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FLOWING ELECTROLYTE AS COOLANT INSIDE THE MICROGROOVES EMBEDDED IN THE ELECTRODES: A NOVEL THERMAL MANAGEMENT OF LI-ION BATTERIES

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ABSTRACT

One way to enhance thermal performance of the Li-ion batteries is embedding microgrooves inside the porous electrodes and flowing the electrolyte through these microgrooves. A 2D thermal Lattice Boltzmann Method (LBM) was employed to predict electrolyte flow, heat transfer, and internal heat generation inside the positive porous electrode. Size and number of the microgrooves were investigated, and it was found that embedding microgrooves inside the porous electrode improved the thermal performance of the Li-ion battery by keeping the electrode in lower temperatures and improving its temperature uniformity. Furthermore, increasing the number of microgrooves (in a constant ratio between total size of the microgrooves to size of the porous electrode) kept the porous electrode in lower temperatures and enhanced temperature uniformity.

INTRODUCTION

Global warming, climate change, and environmental pollution are becoming the major issues that force researchers and engineers to explore alternative energy sources. Rechargeable battery is one of the best candidates for storing and transporting electrical energy. Among different types of rechargeable batteries, Lithium-ion (Li-ion) battery has been considered as one of the most promising battery technologies. Like other electric storages, Li-ion batteries generate heat during charge and discharge processes. The generated heat should be transferred out of the battery.

Thermal management of the Li-ion battery is a critical issue as it plays a major role in the Li-ion batteries industry. For heavy power demands like electric vehicles, designing an appropriate thermal management system is crucial to transfer the generated heat out of the battery pack to ensure that the operating temperature of the cells is within the desired range. In the recent years, many studies have been conducted extensively to investigate the thermal management of Li-ion batteries. In this regard, external cooling methods such as phase change materials (PCMs) [1], porous metal foams [2, 3], pin fin heat sinks [4], mini- and microchannels [5, 6], and heat pipes [7] have been utilized to keep the Li-ion batteries in a safe temperature domain. Some of these external thermal management systems were not successful to prevent the batteries from thermal run away [8]. These methods might not maintain the temperature inside the battery at a desirable level. In addition, they might be unable to prepare a desired temperature uniformity inside the battery pack because outer cells would always be at lower temperatures. Therefore, the need to find new thermal management systems is pressing.

One of the novelty cooling methods that proposed by the authors as internal cooling is flowing liquid electrolyte through microgrooves embedded inside the electrodes [9, 10]. These microgrooves are not only efficient for cooling purposes but can also be used to drive out the generated gases during thermal runaway out of the battery cell [11]. In this regard, one of the promising methods to simulate thermal and hydraulic performances of electrolyte flow through porous electrodes and microgrooves is LBM.

LBM is an appropriate approach to investigate fluid flow and diffusion through porous media that involves single or multiple components [12]. Thermal LBM is a stable, accurate and numerically efficient scheme to simulate two-phase flow [13]. It has been used to investigate the performance of a metal foams/paraffin PCM thermal energy storage system [14]. It has also been utilized to simulate multi-phase and multi-component fluid flows in porous electrodes [15].

In this paper, a two-dimensional thermal LBM simulation was carried out to predict electrolyte flow and heat transfer with internal heat generation inside the positive porous electrode with and without embedded microgrooves. Effects of size and number of the microgrooves and electrolyte flow velocity inside the microgrooves on the thermal performance of the positive electrode were investigated.

