Heating and cooling of a battery pack of a solar electric car

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Abstract. The purpose of the research is to analyse forced air cooling of a solar electric vehicle battery. Due to the conditions of safe battery performance, it is obligatory to keep its temperature under 45°C, so cooling should be provided. The battery pack is assembled of 420 battery cells with square pitch. At normal operating conditions of the solar car a forced air cooling thermal calculation is performed. Hydraulic calculation is carried out. The air pressure loss magnitude is calculated. A comparison of the geometric parameters of the corridor beam is presented. Based on a steady-state heat transfer analysis and hydraulic calculation, suitable airflow parameters and battery pack layout are selected.

1. Introduction

Solar energy appliance has advanced considerably in recent years. [1]. Moreover, the concept of creating a vehicle that is capable of travelling over long distances via only solar energy is developing [2, 3].

Every year competitions named Solar Challenge are held, which goal is to pass the distance of about 3000 kilometers using the solar energy. The battery pack of a solar car can be fully charged before the race, but then it receives energy only from the solar array.

A student team «Polytech Solar» designs a solar car [6], Figure 1. The car is powered by a lithium-ion battery pack that is charged by an array of photovoltaic cells.

The design [7], and the technical performance of the vehicle are specified by the competition rules, as well as the desire for aerodynamic drag reduction [8–10].

The battery pack represents 420 battery cells of the 18650 size, see Figure 2. It is assembled in a square pitch layout, see Figure 3.

The battery is heated during operation conditions. The battery performance degradation takes place at a high temperature magnitude. It can cause its capacity decline [11, 12] and even thermal runaway [13], which clarifies the necessity for cooling.
2. Methods

2.1. Heat dissipation analysis
The maximum continuous current passing through a cell is 1.5 A. So, the maximum cell heat dissipation power is 0.27 W, and for all 420 cells – 110 W. Heat dissipation calculations are based on a battery model, described in [14].

2.2. Initial data
The battery assembly includes \( n = 15 \) cells in width and \( m = 28 \) cells in length. The length of an 18650 cell is \( l = 0.065 \) m, diameter \( d = 0.018 \) m. The transverse \( s_1 \) and longitudinal \( s_2 \) pitches are \( s_1 = 0.03 \) m and \( s_2 = 0.02 \) m respectively. The total surface area of heat exchange (the side walls are not counted) is:

\[
F = \pi \cdot l \cdot d \cdot (n-1) \cdot m = 1.44 \text{ m}^2.
\]

The ambient temperature of \( t_{\text{amb}} = 38^\circ\text{C} \) was used for the thermal calculation. The key condition is that the battery temperature at steady state cooling does not exceed 45°C.

2.3. Forced air cooling calculation
Fan forced air cooling is the most appropriate in these conditions [15]. Airflow should pass along the narrowest cross section of the battery assembly [16].
The border, top and bottom sides are wrapped to be isolated from the ambience. Thereby, the airflow goes directly through the cells.

Several assumptions were proposed:

- The internal heat dissipation and rate of heat flow remains constant across the whole heat-exchange surface.
- Specific heat is independent of air temperature.
- Airflow enthalpy is independent of air pressure, and equals to:
  \[ \int dh = c_p \cdot \Delta t_{\text{air}}, \]
  where \( h \) is specific air enthalpy, \( c_p \) – specific heat and \( \Delta t_{\text{air}} \) – air temperature difference between inlet and outlet.
- Rate of heat flow between the airflow and the battery is conditioned by the internal heat at steady state and equals to:
  \[ Q_v = Q_\alpha = G \cdot c_p \cdot \Delta t_{\text{air}}, \]  
  where \( Q_\alpha \) is heat flow rate between solid and liquid, \( Q_v \) is the internal heat power in the battery and \( G \) is mass airflow rate.

2.4. Air pressure loss estimation

When calculating forced air cooling, it is important to know the amount of pressure loss of the airflow as it passes through the battery pack in order to further select the fan operating characteristics.

The Darcy-Weisbach equation was used to calculate pressure losses:

\[ \Delta p = 0.5 \cdot \zeta \cdot w^2 \cdot \rho, \]  
where \( \zeta \) is the coefficient of local resistance.

For a corridor beam of smooth pipes, the local resistance coefficient for a row of a beam is determined by the following dependence \([17,18]\):

\[ \zeta_0 = 0.38 \cdot (\sigma_1 - 1)^{0.5} (\Delta - 0.94)^{-0.59} \cdot \text{Re}^{-0.2} \cdot \Omega, \]

where \( \Delta = (\sigma_1 - 1)/(\sigma_2 - 1), \Omega = (\sigma_2 - 1)/(\sigma_1 - 1), \sigma_1 = s_1/d, \sigma_2 = s_2/d. \)

3. Results and Discussion

3.1. Thermal calculation

The temperature distribution diagram with assumptions considered is shown in Figure 4.

