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Influence of static bubbles at the surface of electrodes on the natural convection flow for application in high performance lead-acid battery

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ABSTRACT

The natural convection heat transfer is investigated in the cavities which are filled with sulfuric acid-water (25–75%) and with different numbers of generated bubbles at the surfaces of side walls. The heatline visualization approach is employed to detect the heat energy path in the cavity from heat sources to heat sinks. The operating fluid is sulfuric acid-water (25–75%) with constant thermo-physical properties. The Navier-Stokes equations are solved based on two-dimensional form, and finite volume approach is utilized. The side walls are heated with constant/uniform heat flux and no-slip condition is applied to them. The top and bottom walls are cooled by environment temperature with no-slip condition. The influences of different governing parameters of Rayleigh number ($10^3 < Ra < 10^5$), and three different numbers of generated bubbles on the heat flux on the flow structure, temperature field, velocity and temperature distributions, average Nusselt number, and heatlines have been presented comprehensively.

1. Introduction

The free convection within the open and rectangular enclosure is one of the basic problem and phenomenon in the heat transfer. At the recent decades, the applied studies have been increased in these regard. Some of the applications of natural convection heat transfer are: solar collectors, cooling of nuclear reactors and electronic components, lead-acid battery, double pane windows etc. [1–4]. There are a large number of researchers investigated the natural convection heat transfer within the enclosure with different shapes, fluids and different thermal and physical boundary conditions [5–7]. It is important to use the numerical simulation for prediction and a better understanding of the phenomena and reduce the cost of researches. Also, the importance of numerical study is significant when the case study has a small dimension and it is difficult to measure the temperature or flow visualization.

The thermal management of the batteries attracts many attentions due to importance of this issue on determining the efficiency of the battery systems. It should be noted that there is a lack of investigations on the fluid flow and heat transfer of lead-acid batteries and the effective parameters on the thermal management of battery systems. To explain the importance of thermal management in different types of batteries, the results of some works are presented here. Ahmad A. Pesaran [8] analyzed the thermal management of the batteries in electric vehicles (EVs) and hybrid electric vehicles (HEVs). He comprehensively reviewed different approaches and solutions contributing on efficient thermal management systems. Different methods of cooling are compared with each other such as active cooling/passive cooling, liquid cooling/air cooling for different types of batteries like VRLA, NiMH, and Li-Ion batteries. Chen and Ivass [9] proposed a two-dimensional model to assess the impact of various cell components, syz attack and cooling conditions on the performance of polymer electrolyte lithium batteries at different discharging rates. Based on the obtained temperature profile, they have a useful view to maintain the operating temperature with a proper cell stack design and choosing a suitable cooling system in terms of heat transfer. Kizilel et al. [10] proved the advantage of a thermal management system on active cooling systems for lithium-ion battery packs. They showed that the high power packs with phase-change material in discharging are safe in high currents.

There are a large number of researchers investigate the natural convection heat transfer in an enclosure [11–24]. In this context, The numerical and experimental study of natural convection in an inclined hemispherical cavity filled with air investigated by Baïri et al. [25]. They proposed a correlation of Nusselt-Rayleigh for different ranges of inclination angles. Jou and Tzeng [26] in a numerical research investigated the natural convection heat transfer in a rectangular enclosure filled with different types of nanofluids. They used the Khanafer̓s model to analyze heat transfer performance of nanofluids in an

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Nomenclature

H	high of enclosure (m)
L	width of enclosure (m)
g	gravity $\left(\frac{m}{s^2}\right)$
K	thermal conductivity $\left(\frac{W}{mk}\right)$
Nu	local Nusselt number
Nu_{avg}	average Nusselt number
q″	heat generation per area $\left(\frac{W}{m^2}\right)$
P_r	Prandtl number
R_a	Rayleigh number
T	temperature (c°)
T_c	cold temperature (c°)
$\vec{U}$ and $\vec{V}$	dimensionless velocity components $(U = uH/\alpha,\ V = vH/\alpha)$
x, y, z	Cartesian coordinates (m)
X, Y	dimensionless of Cartesian coordinates $\left(\frac{x}{L},\frac{y}{H}\right)$
h	heatfunctions parameter

Greek symbols

α	Thermal diffusivity $\left(\frac{k}{\rho c_p}\right)$
β	Thermal expansion coefficient, k^{-1}
θ	dimensionless of temperature
ΔT	Ref. temperature difference
μ	dynamic viscosity, Nsm^{-2}
ν	kinematic viscosity, m^2s^{-1}
ρ	Density, kgm^{-3}
Π	Dimensionless heatfunction

Subscripts

c	cold
w	water
el	Electrolyte
h	hot
s	Surface

enclosure. They showed that the buoyancy parameter and volume fraction of nanofluids are two significant parameters of heat transfer enhancement. Jahanshahi et al. [27] studied the free convection of water/SiO2 nanofluid in a square cavity based on experimental-measured thermal conductivity for $Ra = 10^5$–10^7 and the volumetric fraction of nanoparticles were between 0 and 4%. They concluded that the heat transfer increases by increasing the Rayleigh number.