MODEL DESCRIPTION

In this study double distribution LBM has been utilized. To approximate the collision term, the BGK model was implemented. The discrete particle distribution functions f_i are written as

$$f_i(\boldsymbol{x} + \boldsymbol{e}_i\Delta t, t + \Delta t) = f_i(\boldsymbol{x}, t) - \frac{\Delta t}{\tau_f}\left[f_i(\boldsymbol{x}, t) - f_i^{eq}(\boldsymbol{x}, t)\right] \quad (1)$$

where $f_i(\boldsymbol{x}, t)$ is the probability of finding a particle in the ith velocity e_i at $(\boldsymbol{x}, t)$, Δt is the time step, and τ_f is the relaxation time that controls the tendency of the system to relax the local equilibrium, and is related to the kinetic viscosity ν. f_i^{eq} is the equilibrium distribution that is defined as

$$f_i^{eq} = \rho w_i \left(1 + \frac{\boldsymbol{e}_i.\boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_i.\boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}.\boldsymbol{u}}{2c_s^2}\right) \quad (2)$$

where c_s and w_i are the speed of sound and the weight factor, respectively. In this study, a two-dimensional nine velocities (D2Q9) model was used for the flow field. The mass density ρ and momentum density ρu can be found as

$$\rho(\boldsymbol{x}, t) = \sum_i f_i(\boldsymbol{x}, t),\ \rho\boldsymbol{u}(\boldsymbol{x}, t) = \sum_i \boldsymbol{e}_i f_i(\boldsymbol{x}, t) \quad (3)$$

With the kinematic shear viscosity given by the relaxation time τ_f, the LBE results in macroscopic behavior according to the Navier Stokes equation as

$$\nu = c_s^2\left(\tau_f - \frac{\Delta t}{2}\right) \quad (4)$$

Lattice Boltzmann equation for energy equation, and thermal diffusivity can be defined as:

$$g_i(\boldsymbol{x} + \boldsymbol{e}_i\Delta t, t + \Delta t) = g_i(\boldsymbol{x}, t) - \frac{\Delta t}{\tau_g}\left[g_i(\boldsymbol{x}, t) - g_i^{eq}(\boldsymbol{x}, t)\right] + Q_i(\boldsymbol{x}, t) \quad (5)$$

$$\alpha = c_s^2\left(\tau_g - \frac{\Delta t}{2}\right) \quad (6)$$

where α is related to relaxation time τ_g like the relation between kinematic viscosity ν and relaxation time τ_f for the standard LBM. In LBM for energy equation, only T is conserved and the velocity u is not obtained from g_i and it is imposed externally [16]. In this study, a two-dimensional five velocities (D2Q5) model was used for the thermal field. The equilibrium distribution function g_i^{eq} can be found as

$$g_i^{eq} = w_i T \left(1 + \frac{\boldsymbol{e}_i.\boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_i.\boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}.\boldsymbol{u}}{2c_s^2}\right) \quad (7)$$

and the temperature (T) is extracted as

$$T(\boldsymbol{x}, t) = \sum_i g_i(\boldsymbol{x}, t) \quad (8)$$

The heat generation in Eq. (9) can be defined as:

$$Q_i = w_i q_L \Delta t \quad (9)$$

where q_L is heat generation in lattice units $[q_L] = LT/Lt$ (Lattice Temperature/Lattice time).

RECONSTRUCTION OF POROUS GEOMETRY

In this study, to generate porous medium geometry of positive electrode, the porosity and pore size were considered. It was assumed that the porous electrode has the porosity and the pore size of 0.4 and $112nm$, respectively [17, 18]. To generate these porous geometry, a random porous medium generator code was developed. Generated porous geometry was illustrated in Fig. 1.

Furthermore, to represent the microgrooves inside the electrodes, the ratio of total size of the microchannels to the size of the porous electrode was defined. This ratio was chosen to be $r_A = A_{Microgrooves}/A_{Porous\ electrode} = 0.12$. Using this ratio, the width of the microchannels were $30\ nm$ for the cases with two microchannels and $15\ nm$ for the cases with four microchannels.

