 mm.

Experimental setup included the anemometer and differential manometer with Pitot probes for air flow velocity measurements. Also we used differential manometer to measure the inlet and outlet air flow pressures for the entire chamber. The hardware accuracy of velocity and pressure measurements in the gap between simulators was less than 3 %. The average inlet and outlet air temperatures were also measured.

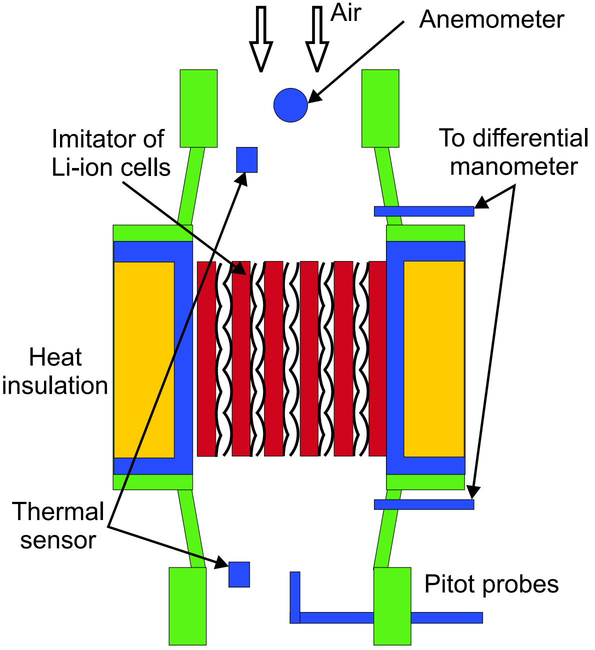

Fig. 5. *Experimental setup.*

For our studies we have also designed and manufactured simulators of Li-ion battery power cells. The simulators have the same thermal properties as the original power cells used in [2]. The size of Li-ion battery simulator was 200×150×12 mm. Each simulator contained 20 temperature sensors to control the temperature regime during the cooling process. Each sensor was capable of continuous temperature measurement with internal error of 0.1°C. Data from the sensors was transmitted to PC using NI-6225 PCI card and preprocessed (see Fig. 6). To reduce the measurements error we averaged data over 100 independent measurements.

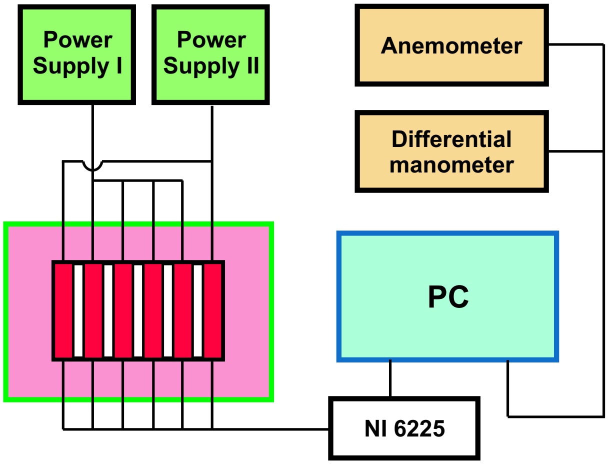

Fig. 6. *Schematic drawing of simulator power circuits and DAQ measuring equipment.*

We have manufactured open pyramids and twisted ribbons surfaces for cooling process studies. The parameters of the real surfaces are the same as those used for computer simulation (see Tab. 1). Fig. 7 and Fig. 8 shows the photos of the real surfaces.

Fig. 7. *Twisted ribbon surface.*

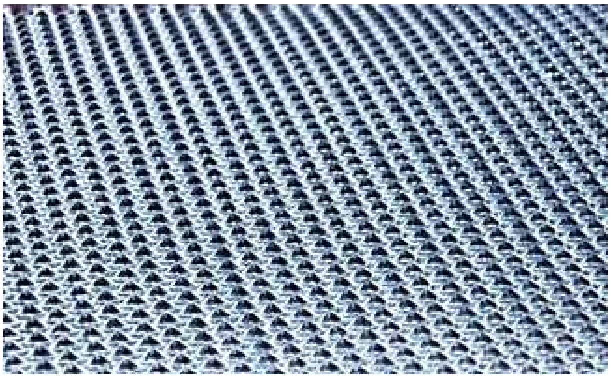

Fig. 8. *Open pyramids surface.*

4. EXPERIMENTAL MEASUREMENTS - STATIONARY MODE

Calorimeter chamber provided the necessary environment for studies of accumulator battery cooling. We focused on the two main aspects: cooling efficiency for steady battery heat output and transient cooling process. The later correspond to the two-step process: 1) temporary battery power overload; 2) power-off battery cooling.

