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# Experiment and simulation of natural convection heat transfer of transformer oil under electric field

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ABSTRACT

The heat transfer characteristics of transformer oil natural convection in a cavity with a linear electrode were investigated by experiment and numerical simulation. The coupled physical and mathematical models of electric field, flow field and temperature field were established by the lattice Boltzmann method. The experimental results are in good agreement with the numerical simulation. In the absence of gravity, the enhancement effect of electric field on heat transfer is significant, and increases with the increase of voltage and heat flux. As to coupled convection caused by gravity and electric field force together, the electric field force destructs the natural convection caused by gravity, so applying an electric field at a low voltage will degrade heat transfer performance; as the voltage increases, heat transfer gradually becomes intensive, but the effect is limited. The study results revealed the enhancing mechanism of natural convection heat transfer under electric field and provided useful technical support for practical application.

## 1. Introduction

In active heat transfer enhancement field, the electric field enhancement method is getting more and more researchers' attention, which is called EHD (electrohydrodynamics). It applies the basic theory of electric fielD coupled with temperature and flow fields, so heat transfer will be enhanced with the interaction and synergy among the electric field, the flow field and the temperature field. It is well known that EHD enhanced heat transfer has several obvious advantages: a significant effect of heat transfer, simple electric field generator, easy to control heat flow and temperature, suitable for micro-gravity and other special occasions, low energy consumption et al. [1]. As early as 1916, the British scholar Chubb found that EHD can strengthen the boiling heat transfer; in 1936, Senftleben found that the electric field also has an enhancement effect on natural gas convection. In the early 1950s, Kronig et al. demonstrated that the electric field can increase the convection heat transfer coefficient of the insulating dielectric fluid, and thus EHD enhanced heat transfer has attracted the attention of many scholars.

In the EHD enhanced heat transfer experiments, most researches use refrigerants as working fluids. The significant heat transfer enhancement effect of EHD for various working fluids (R-113, R-123 and other organics) was confirmed by Didkovshy, Bolog-a, Yabe, and Sunada [2–4]. Didkovshy and Bolog-a [3] studied with ethane, freon and ether, which had different electrical parameters. It was concluded that the electrical parameters of the materials affected the effect of electric field.

Yamashita et al. [5] tested the EHD effect of R123 in condensation heat transfer. The experiment showed that the condensation rate of R123 was greatly improved under electric field. Since R123 is a substitute for CFC, this work makes the EHD technology more practical.

Marucho et al. [6] studied the electro-hydrodynamic (EHD) natural convection enhancement for isothermal, horizontal axisymmetric bodies, which are immersed in a liquid metal under the effects of uniform electric fields. It was found that when external electric fields are applied to liquid metals the average Nusselt number may be enhanced by up to 55%. Nasirivatan et al. [7] investigated the influence of external electrohydrodynamic forces on natural convection from a flat plate. In the presence of the field, heat transfer can be improved by 61%.

Paschkewitz and Pratt [8] carried out a series of experiments on EHD enhanced forced convection heat transfer, which used three kinds of cooling oils with different physical properties for investigation. The effects of pressure drop, input electric power, viscosity and electric field strength on the EHD enhanced efficiency were studied in detail. The experimental results showed that the medium with low viscosity and low conductivity has better heat

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## Nomenclature

| | |
|---|---|
| $A$ | heating area ($m^2$) |
| $cp$ | specific heat at constant pressure (J/kg/K) |
| $c$ | the moving velocity between grids (–) |
| $D$ | the diameter of the cavity (m) |
| $De$ | charge diffusion coefficient ($m^2/s$) |
| $e$ | lattice velocity (–) |
| $E$ | electric field intensity (V/m) |
| $El$ | dimensionless electrical characteristic parameter (–) |
| $F$ | force (N) |
| $F_e$ | electric field force (N) |
| $F_q$ | electrophoretic force (N) |
| $F_\varepsilon$ | dielectrophoretic force (N) |
| $F_s$ | electrostrictive force (N) |
| $F_{LB}$ | external force in lattice system (N) |
| $\mathrm{F}_{\mathrm{BU}}$ | buoyancy in lattice system (N) |
| $\mathrm{F}_{\mathrm{ELB}}$ | electric field force in lattice system (N) |
| $g$ | gravitational acceleration ($m/s^2$) |
| $h$ | heat transfer coefficient ($W/m^2/K$) |
| $h_e$ | heat transfer coefficient under electric field ($W/m^2/K$) |
| $h_0$ | heat transfer coefficient without electric field ($W/m^2/K$) |
| $H$ | the height of the cavity (m) |
| $I$ | current (A) |
| $J$ | current density ($A/m^2$) |
| $Nu$ | Nusselt number (–) |
| $Pr$ | Prandtl number (–) |
| $q$ | heat flux ($W/m^2$) |
| $q_e$ | the charge density ($C/m^3$) |
| $Ra$ | Rayleigh number (–) |
| $Ra_{El}$ | electric Rayleigh number (–) |
| $r_{ele}$ | the radius of the linear electrode (m) |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $T_w$ | wall temperature(°C) |
| $T_H$ | the temperature of the heating surface (°C) |
| $T_C$ | the temperature of the cooling surface (°C) |
| $u$ | speed (m/s) |
| $U$ | voltage (V) |
| $W$ | the width of the cavity (m) |
| $X$ | dimensionless x-coordinate (–) |
| $Y$ | dimensionless y-coordinate (–) |
| $z$ | the distance from the heating plate (m) |
| $\Delta T$ | temperature difference (K) |
| $\delta x$ | distance between adjacent nodes of lattice system (–) |
| $\delta t$ | time step between adjacent nodes of lattice system (–) |

