Behaviour of Ferrofluidic Liquid in Heat Pipe Affected by External Magnetic Field

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***Abstract*—The process of transporting magnetic fluid in a heat pipe is modeled. Motion of the fluid is driven by several forces (gravitational force, surface tension, magnetic force and in a small extent also wettability). From the physical viewpoint, the task represents a coupled problem. The paper deals with its continuous mathematical model and its numerical solution. The methodology is illustrated by a typical example.**

***Keywords*—heat pipe, magnetic fluid, coupled problem, magnetic field, numerical analysis.**

I. INTRODUCTION

The process of transport of magnetic fluid in the considered heat pipe at the presence of magnetic field is characterized by a relatively complicated interaction of several forces acting on its particles. In order to obtain sufficient information for their quantification a quantitative analysis of the situation in the pipe in the presence of external magnetic field is needed, as is illustrated in Fig. 1a.

Without the presence of external magnetic field, the cooling medium, condensing in the upper part of the heat pipe, flows freely down along the internal surface of the heat pipe. Its movement is only influenced by the gravitational force, surface tension and (at a small extent) also by wettability.

The situation changes, when the magnetic field ***B*** starts growing from zero. In the vicinity of magnetic poles **4** of a considered electromagnet (see Fig. 1a, b) the field is characterized by a steep gradient oriented toward the edges of the tapered poles of the magnetic circuit. Here the particles of the condensate are influenced by magnetic forces oriented in the same direction. And when the axial component of this magnetic force together with the analogous component of the force generated by the surface tension exceed the corresponding pressure and gravitational force, the particle stops flowing down and takes part in forming a relatively stable droplet. The volume of the droplet increases with growing magnetic field and after reaching a predetermined value of magnetic flux density in the axis of the heat pipe the droplet fills in its whole cross section, preventing the condensate from continuing flowing down. Now, the operation of the heat pipe is practically stopped because of no transport of heat (provided that the total weight of the condensate does not exceed the magnetic and tension forces).

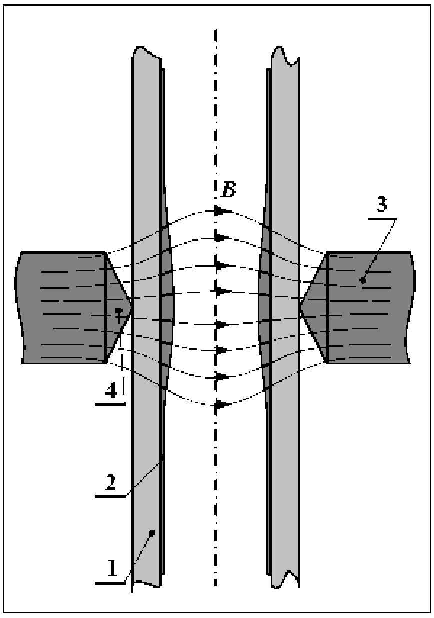

Fig. 1a: Arrangement of the considered heat pipe (front view)

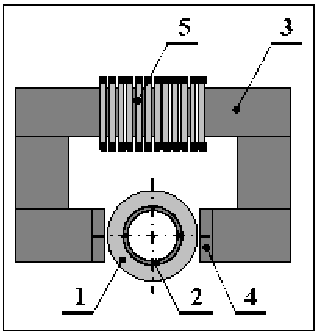

Fig. 1b: Arrangement of the considered heat pipe (top view): **1** – heat pipe, **2** – condensate flowing down along the pipe, **3** – magnetic circuit, **4** – poles of the circuit, **5** – direct current carrying field coil

In the axis of the pipe the magnetic forces vanish (due to anti-symmetry of the arrangement). In case that the droplet fills in the whole cross section of the pipe, the column of the condensate in the axis and its vicinity is kept in balance only by the surface tension.

The magnetic field-dependent evolution of the situation in the pipe is shown in Fig. 2. The distribution of magnetic force lines in particular sub-figures must be considered only orientationally; the presence of magnetic fluid, in fact, leads to changes in their distribution together with the change of the shape of the droplet.