Firstly we studied the steady cooling regime. We have measured surface temperature fields both for open pyramids and twisted ribbons surfaces. The results are shown in the Fig.9 and Fig.10. In both cases the inlet air temperature was 23°C.

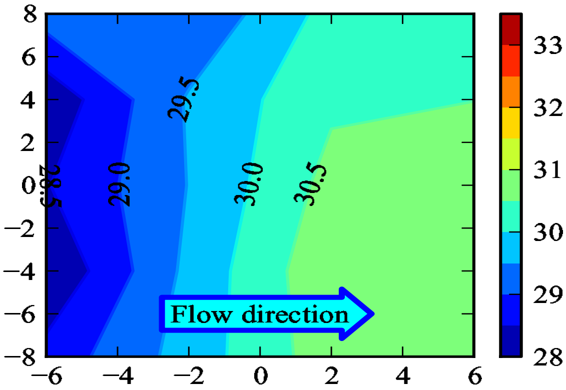

Fig. 9. *Surface temperature for open pyramids.*

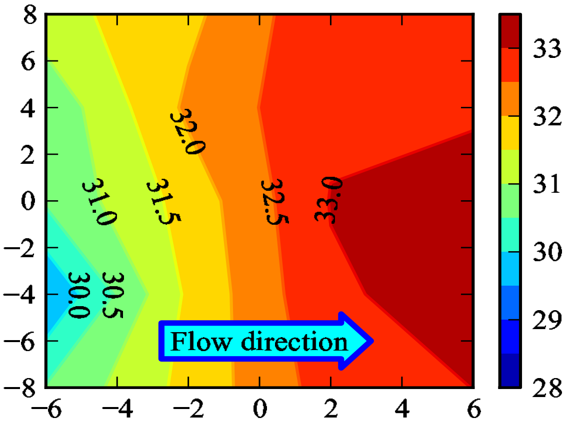

Fig.10. *Surface temperature for twisted ribbons.*

To rate the cooling efficiency we used Q/ITD parameter defined as

$$Q/ITD = \frac{Q}{T_{inlet} - T_{surface}}, \quad (1)$$

where Q is heat generation rate (W), T_{inlet} – inlet air temperature, $T_{surface}$ – average surface temperature. The difference in the denominator of (1) is often called inlet temperature difference.

During the Q/ITD measurements the gap between power cell imitators was 3 mm. $T_{surface}$ was derived from measured temperature data as simple average over 20 surface temperature sensors. As sensors form a regular grid this gives the correct approximation of the average surface temperature.

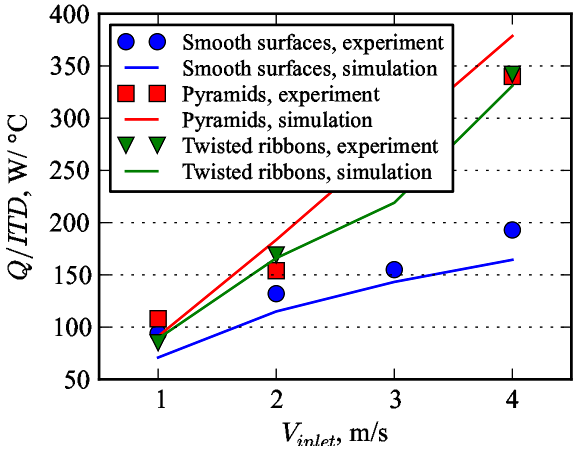

Fig.11. *Calculated and measured values of Q/ITD.*

In the Fig. 11 we present both experimental values of Q/ITD and those calculated from computer simulation (see Section 2). The Fig. 12 shows experimental and calculated pressure drop values. For the comparison we have also included values for smooth surfaces. As follows from the Fig. 11 experimental and calculated values of Q/ITD are in good agreement for all surfaces. But for pressure drop values we have observed systematic discrepancies, especially for open pyramids. Pressure drop from computer simulation always exceeded the experimental value. In our opinion the main reason for this is some difference in computer model and experimental setup. In the computer model we calculated pressures strictly at the air channel inlet and outlet. The real pressures are measured at some distance from the inlet and outlet.