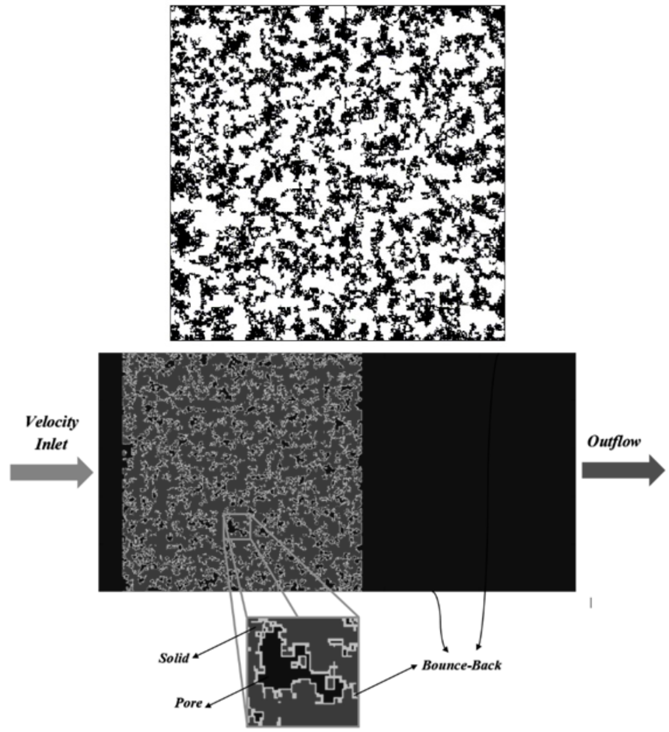

Fig. 1 Cathode porous medium geometry (Top), and boundary conditions (Bottom)

NUMERICAL SOLUTION AND BOUNDARY CONDITIONS

In this study, the pore scale was carried out for LBM application in porous media. The pore scale uses the standard lattice Boltzmann equation to simulate fluid flows in pores, and the local information of the fluid flow are obtained directly. In this scale, a detailed geometric information of the pores should be provided [19].

The two-dimensional domain size of $10 \times 5\ \mu m^2 \equiv 1000 \times 500\ LU^2$ was considered to simulate the process of electrolyte flow and heat transfer with internal heat generation inside the porous electrode. On the solid-liquid interface and channel walls, the bounce-back boundary condition was applied. On the left side as inlet, the velocity inlet boundary condition was set with two flow velocities of $0.75\ m/s$, and inlet temperature of $300K$. On the right side as outlet, the outflow boundary condition was utilized. The isothermal boundary condition was applied on the solid-liquid interface. It was assumed that the initial temperature inside the porous electrode is $315\ K$, and heat generation inside the porous electrode is $28{,}000\ W/m^3$ [4]. It was also assumed that electrolyte acts like a Newtonian fluid. In this study, it was defined that $0\ LT \equiv 273.15K$ and $1\ LT \equiv 373.15K$ and, also it was found that $0.75 m/s \equiv 0.0005 LU/Lt$.

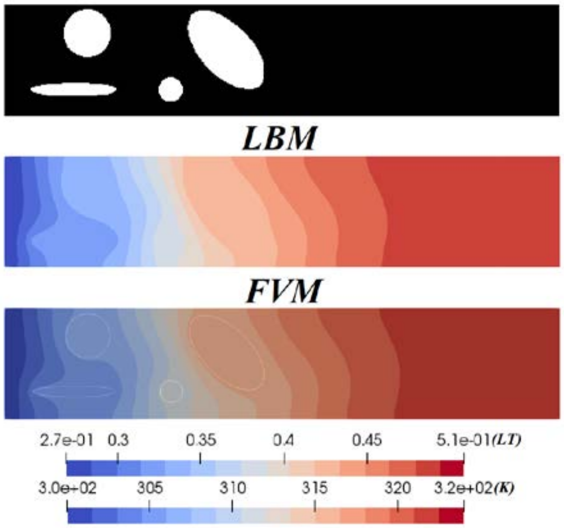

Fig. 2 Comparison of LBM and FVM results

To validate the present LBM, a flow channel with simple geometry as illustrated in Fig. 2 was employed. Fluid flow and heat transfer with internal heat generation inside this geometry was simulated using both LBM and finite volume method (FVM) and their results were compared. In the simulations, the channel size was $50 \times 10\ mm^2 \equiv 500 \times 100\ LU^2$. The inlet velocity and temperature were $50\ \mu m/s$ and $300\ K$, respectively. The initial temperature and internal heat generation were assumed to be $315\ K$ and $1 \times 10^5\ W/m^3$, respectively. It was also assumed that the fluid is water and the solid is aluminum.

