Three-dimensional thermocapillary flow regimes with evaporation

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Abstract.

A three-dimensional problem of evaporative convection in a system of the immiscible media with a common thermocapillary interface is studied. New exact solution, which is a generalization of the Ostroumov–Birikh solution of the Navier–Stokes equations in the Oberbeck–Boussinesq approximation, is presented in order to describe the joint flows of the liquid and gas–vapor mixture in an infinite channel with a rectangular cross-section. The motion occurs in the bulk force field under action of a constant longitudinal temperature gradient. The velocity components depend only on the transverse coordinates. The functions of pressure, temperature and concentration of vapor in the gas are characterized by the linear dependence on the longitudinal coordinate. In the framework of the problem statement, which takes into account diffusive mass flux through the interface and zero vapor flux at the upper boundary of the channel, the influence of the gravity and intensity of the thermal action on flow structure is studied. The original three-dimensional problem is reduced to a chain of two-dimensional problems which are solved numerically with help of modification of the method of alternating directions. Arising flows can be characterized as a translational-rotational motion, under that the symmetrical double, quadruple or sextuple vortex structures are formed. Quantity, shape and structure of the vortexes also depend on properties of the working media.

1. Introduction

Comprehensive study of convection accompanied by evaporation/condensation is motivated by widespread application of the evaporating media in many manufacturing processes and experimental engineering systems. Among them the advanced mini- and microscale cooling technologies, are emphasized. The technologies with use of joint flows of evaporating liquid and co-current gas flux are applied in heat exchangers and heat pipes, jet-spray evaporative cooling systems, electronic setups of planar geometry with multibranch microreactors and microchips, shear-driven film evaporators, etc. For a detail review of analytical, numerical and experimental investigations of the convective fluid flows with mass transfer at interface due to evaporation or condensation we refer to [1]. Preliminary theoretical study of convective processes and evaporation/condensation dynamics can help us to clarify physical aspects of evaporative convection, to define the driving mechanisms and to examine the phenomena in the liquid media caused by the gas flow. Obtained analytical results allow one to predict the outcome of physical experiments and to specify ways of improving the technologies.
The structure of the joint liquid and gas–vapor flows can be described on the basis of the Boussinesq approximation of the Navier–Stokes equations. Seeing the problems of evaporative convection are the multiparameter and very difficult ones, various methods of investigations should be applied. One of the most important and effective methods is obtaining the exact solutions of the governing equations. Exact solutions allow one to model the convective fluid flows rather rapidly and to obtain the qualitative and quantitative flow characteristics (see, for instance, [2–5]). The exact solutions give a possibility to evaluate the degrees of influence of various factors on flow characteristics and to validate the mathematical models.

In the paper we present a generalization of the well-known Ostroumov–Birikh solution [6,7] for three-dimensional non-axis-symmetrical case. We carry out the mathematical modeling of the three-dimensional convective fluid flows with evaporation to analyze the influence of intensity of the gravity force and size of the liquid layer thickness on the flow patterns and temperature distribution. The study is performed with respect to the Soret and Dufour effects in the vapor–gas phase.

2. Governing equations
Let two viscous incompressible fluids (liquid and gas–vapor mixture) fulfill an infinite horizontal channel. Liquid layer $\Omega_1 = \{(x, y, z) : -x_0 < x < 0, 0 < y < 1, -\infty < z < \infty\}$ and gas-vapor layer $\Omega_2 = \{(x, y, z) : 0 < x < x_0, 0 < y < 1, -\infty < z < \infty\}$ are separated by the thermocapillary interface $\Gamma$ given here by the equation $x = 0$. The boundaries of the domains $\Omega_1$, $\Omega_2$ defined by $x = -x_0$, $x = x_0$, $y = 0$ $y = 1$ are the fixed impermeable walls. Note, that the Cartesian coordinate system is chosen so that the gravity acceleration vector $g$ is directed opposite to the $Ox$ axis ($\mathbf{g} = -g_i$, $i$ is the unit vector of $Ox$).