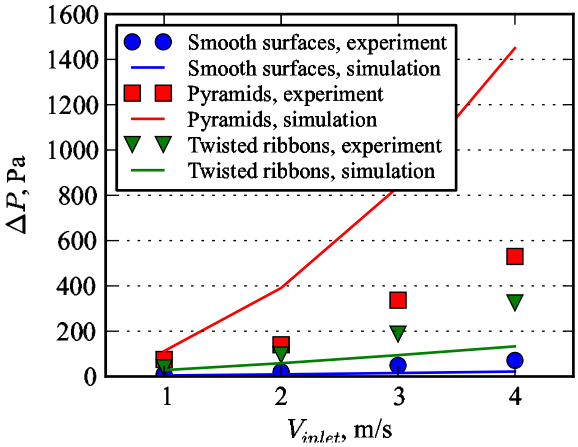

Fig.12. *Calculated and measured values of the pressure drop.*

Besides that, the significant discrepancy in the case of open pyramids is the result of the some simplifications in the computer model of the surface. Only the basic surface geometry peculiarities were preserved because of the considerable complications in reproducing the real surface in the computer model. This difference between model and real surface contributes more at a higher flow rates and leads to considerable discrepancies (see Fig. 12).

5. EXPERIMENTAL MEASUREMENTS - TRANSIENT MODE

The real-world operation of the Li-Ion batteries in mobile vehicles implies not only steady power output, but also short-time power overloading. This short-time overloading could in several times exceed the normal output. We used the calorimeter chamber to simulate this short-time overloading and to study the heating and cooling dynamics. Twisted ribbon and open pyramids surfaces described above were used during the experiment.

To study the heating and cooling dynamics we initially took the simulators at room temperature but with air cooling system switched on. On the first stage we applied constant heating power on the simulators. The heating continued until the temperature excess $\Delta T = T_{surface} - T_{room}$ exceeds 5...15°C. Then the heating power was switched off but air cooling continued. Fig. 13-16 show the time dependence of the ΔT for different heating powers and flow rates. Analysis of the temperature dependencies shows that cooling system efficiently damps the overheating effect.

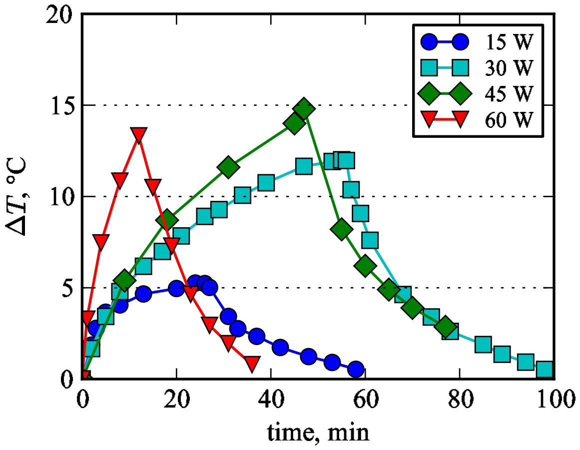

Fig.13. *Heating and cooling dynamics (twisted ribbons, 1.2 l/s)*

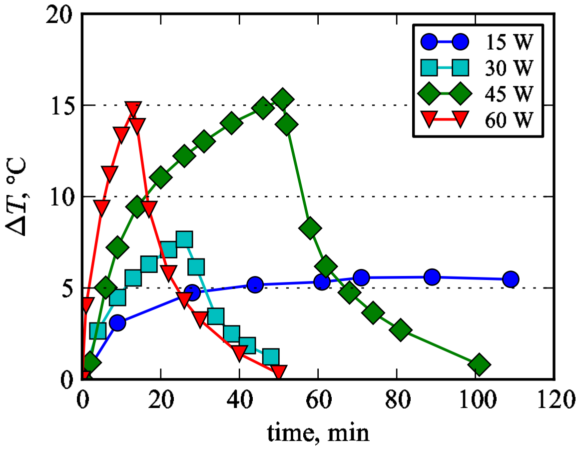

Fig.14. *Heating and cooling dynamics (twisted ribbons, 1.8 l/s)*

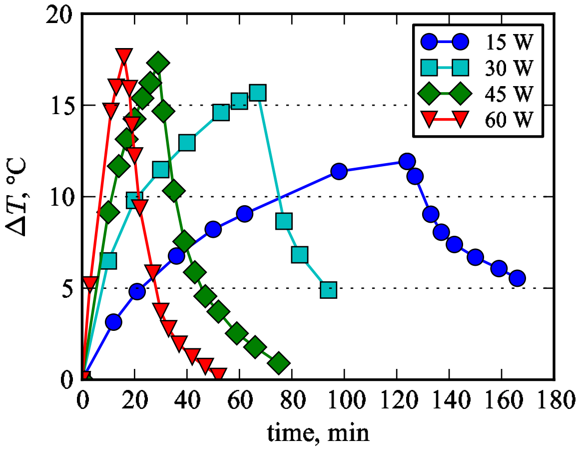

Fig.15. *Heating and cooling dynamics (open pyramids, 1.2 l/s)*

For 30 W heating that corresponds to double power overload rather continuous operation is possible with temperature excess below 10°C provided the air flow ratio is increased (see Fig. 14 and Fig. 16).

