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Determination of Operation Parameters through Numerical Analysis of Coupled Thermal, Hydro Mechanical and Electrical Fields in 10kV Electric Heater

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Summary

An electric heater of high–voltage such as 10kV is predominant in the view of economy because it doesn't need transformer. However, it is problematic to guarantee the safety in the former types of high–voltage electric heater. It is also difficult to predict the thermal power of the heater in the step of design because it depends on temperature, velocity and specific resistance of the fluid that are also changed in relation to each other. To solve these problems, we propose a 10kV electric heater in which a ceramic insulation tube was installed and different from former types, and determine its geometrical sizes and operation parameters through numerical analysis of coupled thermal, hydro mechanical and electrical fields in the water heating process.

Keywords: Electric heater; Water heating; Thermal power;

1. Introduction

The study on electrical liquid heaters can be divided in two categories: low voltage electric heater (LVEH) and high voltage electric heater (HVEH). In case of LVEH, the heat is generated by Joule heating effect in electrical resistor as electrical heating element below 380V and transferred to fluids. Metallic tubes with direct current passage are commonly used for fluids or gas heating [6, 7]. The works presented in papers [18, 12] relate to the design and testing of a compact electric heater used for heating various liquids at moderate temperature (<60°C), for example, water to heat buildings, swimming pools and ponds used for aquaculture, and also for heating sensitive products used in chemical and agro alimentary processes. Usually, one electrical heating element which is introduced in LVEH has thermal power of several kilowatts.

The HVEH offers several advantages, such as high electro–thermal power of thousands of kilowatts, low investment compared to its high thermal power values and the good points that it can be easily manufactured and be operated without transformer thanks to being supplied directly from electric power net [2, 15]. To decrease the thermal power to hundreds of kilowatts, the electrical resistance should be increased. To solve this problem, we propose the HVEH with the ceramic insulation tube and try to investigate the influences of fluid flow, temperature field and electrical field that are related to thermal power in the designing stage.

The papers [3, 20] presented experimental validation of a numerical model of coupled processes within a three–phase medium–power dry–type electrical transformer. The thermal and fluid flow analysis was combined with an electromagnetic model in order to examine the specific power losses within the coils and the core. The authors of [4, 14, 19, 21] considered detailed numerical analyses employed a multidisciplinary approach including heat, fluid flow and electric fields and suggested mathematical models and procedures.

In papers [8~11] the electro–thermal behavior of conductive polymer composites with electrical conductive fillers (carbon black, carbon fibers or metal particles) as heating elements is evaluated experimentally and numerically.

In the case of the HVEH with the ceramic insulation tube, differently to previous works, the fluid should be considered as electrical resistor and heat source. The equations presented and applied to a 3D axis–symmetric geometry were computed using COMSOL [5].

2. Modeling of electro–thermal behaviors

To study the electro–thermal phenomena, a steady state 3D model is developed and mathematical model is solved using the finite element method [22].

Using the model creation tool of COMSOL, the 3D–model with the size of $\Phi 0.26\times H$ 1.0m was partitioned in tetrahedron elements with the number of these 207318. Electrical conduction is governed by a Laplace–equation [16, 17]

$$\nabla J = -\nabla\cdot(\sigma\nabla U) = 0 \tag{1}$$

Electrical current density J is expressed as follows, by the Ohm's law:

$$J = \sigma E \tag{2}$$

Where electrical conductivity σ and electrical field E are obtained by:

$$\sigma = \frac{1}{\rho_t(T)} \tag{3}$$

$$E = \nabla U \tag{4}$$

The generated heat can then be written as Eq. (5).

$$Q = JE \tag{5}$$

The thermal power P_{th} is expressed as Eq. (6).

$$P_{th} = MC_p(T_{out} - T_{in}) \tag{6}$$

The computed flow velocity is coupled with the heat transfer equation in turbulent mode and steady state [13, 1]:

$$\nabla\cdot(\vec{u}\rho C_P T) = \nabla\cdot(\lambda_{eff}\nabla T) + Q \tag{7}$$

where $\lambda_{eff} = \lambda_f + \lambda_{turb}$

The Navier–Stokes equations for non–isothermal flows and transport equations for the standard k–ε model are coupled with the heat transfer equation in the space of the heater body:

$$\nabla\cdot(\rho\vec{u}\vec{u}) = -\nabla p + \nabla\begin{bmatrix}\mu_{eff}\left(\nabla\vec{u}+\nabla\vec{u}^{T}\right)- \\ \frac{2}{3}\nabla\cdot\mu_{eff}\nabla\vec{u}I_{turb}\end{bmatrix} \quad (8)$$

where $\mu_{eff} = \mu_f + \mu_{turb}$

$$\nabla\cdot(\rho\vec{u}) = 0 \quad (9)$$

Transport equations for the Standard k–ε Model are written as Eq. (10), Eq. (11) and Eq. (12).

$$\nabla\cdot(\vec{u}\rho k) = \nabla\cdot\left[\left(\mu_f + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G - \rho\varepsilon \quad (10)$$

$$\nabla\cdot(\vec{u}\rho\varepsilon) = \nabla\cdot\left[\left(\mu_f + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + c_1\frac{\varepsilon}{k}G - c_2\rho\frac{\varepsilon^2}{k} \quad (11)$$

$$G = \mu_{turb}\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)^2\right\} \quad (12)$$

$$\mu_{turb} = \rho_f c_\mu \frac{k^2}{\varepsilon}, \quad \lambda_{turb} = C_{pf}\frac{\mu_t}{\sigma_T}.$$

where c_μ=0.09, c_1=1.44, c_2=1.92, σ_k=1.0, σ_ε=1.4, and σ_T=0.9 are model constants. The fluid enters the body with a nearly uniform velocity profile. A constant flat profile for axial velocity u is assumed in this hydrodynamic inlet region:

$$u(r) = u_0\left(1 - \left(\frac{\left|r - \frac{r_b + r_c}{2}\right|}{\frac{r_b + r_c}{2}}\right)^n\right) \quad (13)$$

with n=8

where u_0=(0.1~0.5)m/s is imposed.