Figure 2 shows the results of both LBM and FVM after $300\ s$. Good agreement can be seen between the results of LBM and FVM that confirms LBM utilized in this study can accurately simulate the electrolyte flow and heat transfer with internal heat generation inside the porous electrode.

RESULTS AND DISCUSSIONS

Figure 3 shows the temperature contours in different time steps. As it is deduced from this figure, with the passage of time, heat diffusion (conduction) occurs on both cases of with and without microgrooves. However, in the case with microgrooves, additional convection leads to higher heat transfer compare

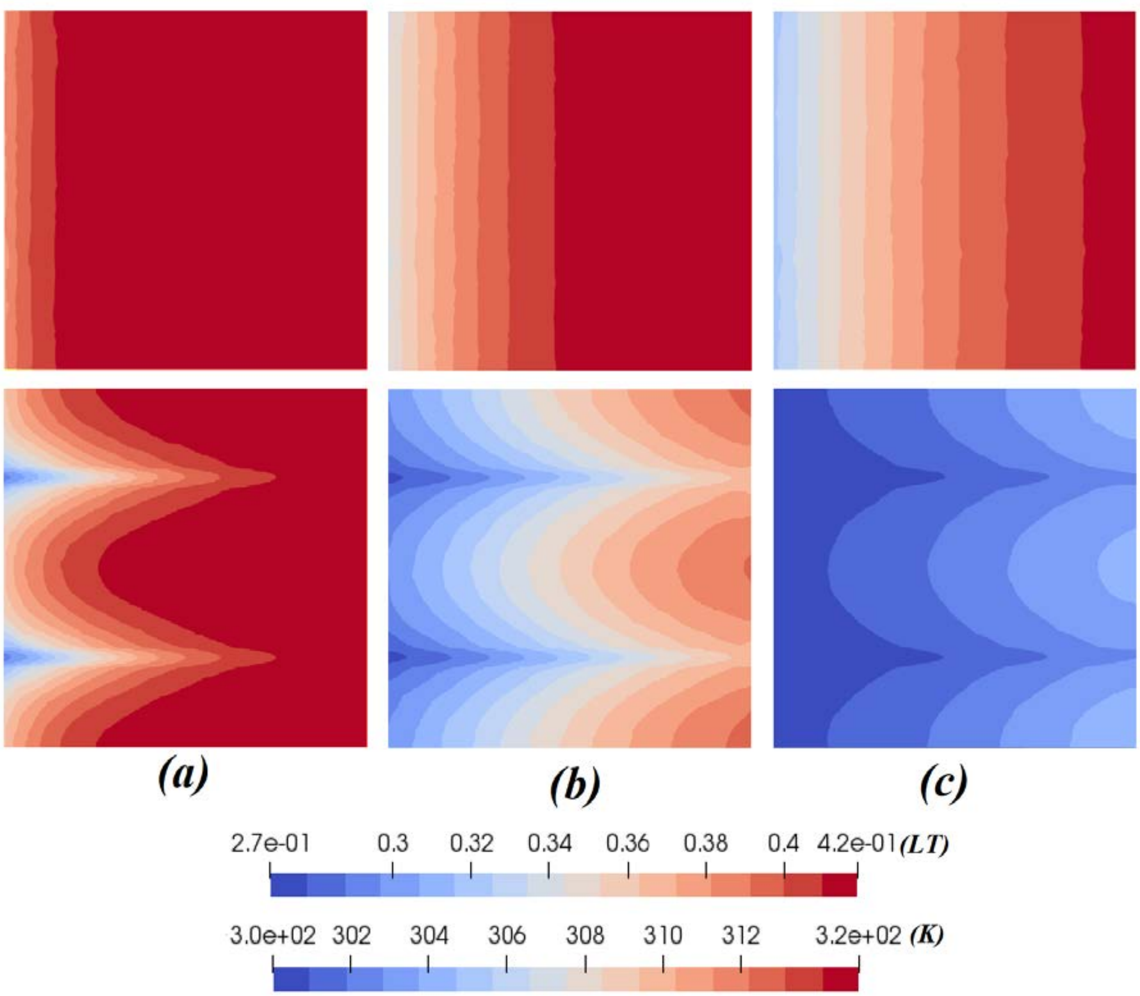

Fig. 3 Temperature contours of cathode porous electrodes without (Top) and with (Bottom) microgrooves after (a) 1 μs (150,000 Lt), (b) 4 μs (600,000 Lt), and (c) 10 μs (1,500,000 Lt)

with the case without microgrooves. This higher heat transfer in the case with microgrooves leads to lower temperature in the porous electrode as well as better temperature uniformity inside it. After $10\ \mu s$, the maximum temperature inside the porous electrode reduced from $315\ K$ to $305\ K$ by embedding microgrooves inside the electrode. Furthermore, the electrolyte flow through microgrooves lowered the temperature difference inside the electrode from $10\ K$ to $5\ K$ which shows higher temperature uniformity.

To analyze the effects of size and number of microgrooves on the thermal performance of the porous electrode, the number of microgrooves changed from two to four by keeping the constant ratio between total size of the microgrooves to the size of the porous electrode $r = A_{Microchannels}/A_{Cathode} = 0.12$. The results of this substitution after $4\ \mu s$ were illustrated in Fig. 4. From this figure it can be concluded that using four microgrooves instead of two can improve the thermal performance of the porous electrode by keeping it at lower temperatures. Using four microgrooves instead of two microgrooves decreased the maximum temperature inside the electrode from $313K$ to $311K$. Furthermore, this figure shows that the temperature difference inside the electrode decreased from $13K$ to $11K$ that demonstrates higher temperature uniformity inside the electrode when four microgrooves has been utilized instead of two microgrooves.