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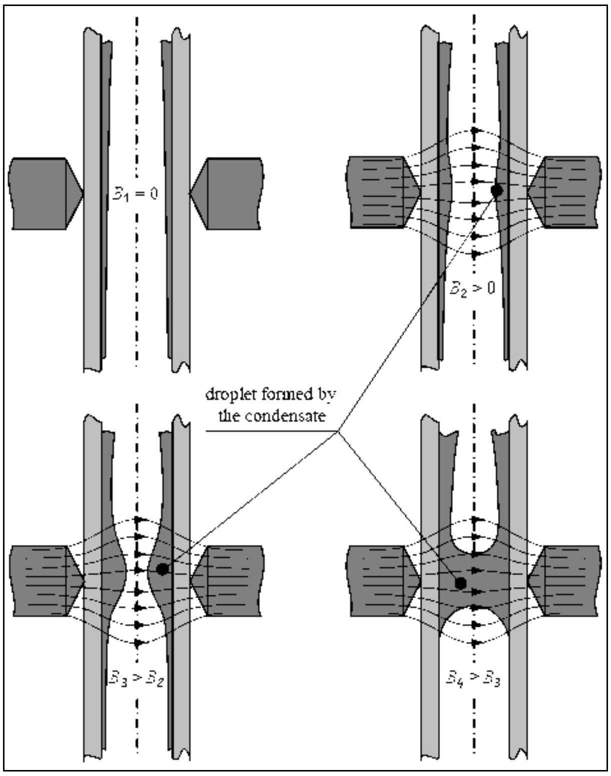

Fig. 2: Droplet of condensate formed by forces acting on it for increasing magnetic field

II. INVESTIGATED ARRANGEMENT

The task will be modelled in the Cartesian coordinates *x*, *y* as a 2D problem (Fig. 3). Thus, it is considered infinite in the direction of the *z*-axis. The droplet is considered a static body, the dynamic phenomena being neglected. This means that its shape is rigid and no fluid is supposed to flow into it or out of it. In other words, in the course of investigation its curved surface remains unchanged.

III. MATHEMATICAL MODEL

The distribution of magnetic field in the investigated part of the system (see Fig. 3) obeys the equation for the magnetic vector potential ***A*** in the form

$$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\,\boldsymbol{A}\right) = \boldsymbol{0}\,, \tag{1}$$

where μ denotes the magnetic permeability. The magnetic vector potential has only one component $A_z\,(x,\,y)$ in the *z*-direction. Equation (1) is solved in an area surrounded by the artificial boundary PSQR. The boundary has to be determined in the manner that its increase no longer affects the field distribution within the heat pipe. Equation (1) has to be supplemented with correct boundary conditions. It is clear that the parts PQ and RS of the boundary are characterized by the perpendicular entry of force lines, so that

$$\frac{\partial A_{\mathrm{z,PQ}}}{\partial x} = \frac{\partial A_{\mathrm{z,RS}}}{\partial x} = 0\,. \tag{2}$$

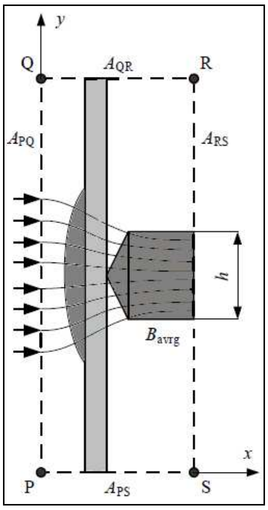

Fig. 3: 2D model for computation of magnetic field

Now we can choose

$$A_{\mathrm{z,PS}} = 0\,,\ A_{\mathrm{z,QR}} = h \cdot B_{\mathrm{avrg}}\,. \tag{3}$$

After obtaining the distribution of quantity $A_z\,(x,\,y)$ we determine the distribution of magnetic field strength $|H\,(x,\,y)|$ following from the formula

$$H\left(x,y\right) = \frac{1}{\mu}\sqrt{\left(\frac{\partial A_{\mathrm{z}}\left(x,y\right)}{\partial x}\right)^2 + \left(\frac{\partial A_{\mathrm{z}}\left(x,y\right)}{\partial y}\right)^2} \tag{4}$$

and distribution of the volumetric energy $w_{\mathrm{m}}\,(x,\,y)$ of magnetic field

$$w_{\mathrm{m}}\left(x,y\right) = \frac{1}{2}\mu H^2\left(x,y\right). \tag{5}$$

The volumetric magnetic force $\boldsymbol{f}_{\mathbf{m}}\,(x,\,y)$ acting on a particle of the droplet at point *x*, *y* is then given as

$$\boldsymbol{f}_{\mathrm{m}}\left(x,y\right) = -\mathrm{grad}\ w_{\mathrm{m}}\left(x,y\right). \tag{6}$$

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