Let the linear size of the flow domains in the $y$-direction $h$ be the characteristic length. We introduce the characteristic values of parameters for the coupled problem on the basis of the characteristic values of the liquid parameters in $\Omega_1$, namely: $u_*$, $T_*$, $\rho_0 = \rho_1 u_0^2$ are the characteristic velocity, temperature and pressure, respectively. The stationary three-dimensional convective flows of $j$-th medium (here and subsequently $j = 1, 2$ relate to the liquid and gas–vapor mixture, respectively) will be described by the Oberbeck–Boussinesq approximation of the Navier–Stokes equations [8] in the non-dimensional form:

$$
(v_j \cdot \nabla)v_j = -\eta_j^0 \nabla p_j + \frac{\eta_j^V}{Re} \Delta v_j + G_j, \quad \text{div} \ v_j = 0, \quad v_j \cdot \nabla T_j = \frac{\eta_j^T}{RePr} (\Delta T_j + \delta \Delta C), \quad (1)
$$

$$
v_2 \cdot \nabla C = \frac{1}{Pe} (\Delta C + \delta \Delta T_2), \quad (2)
$$

Here $v_j$ is the velocity vector, $T_j$ is the temperature, $p_j$ is the pressure (deviation of pressure from the hydrostatic one), $C$ is the vapor concentration function, $G_1 = \bar{i}(Gr/Re^2) T_1$, $G_2 = \bar{i}(\beta (Gr/Re^2) T_2 + \gamma (Ga/Re^2) C)$. The equations (1), (2) with marked terms are considered to model the gas-vapor flows in the upper layer. The effects of diffusive thermal conductivity and thermodiffusion (or the Dufour and Soret effects) are taken into account in the gas phase. The equations (1) without marked terms are used to describe the liquid flows in the lower layer.

We supposed here that the vapor is a passive admixture, the vapor diffusion in the gas phase.

The problem is characterized by the following dimensionless parameters: $Re = u_0 h/\nu_1$ is the Reynolds number, $Pr = \nu_1/\chi_1$ is the Prandtl number, $Gr = \beta_1 T_* gh^3/\nu_1^2$ is the Grashof number, $Ga = gh^3/\nu_1^2$ is the Galilei number, $g = |\mathbf{g}|$, $Pe = u_0 h/D$ is the Peclet number (diffusive Peclet number), $\eta_1^V = 1$, $\eta_2^V = 1/\beta$, $\eta_2^T = 1$, $\eta_2^\delta = \bar{\chi}$, $\beta_2/\beta_1$ are the ratios of the densities $\rho_j$ and coefficients of kinematic viscosity $\nu_j$, thermal...
diffusivity $\chi_j$ and thermal expansion $\beta_j$ of the gas and liquid, respectively; $\gamma$ is the concentration coefficient of the gas density; $\bar{\alpha} = \alpha T_s$, $\bar{\delta} = \delta / T_s$, the coefficients $\alpha$ and $\delta$ characterize the Soret and Dufour effects in the gas-vapor layer, $D$ is the coefficient diffusion of vapor in the gas.

3. Exact solution of the Oberbeck–Boussinesq equations

3.1. Form of exact solution

We construct the exact solution of the equations (1), (2), which is characterized by dependence of the components of the liquid and gas velocity vectors $v_j = (u_j, v_j, w_j)$ on the transverse coordinates $(x, y)$. The temperature and pressure functions $T_j, p_j$ and the vapor concentration $C$ have the terms $\Theta_j, q_j, \Phi$, which also depend on the transverse coordinates:

$$
u_j = u_j(x, y), v_j = v_j(x, y), w_j = w_j(x, y), \quad T_j = -Az + \Theta_j(x, y), \quad C = Bz + \Phi(x, y),$$

$$p_1 = -\frac{A}{Re^2} Gr \frac{xz}{x^2} + q_1(x, y), \quad p_2 = -\frac{A}{Re^2} Gr \frac{y\bar{\gamma}}{y^2} + \frac{B}{Re} \frac{Ga}{x^2} + q_2(x, y).$$

(3) The coefficients $A = A_s h / T_s$ and $B = B_s h$ determine the constant longitudinal temperature and concentration gradients along the interface; $A_s$ and $B_s$ are the corresponding dimensional gradients.

The presented solution is an analogue of the Ostroumov–Birikh solution [6, 7]. Group-theoretical nature of class of the Ostroumov–Birikh type solutions was proved in [9].

3.2. Boundary conditions

In order to find the functions $u_j, v_j, w_j, \Theta_j, \Phi_j$ we formulate the boundary conditions on the interface and fixed impermeable walls of the channel. The interface conditions are formulated on the basis of the conservation laws and some additional assumptions [8, 10, 11]. Conditions of continuity of tangential velocities and temperature are assumed to be fulfilled on the thermocapillary interface $x = 0$: $v_1 = v_2$, $w_1 = w_2$, $T_1 = T_2$.