There are a few studies which analyzed the free convection in an enclosure with non-uniform heat flux or different profiles of heat flux. Bouhalleb and Abbasi [28] studied a two-dimensional steady laminar natural convection in a tilted enclosure filled with CuO-H2O nanofluid with sinusoidal temperature distribution and different aspect ratios. They showed that the rate of heat transfer decreases with increasing of aspect ratio. Rashidi et al. [29] investigated the natural convection of Al2O3/Water nanofluid in a square enclosure with heterogeneous heating from bottom. They considered nine various cases for the non-uniform heat flux which the total heat flux applied to the enclosure is same for all cases quantitatively, but the profiles are different. They claimed that the Nusselt number is related to the profile of heat flux. Ghasemi et al. [30] in a numerical study considered the natural convection heat transfer in enclosure with oscillating heat flux and investigated the effect of the Rayleigh number, solid volume fraction, and the position of heat flux and oscillation period on performance of cooling system. They showed that the oscillating heat flux causes an oscillating behavior of flow field, temperature distribution and the Nusselt number; As well as, they represented that the increasing of the Rayleigh number is a significant parameter for enhancement of heat transfer rate. Sathiyamoorthy et al. [31] analyzed the steady natural convection heat transfer within a square enclosure filled with a porous medium and linearly heated from side walls. They showed that the secondary circulations become weaker at low Prandtl number fluid.

There are some studies investigated natural convection heat transfers within enclosure with obstacle or roughness elements in the wall. Yousaf and Usman [32] studied the natural convection heat transfer in a two-dimensional square enclosure with sinusoidal roughness elements. They concluded that the sinusoidal roughness considerably affects on the thermal and hydrodynamic behavior of fluid in a square cavity. The Natural convection and entropy generation of Cu-water nanofluid around an obstacle within an enclosure were studied by Sheikhzade et al. [33]. They considered the effect of various Rayleigh numbers and obstacle dimensions on the heat transfer characteristics and entropy generation for both nanofluid and pure water. They showed that by increasing of Rayleigh number, both terms of entropy generation and Bejan number increases. Also, they observed that the increasing of obstacle dimension has a better effect at the low Rayleigh number on the present thermal system.

The main aim of present study is to investigate the effect of static bubbles located at the side walls on heat transfer characteristics and flow field in a rectangular enclosure heated from side walls and cooled from top and bottom walls, which is a simple model of a cell of lead-acid battery, for different number of bubbles and various Rayleigh numbers.

2. Problem presentation, numerical approach and validation

2.1. Problem presentation

The schematic of considered geometry is presented in Fig. 2. This configuration can represent a cell of lead-acid battery affected by heat flux from side walls due to chemical reaction of side walls with electrolyte. Actually, it can be assumed that the parts of side walls that are exposed in liquid phase, simulated the electrodes at lead-acid battery as shown in Fig. 3. It can be observed that it is a simplified model of the cell including single pair of cathode and anode. It is worth to explain that the generated bubbles at the surface of the electrodes, as a result of

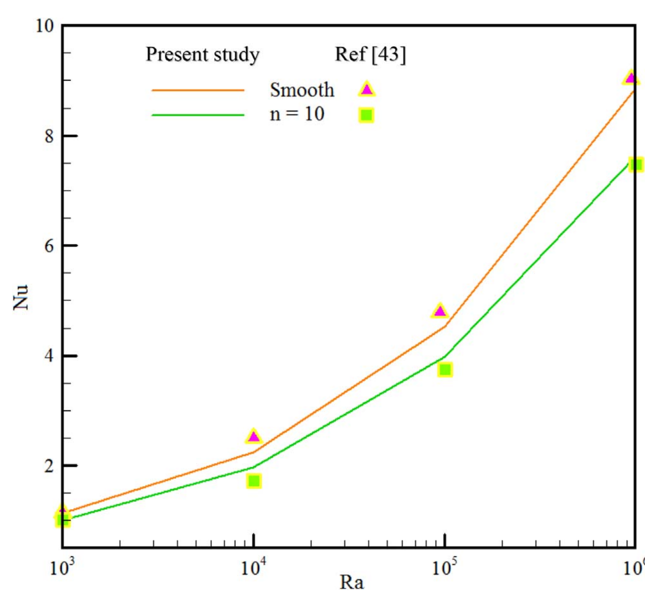

Fig. 1. Validation of the present study for smooth and 5 bubble compared with Ref. [32].