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Shortcut computation for the thermal management of a large air-cooled battery pack

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HIGHLIGHTS

- Shortcut computation for the thermal management of a large battery pack is developed.
- The effects of non-uniform airflow on battery temperature uniformity are considered.
- A flow resistance network model is built to rapidly estimate the non-uniform airflow.
- Structural parameters are analyzed to improve the battery temperature uniformity.

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ABSTRACT

Thermal management is crucial to maintain the performance of large battery packs in electric vehicles. To this end, we present herein a shortcut computational method to rapidly estimate the flow and temperature profiles in a parallel airflow-cooled large battery pack with wedge-shaped plenums for airflow distribution. The method couples a flow resistance network model with a transient heat transfer model to calculate the temperature distribution in a battery pack as influenced by the airflows within and among battery modules in the pack. The effects of the plate angle of the plenums, the minimal plenum width and the battery unit spacing on the airflow and temperature distributions are presented. Additionally, an example of collective parameter adjustment for acceptable temperature uniformity of a battery pack subjected to total volume constraint is given.

1. Introduction

The development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) under the pressures of oil shortages and environmental protection has stimulated a high demand for high energy rechargeable battery packs, e.g., lithium-ion battery packs, in recent years. The thermal management of a battery pack is important to ensure a safe and sustained power supply from the battery pack. A number of thermal management systems have been proposed to date, and these systems can be divided into active cooling and passive cooling generally. For the former, the heat generated within the battery is actively removed by forced air [1–3] or liquids [4] via convective heat transfer; for the latter, the heat is passively absorbed by phase change materials [5–7]. Rao et al. [8] has published a detailed comparison of these methods. It is shown that the forced parallel airflow cooling is advantageous over other active cooling methods in maintaining the uniform battery temperature distribution, because the cooling air distributed into different cooling channels or modules can theoretically be of the same flow rate and initial temperature.

The thermal characteristics of parallel airflow-cooled battery packs have been numerically simulated using Computational Fluid Dynamics (CFD) in recent years [9–14]. In some of these works [9–12], the computational domain was reduced from a whole battery pack to one of its repeating units to save computation time because the CFD method is demanding on high-performance computer hardware. This treatment was justified by the theoretically uniform airflow distribution of forced parallel airflow cooling. However, the airflow distribution is affected by many factors and its uniformity cannot be always guaranteed. When the airflow is non-uniform, the uniformity of temperature distribution in battery packs will become worse. In this case, the entire battery pack should be included in the computational domain and the simulation can be

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very time consuming because of a huge number of mesh elements required. For example, in Fan's simulation [13], the computational domain had about 100,000 elements, and in Park's work [14], the total number of meshes was about 2,400,000. Alternative computation methods other than CFD, consequently, are necessary when quick analysis of the pack's thermal behaviour is required. However, the factor of airflow maldistribution was not considered in previously reported methods [15–17], new method that takes account of uneven airflow should be developed.

In this paper, we report a shortcut method to estimate the flow and temperature profiles in a parallel airflow-cooled large battery pack (as shown in Fig. 1). The method couples a flow resistance network model and a transient heat transfer model. The former simulates the flow field of the air-cooling system and provides convective heat transfer coefficients on battery unit–air interfaces for subsequent use; the latter calculates the temperature rise of each battery unit without considering its internal details. As such, the non-uniform airflow distribution and its effect on the battery temperature uniformity are considered in the simulation. The method is then applied to discuss structure parameters to improve the temperature uniformity in the battery pack.

2. Model development

2.1. Illustrations of the parallel airflow configuration

The parallel airflow-cooled large battery pack simulated in this paper is shown in Fig. 1. It consisted of eight battery modules, and each module contained eight battery units with five battery cells per unit. The cylindrical 18650 lithium-ion battery cells were used. A nested parallel airflow cooling system was built to manage the thermal behaviour of the battery pack, which could be divided into two subsystems, one between the battery units inside each module and the other between the modules. The structural similarity of these subsystems led to the same computational principle, so the former was chosen to expound the flow resistance network model in detail. In the subsystem shown in the dashed area of Fig. 1(a), air is distributed and converged by wedge-shaped plenums called the distribution plenum (DP) and the convergence plenum (CP). Heat transfer takes place in the cooling channels (CCs) between adjacent battery units. The plenums' plate angle, θ, the minimal plenum width, $w_{\min}$, and the battery unit spacing, l_{sp}, determine the structure of the subsystem and thus affect the airflow distribution. The cooling channels, whose cross sections are the same as the filled area in Fig. 1(b), should be separated from each other in the design of the air-cooling system to ensure parallel airflow.