*Greeks*

| | |
|---|---|
| $\alpha$ | thermal diffusivity ($m^2/s$) |
| $\beta$ | isobaric expansion coefficient (–) |
| $\varepsilon_r$ | relative permittivity (–) |
| $\varepsilon$ | permittivity (F/m) |
| $\lambda$ | thermal conductivity (W/(m·K)) |
| $\mu$ | dynamic viscosity coefficient (Pa·s) |
| $\nu$ | kinematic viscosity coefficient ($m^2/s$) |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | electrical conductivity (nS/m) |
| $\tau$ | relaxation time (s) |
| $\Phi$ | potential (V) |
| $\omega$ | the weight coefficient of lattice Boltzmann method (–) |
| $\Theta$ | dimensionless temperature (–) |

*Subscripts*

| | |
|---|---|
| $e$ | under electric field |
| 0 | initial value |
| $LB$ | lattice system |

transfer enhancement effect under the given electric field strength. For working fluids with a small charge relaxation time, defined as the ratio of the dielectric constant to the conductivity, a greater electric field strength was required to obtain a given heat transfer coefficient.

Liu et al. studied the EHD heat transfer characteristics of lubricating oil and vacuum pump oil in forced convection heat transfer inside a tube [9,10] and natural convection heat transfer around a horizontal tube of 10 mm diameter [11], respectively. The results showed that in the tube with diameter of 20 mm, the maximum enhancement effect of heat transfer coefficient can reach about 8 times when the applied electric voltage is 4 kV under laminar flow condition, and it can reach about 2 times for natural convection outside a tube of 10 mm diameter. This indicates that EHD has a very excellent effect for the dielectric with a weak polarity like insulating oil.

Wang et al. [12–14] chose benzene, diethyl ether and ethyl acetate as the working fluids, carried out both theoretical and experimental researches about the enhancement effect of the electrical properties and molecular structure of working fluids to the natural convection heat transfer. The experimental results showed that the high voltage direct current (DC) electric field can greatly enhance the natural convection heat transfer of all the three working fluids on the horizontal plate surface. The effect of electric field first increases with the increase of electric voltage and then becomes stable. Moreover, the effect of the electric field on the natural convection heat transfer of benzene is independent of the heat flux; however, the electric field effect of the other working fluids decreases with the increase of the heat flux, but the change rate of the effect varies with working fluids, which means the properties of the working fluids having important influence on the EHD effect.

Wang et al. [15] investigated the EHD effect on forced convection heat transfer of transformer oil in a horizontally positioned smooth tube under high-temperature conditions. Experimental results showed that the average enhancement ratio of heat transfer coefficient can exceed 6 under 8.0 kV voltages, while that of friction ratio approaches only 1.5.

Sheikholeslami et al. [16] studied the EHD enhanced convective heat transfer of $Fe_3O_4$-Ethylene glycol nanofluid by Control Volume based Finite Element Method. Result showed that the Coulomb forces enhanced heat transfer especially for small Reynolds number.

In the researches on the mechanism of EHD enhanced heat transfer, scholars usually begin with electric field force of the working fluid. According to the theory of electromagnetism, Panofsky put forward the general expression of the electric field force for the working fluid under electric field [1]:

$$F_e = q_e E - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right] \tag{1}$$

The first term in the right side of Eq. (1) is the electrophoretic force or the coulomb force, whose direction depends on the polarity of the free charge and the direction of the electric field. The second term is the dielectrophoretic force, represents the force applied to the fluid due to the spatial variation of the dielectric