![Figure 4. The temperature distribution over surface.](image)

The highest temperature of the battery in steady state consists of the ambient temperature, the inlet and outlet airflow temperature difference \( \Delta t_{\text{air}} \) and the battery and airflow temperature difference \( \Delta t. \)
The value is set in the first approach to calculate airflow rate which is enough to heat the air to the temperature $t_{\text{air}}^{\text{outlet}}$, that equals to:

\[ t_{\text{air}}^{\text{outlet}} < t_{\text{max}}^{\text{bat}} - \Delta t, \]

where $t_{\text{max}}^{\text{bat}}$ is maximum temperature of the battery pack.

Assuming that $\Delta t$ will not exceed 2°C, the air temperature at the outlet is set as 43°C and $\Delta t_{\text{air}}$ is set as 5°C, so applying the (1) dependence the airflow rate is calculated as:

\[ G = \frac{Q_{\alpha}}{c_{p} \Delta t_{\text{air}}} = 0.021 \text{ kg/s} \]

$\Delta t$ is determined using Newton’s law of cooling

\[ Q_{\alpha} = \alpha \cdot F \cdot \Delta t, \]

where $\alpha$ is heat transfer coefficient.

To find $\alpha$, the flow mode is determined and the convective heat transfer criterion equation is resolved.

The narrowest cross section area of the battery assembly:

\[ f = (s-d)l(n-1) = 1.09 \times 10^{-2} \text{ m}^2. \]

Airflow velocity:

\[ w = \frac{G}{\rho f} = 1.75 \text{ m/s}, \]

Reynolds number:

\[ \text{Re} = \frac{w d}{\nu} = 1.82 \times 10^3, \]

where $d$ is the cell diameter, that is used to calculate Reynolds criterion for smooth tubes, $\nu$ is air kinematic viscosity coefficient.

At advanced turbulent regime ($\text{Re} = 10^3...10^5$) for square pitches of tubes, the heat transfer criterion equation is [19,20]:

\[ \text{Nu} = 0.27 \cdot \text{Re}^{0.63} \cdot \text{Pr}^{0.33} = 27.1, \]

where Nu is the non-dimensional heat transfer coefficient, Pr – Prandtl criterion.

3.2. The discussion of the results

3.2.1. Thermal calculation

The following conclusions can be drawn based on the calculation results analysis.

1. There is a lack of heat transfer data of narrow square pitch bundles.

2. Numerous researchers recommend using as a characteristic velocity:
   - the most constrained cross section average velocity;
   - the narrowest section velocity;
   - velocity in a narrow cross section of the studied beam row.

As a characteristic speed to clearly compare the results, the velocity in the narrowest beam cross section is adopted.

Heat transfer coefficient equals to:

\[ \alpha = \text{Nu} \cdot \lambda / d = 42.2 \text{ W/(m}^2 \cdot \text{K).} \]

The airflow and battery pack temperature difference is

\[ \Delta t = \frac{Q}{\alpha F} = 1.9^\circ \text{C}. \]

Calculated maximum battery temperature is:
As long as the maximum battery temperature must not exceed 45°C under the conditions of safe battery operation, fan with airflow rate of \( G = 0.021 \) kg/s ensures adequate battery pack cooling.

3.2.2. Hydraulic calculation
With equations (2) and (3), the pressure loss for 28 rows is 8.02 Pa.

The dependence of the pressure loss on airflow rate at various relative transverse pitches is shown in Figure 5. The points are indicated at the figure at which the airflow is minimal to ensure the required battery temperature.

![Figure 5](image-url)

**Figure 5.** The dependence of the pressure loss on airflow rate at different relative transverse steps.

1. \( \sigma_1 = 1.5 \)  
2. \( \sigma_1 = 1.56 \)  
3. \( \sigma_1 = 1.61 \)  
4. \( \sigma_1 = 1.67 \)

It can be seen that with an increase in the relative transverse pitch \( \sigma_1 \) the required minimum airflow rate increases slightly, while the pressure loss decreases significantly. At the same time, as the pitch increases, the airflow rate decreases, as well as the Reynolds number. Therefore, it is advisable to increase the step \( \sigma_1 \) to such a value that the Reynolds criterion remains within the limits of the turbulent flow of air. When \( \sigma_1 = 1.67 \), the Reynolds number is \( \text{Re} = 1.8 \cdot 10^3 \).

4. Conclusions
Following conclusions can be made:

1. The heat transfer coefficient is determined for battery pack of stated parameters forced air cooling.
2. According to the results of the calculation, a fan with an airflow rate of 0.021 kg/s is selected. With steady state heat transfer and under the most powerful battery discharging mode it can keep the battery temperature that is suitable for maintaining reliability of lithium-ion battery.
3. Comparison of the dependences of the pressure loss on airflow at different relative transverse steps was made. It is advisable to use possibly large transverse pitch values; however, it is necessary to provide a turbulent flow regime.

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