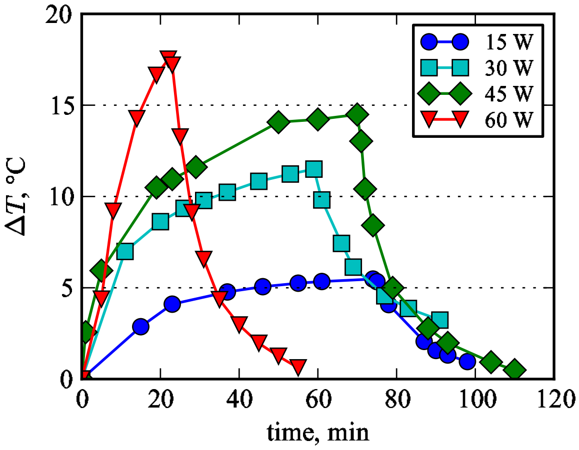

Fig.16. *Heating and cooling dynamics (open pyramids, 1.8 l/s)*

So the the real cooling system should provide output power control and increase the air flow rate for high power outputs.

6. CONCLUSIONS

The calorimeter chamber with air duct provided the robust instrument for cooling process studies. Using the simulators of Li-Ion battery power cell with temperature sensors we were able to control the essential parameters of the air flow and temperature regime. Various flow rates and heating modes and different cooling surfaces were studied.

The reliability of the experimental measurements was proved by computer simulation. For steady heating model we obtained good agreement between experimental and calculated values, especially for surface temperatures.

The stationary cooling studies showed that twisted ribbon cooling surface has the optimal characteristics: rather high cooling effect comparable to that for open pyramids and also relatively low pressure drop. The future studies should increase the efficiency of such cooling elements through adjustment of their geometry.

Studies of the transient operational mode showed that temporary power overload is generally permissible. If the cooling system provides higher flow rates during overload the battery successfully sustains overheating.

7. ACKNOWLEDGEMENTS

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ИЗМЕРЕНИЕ ХАРАКТЕРИСТИК ВОЗДУШНОГО ОХЛАЖДЕНИЯ ДЛЯ НЕКОТОРЫХ ВИДОВ ПОВЕРХНОСТЕЙ Li-ИОННОЙ БАТЕРЕИ

Андрей А. Беляев, Дмитрий В. Федорченко, Манап А. Хажмурадов, Александр А. Луханин, Алексей А. Луханин, Сергей А. Мартынов, Егор В. Рудычев, Евгений А. Споров, Упендра С. Рогаджи

Рассмотрена система воздушного охлаждения для Li-Ion-батарей. Экспериментальная установка включала в себя термокамеру и симуляторы ячеек Li-Ion-батареи с датчиками температуры. Мы исследовали статические и динамические режимы охлаждения для нескольких типов охлаждающих поверхностей, для различных зазоров между симуляторами и скоростей потока. Экспериментальные результаты сравнивались с данными компьютерного моделирования при помощи программного обеспечения SolidWorks Flow Simulation. Сравниваются эффективности охлаждения для различных поверхностей при статическом и переходных режимах тепловыделения.

ВИМІРЮВАННЯ ХАРАКТЕРИСТИК ПОВІТРЯННОГО ОХОЛОДЖЕННЯ ДЛЯ ДЕЯКИХ ВИДІВ ПОВЕРХОНЬ Li-ІОННОЇ БАТАРЕЇ

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Розглянуто систему повітряного охолодження для Li-Ion-батарей. Експериментальна установка включала в себе термокамеру та симулятори чарунок Li-Ion-батареї з датчиками температури. Ми досліджували статичні та динамічні режими охолодження для декількох типів охолоджуючих поверхонь, для різних зазорів між симуляторами та швидкостей потоку. Експериментальні результати порівнювалися з даними комп'ютерного моделювання за допомогою програмного забезпечення SolidWorks Flow Simulation. Порівнюються ефективності охолодження для різних поверхонь при статичному і перехідному режимах тепловиділення.