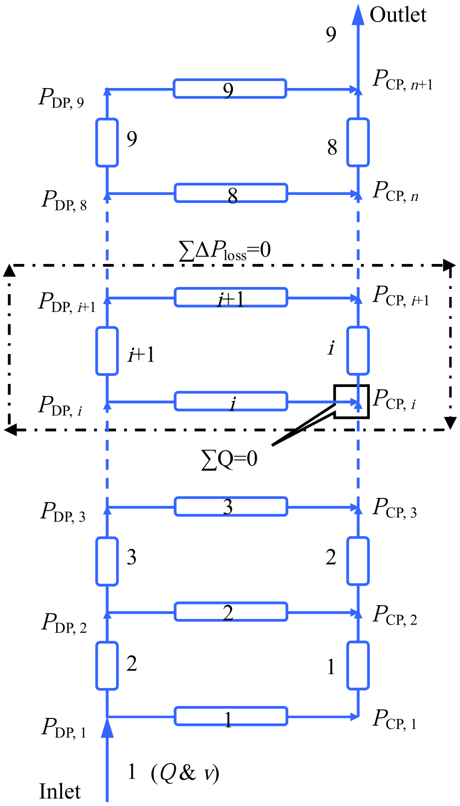

Fig. 2. The flow resistance network model for the air-cooling system in a battery module. Calculation segments are partitioned by the distribution/convergence points of the airflow, and the blocks indicate the flow resistances. The static pressure, P, is read on the main duct side at each distribution/convergence point of the airflow.

2.2. The flow resistance network model

When airflows inside the air-cooling system, its static pressure is simultaneously varied and labelled by segment in Fig. 2. This phenomenon is primarily caused by (1) the energy transformation of air between its kinetic energy and static pressure when the airflow velocity changes; and (2) the energy losses, including the irreversible loss due to the friction between the air and the rough channel walls and the local loss due to the air distribution and convergence at specific sites. The air is assumed to be an incompressible Newtonian fluid here. For a continuous flow process,

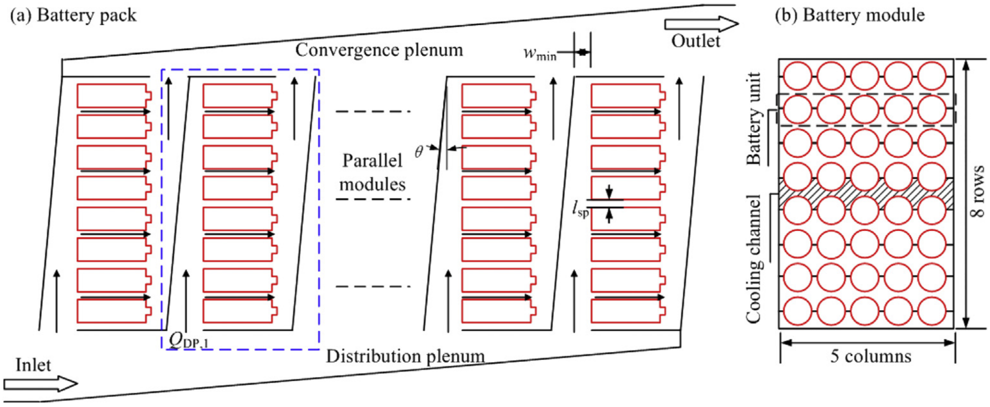

Fig. 1. (a) The schematic of a nested air-cooling system in a battery pack, in which the arrows indicate the airflow directions. (b) The arrangement of battery cells in a battery module.