The kinematic and dynamic conditions are to be valid on the interface $x = 0$. For considered exact solution the first condition is written as $u_1 = u_2 = 0$. Projections of the dynamic boundary condition on the tangential vectors to the interface are

$$u_{1y} + v_{1x} - \bar{\nu}(u_{2y} + v_{2x}) = -\frac{Ma}{Re Pr} \Theta_{1y}, \quad w_{3x} - \bar{\nu}w_{2x} = \frac{Ma}{Re Pr}.$$

Projection on the normal vector $n$, that coincides with the unit vector of the $Ox$ axis, is [10]:

$$-Re(q_1 - q_2) + 2(u_{1x} - \bar{\nu}u_{2x}) = \frac{1}{Ca} 2H \sigma.$$

Here $Ma = \sigma T_s h / (\rho_1 \nu_1 \chi_1)$ is the Marangoni number, $Ca = \rho_1 \nu_1 u_s / \sigma_0$ is the capillary number, $H$ is the mean curvature of the interface $x = 0$ (in the case of non-deformed interface $H = 0$), $\sigma$ is the surface tension ($\sigma = 1 - Ma Ca / (Re Pr) (T - T_0)$); the positive constants $\sigma_0$ and $\sigma_T$ are some relative values of the surface tension and temperature coefficient of surface tension, respectively.

At $x = 0$ the heat transfer condition with respect to the diffusive mass flux due to evaporation and the mass balance equation are formulated: $T_{1x} - \bar{\kappa} T_{2x} - \bar{\delta} \kappa C_x = -\lambda M$, $M = -(C_x + \bar{\kappa} T_{2x})$. Here $\bar{\kappa} = \kappa_2 / \kappa_1$ is the ratio of the thermal conductivity coefficients $\kappa_j$. The evaporative mass flow rate $M$ is a function of $y$ defined on the interface $x = 0$. The characteristic value of the evaporative mass flow rate is chosen equal to $M_s = D \rho_2 / \eta$. The linearized form of an equation for saturated vapor concentration at the interface is used to define the vapor concentration function [3, 5]

$$C|_{x=0} = C_s (1 + \bar{\epsilon}(T_2 - T_0)).$$

(4)
Here $C_v$ is the saturated vapor concentration at $T_2 = T_0$ ($T_0$ is equal to 20 °C in [2, 3]), $\bar{z} = \varepsilon T_0$, $\varepsilon = \lambda \mu / (R^* T_0^2)$, $\lambda$ is the latent heat of evaporation ($\bar{\lambda} = \lambda D \rho_k / (\kappa_1 T_0^2)$), $\mu$ is the molar mass of the evaporating liquid, $R^*$ is the universal gas constant. The relation (4) is a consequence of the Clapeyron – Clausius equation and the Mendeleev – Clapeyron equation for an ideal gas (for details we refer to [5]). In virtue of (4) the following relation between gradients of temperature and concentration ($A$ and $B$) will take place $B = -C_v \varepsilon A$.

The no-slip conditions for velocity fields and the conditions of thermal insulating of the lateral walls are set on the fixed impermeable walls of the channel; the condition of absence of vapor flux on the upper and lateral rigid boundaries is used in the present statement:

$$x = -x_0: \quad \psi_j = 0, \quad T_1x = 0; \quad x = x^0: \quad \psi_j = 0, \quad T_2x = 0, \quad C_x = 0;$$
$$y = 0: \quad \psi_j = 0, \quad T_jy = 0, \quad C_y = 0; \quad y = 1: \quad \psi_j = 0, \quad T_jy = 0, \quad C_y = 0. \quad (5)$$

Conditions for the temperature and vapor concentration function on the fixed walls provide a fulfillment of the full heat flux condition with respect to the Dufour effect and of full mass flux condition with respect to the Soret effect [12]: $(\partial T_2 / \partial n) + \delta (\partial C / \partial n) = 0$, $(\partial C / \partial n) + +\bar{\alpha} (\partial T_2 / \partial n) = 0$.