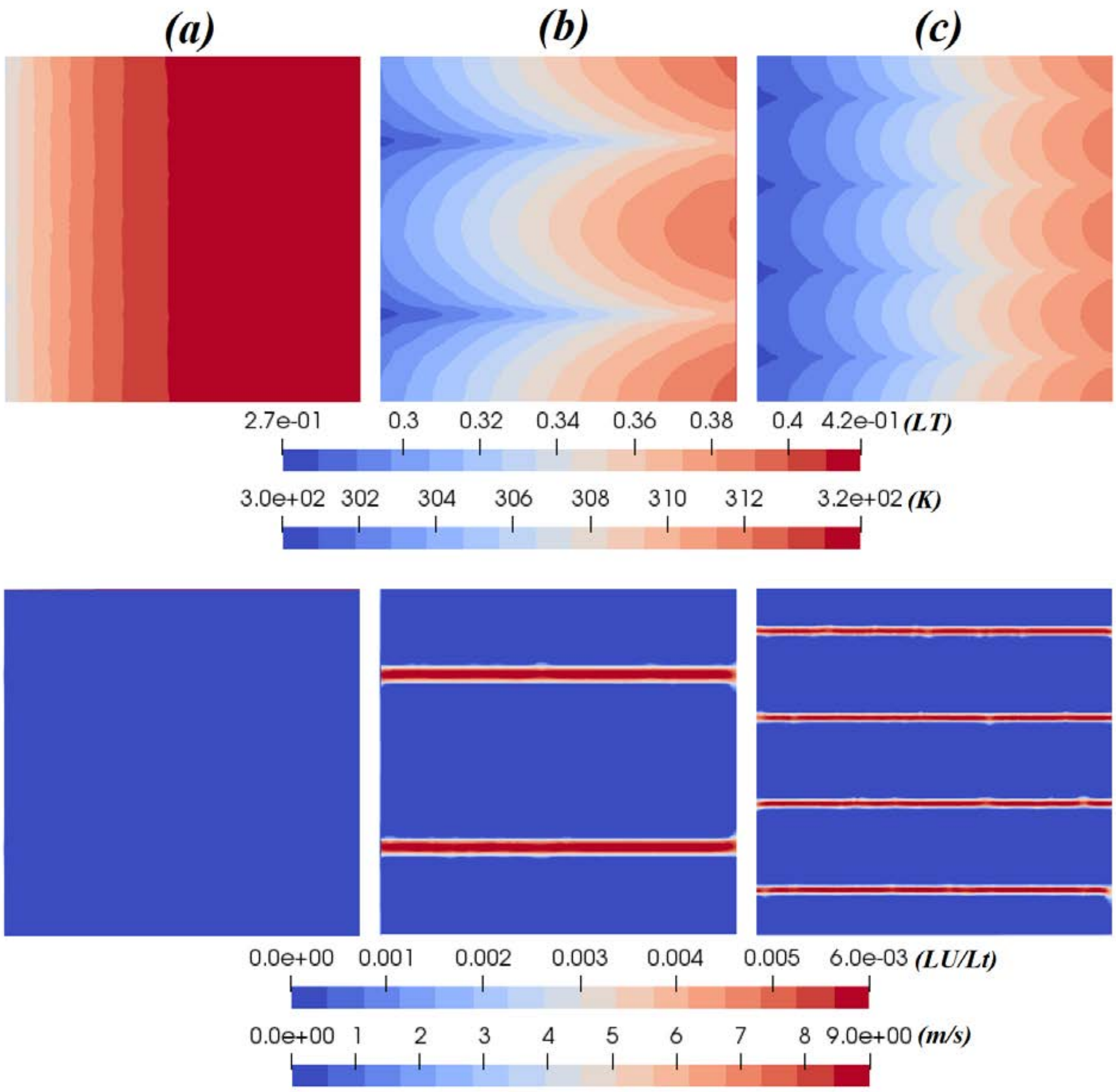

Fig. 4 Temperature (Top) and Velocity (Bottom) contours of cathode porous electrodes after4 μs $(600,000\ Lt)$ for cases (a) without microgrooves, (b) with two microgrooves, and (c) with four microgrooves.

Paying attention to the cases without microgrooves, the case with two microgrooves, and then the case with four microgrooves, one clearly finds that in all cases heat conduction happens. However, the superiority of cases with microgrooves to the case without them is the existence of convection heat transfer. Now, what excels the case with four microgrooves to the case with two microgrooves is the shorter distance between the points with maximum temperatures and the microgrooves which have minimum temperatures. Shortening the distance between the points with higher temperatures and the points with lower temperatures enhanced the total heat transfer from the porous electrode by enhancing the conduction heat transfer.

CONCLUSIONS

In this paper, a two-dimensional thermal LBM was utilized to simulate electrolyte flow, heat transfer, and internal heat generation inside the positive porous electrode of a Li-ion battery. Thermal performance of the positive electrode was investigated for different sizes and numbers of the microgrooves inside them. The results showed that embedding microgrooves inside the porous electrode improved the thermal performance of the Li-ion battery by keeping the electrode at lower temperatures as well as improving its temperature uniformity. It happened because electrolyte flow through microgrooves enhanced the convection heat transfer which leads to higher heat transfer from the porous electrode. Also, increasing the number of microgrooves under a constant ratio between total size of the microgrooves to size of the porous electrode improved thermal management of the Li-ion battery by decreasing the temperature of the electrode and enhancing the temperature uniformity.

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