Furthermore other inflow conditions for the flow field are as follows:

$$I_{turb} = 0.16\,\mathrm{Re}^{-1/8} \quad (14)$$

$$k = 1.5\,I_{turb}^{\;2} \quad (15)$$

$$\varepsilon = \frac{k^{\frac{3}{2}} c_\mu^{\frac{3}{4}}}{l_{turb}} \quad (16)$$

The electrical current is calculated by the relation [18]:

$$I = \int_s J(r)ds \quad (17)$$

The outlet temperature is calculated by the Eq. (18):

$$T_{out} = \frac{\int_0^{r_{out}} u(r)T(r)2\pi r dr}{M/3} \quad (18)$$

Other outflow conditions for the flow field are:

$$P=P_f,\ \partial T/\partial n=0,\ \partial k/\partial n=0 \text{ and } \partial\varepsilon/\partial n=0$$

The specific resistances of water were measured according to the principle and method presented in [15]. The two sorts of water with small specific resistance are selected for the simulation.

3. Results and discussion

Table 1. Simulated maximum values of electrical current density and temperature in HVEH

Length of tubes, mm	J, 10^{-4}A/m^2		T_{out}/T_{max}, K	
	The 1st sort	The 2nd sort	The 1st sort	The 2nd sort
400	0.143	0.107	303.1/317.2	301.1/314.5
500	0.135	0.097	301.6/315.2	300.1/313.1

Table 1 presents maximum values of the electrical current density and the temperature in water flow rate of 3.14kg/s corresponding to 0.1m/s. Previous studies have recommended that the electrical current density on the surface of the electrode should not exceed 1 500A/m^2 [2, 15].

Table 2 shows that the simulated and the experimental results agree well.

Table 2. Comparison between simulated and experimental values of the electrical current and the temperature increase for the tube length of 500mm.

Water	The 1st sort		The 2nd sort	
	Simulation	Experiment	Simulation	Experiment
I, A	21	21.5	16.5	16.1
$\Delta T/T_{out}$, K	8.8/301.6	9.2/302.2	7.1/300.1	6.9/299.9
$P_{th}=M\cdot C_{pf}\Delta T$, kW	349.4	364.1	277.7	273.5
$P_{elec}=\sqrt{3}\ UI$, kW	363.3	372.2	285.1	279.2

Fig. 1 and Fig. 2 show the thermal power of heater changed from 250kW to 900 kW in accordance to the temperature and velocity of the heater inlet.

As shown in comparison, the experimental results are discrepant remarkably to calculated ones in high temperature sphere (>70°C) and almost coincident in low temperature sphere. This fact should be taken account whether in evaluation of simulation results or in modeling of simulation for the work material with the evaporation.

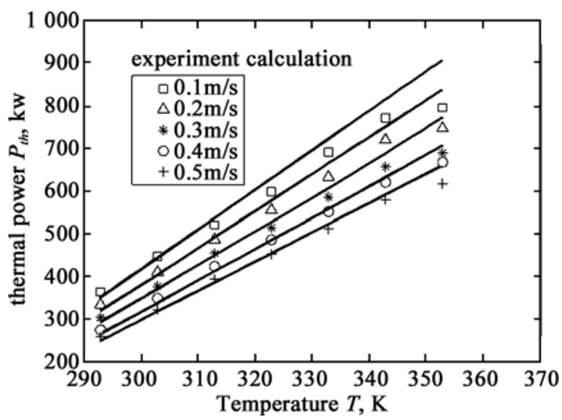

Figure 1. Results for the 1.sort of water with the tube length of 500mm.

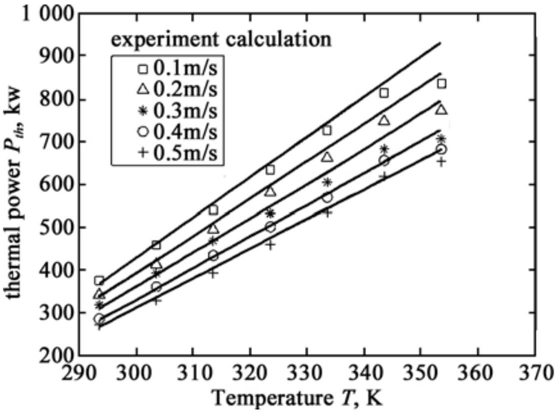

Figure 2. Results for the 1.sort of water with the tube length of 400mm

4. Conclusions

The experimental tests presented show that we can get the stable thermal power of below 650kW in various flow rates.

The insulation tube is appropriate in the size of Φ0.17×H 0.5m for the 10kV water heater in Φ 0.26m×H 1.0m and the electrode with a round form in Φ0.1m×H 0.15m, preserving the sizes of the former type of the heater.

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