### 4. Numerical results of investigations of the fluid flow regimes with evaporation

#### 4.1. Scheme of solution of the coupled problems

Instead of the transverse components $u_j$, $v_j$ of the velocity vectors the stream functions $\psi_j(x, y)$ and vorticity $\omega_j(x, y)$ are introduced according to usual rules $u_j = (\psi_j)_y$, $v_j = -(\psi_j)_x$, $\omega_j = v_{jx} - u_{jy}$. We reformulate the boundary conditions in terms of these new unknown functions. Construction of the stationary solution (3) for the two-layer convective fluid flows is reduced to a sequential solving the corresponding two-dimensional problems for the functions $w_1(x, y)$ and $w_2(x, y)$, $\Theta_1(x, y)$ and $\Theta_2(x, y)$, $\Phi(x, y)$, $\psi_j(x, y)$ and $\omega_j(x, y)$ in the working domains $\bar{\Omega}_j$ ($\bar{\Omega}_1 = \{(x, y) : -x_0 < x < 0, 0 < y < y^0\}$, $\bar{\Omega}_2 = \{(x, y) : 0 < x < x^0, 0 < y < y^0\}$).

Numerical algorithm based on the longitudinal transverse finite difference scheme known as the method of alternating directions [8, 10, 13] was constructed to perform the fluid flow simulations. A general scheme of solution of the coupled problem is described in [11] and [14] (see also [10]).

#### 4.2. Regimes of flows

Numerical investigations are carried out in order to describe the possible flow topology for the liquid–gas system like ethanol–nitrogen and HFE-T100–nitrogen with following physicochemical properties [15, 16] (all the values are presented in the order “ethanol, HFE-7100 and nitrogen” or only “ethanol and HFE-7100”, respectively): $\rho = \{0.79 \cdot 10^3, 1.5 \cdot 10^3, 1.2\}$ (kg/m$^3$); $\nu = \{0.15 \cdot 10^{-5}, 0.38 \cdot 10^{-6}, 0.15 \cdot 10^{-4}\}$ (m$^2$/s); $\beta = \{0.108 \cdot 10^{-2}, 1.8 \cdot 10^{-3}, 3.67 \cdot 10^{-4}\}$ (K$^{-1}$); $\sigma_{\text{FM}} = \{0.8 \cdot 10^{-4}, 1.14 \cdot 10^{-4}\}$ (N/(m·K)); $D = \{0.135 \cdot 10^{-4}, 0.7 \cdot 10^{-5}\}$ (m$^2$/s); $L = \{8.55 \cdot 10^5, 1.11 \cdot 10^5\}$ (W·s/kg); $k = \{0.1672, 0.07, 0.02717\}$ (W/(m·K)); $\chi = \{0.89 \cdot 10^{-7}, 0.4 \cdot 10^{-7}, 0.3 \cdot 10^{-4}\}$ (m$^2$/s); $\gamma = \{0.62, -0.5\}$; $C_v = \{0.1, 0.6\}$ (at $T_0 = 10^5^\circ C$, relation (4)); $\bar{z} = \{0.1, 0.04\}$ (relation (4)); Dufour coefficient $\delta = \{10^{-4}, 10^{-4}\}$ (K); Soret coefficient $\alpha = \{10^{-4}, 10^{-4}\}$ (K$^{-1}$). Computations are performed with the values of the Grashof number equal to 4.7 $\cdot$ 10$^{12}$ and 470 for the ethanol–nitrogen system and to 1.22 $\cdot$ 10$^{10}$ and 1.22 $\cdot$ 10$^{10}$ for HFE-7100–nitrogen system in the case of normal ($g = g_0 = 9.81$ m/s$^2$) and low gravity ($10^{-2} g_0$ m/s$^2$), respectively. The values of the characteristic temperature drop $T_x$ and characteristic length $h$ are equal to $T_x = 10$ K and $h = 10^{-2}$ m. The Reynolds number was chosen equal to 1 so that the characteristic velocity $u_\ast$ is equal to $0.15 \cdot 10^{-5}$ (m/s) for ethanol and $0.38 \cdot 10^{-4}$ (m/s) for HFE-7100.
The examples of the fluid flows (stream lines and trajectories) and corresponding temperature distributions are presented in Figure 1 – 4 for ethanol – nitrogen and Figure 5 – 7 for HFE-7100 – nitrogen systems in the three-dimensional channels, when the thickness $h_l$ of the liquid layer is $h_l = 0.25$ or $h_l = 0.1$, the thickness $h_g$ of the gas-vapor layer is $h_g = 0.5$ (corresponding values of the dimensional thicknesses are equal to $h_l^* = 0.25$ cm or $h_l^* = 0.1$ cm, $h_g^* = 0.5$ cm). In the numerical experiments the non-dimensional longitudinal temperature gradient $A$ has the values $A = 0.1, A = 0.3, A = 0.4$ (the values of the dimensional longitudinal temperature gradient are equal to $A_* = 100$ K/m, $A_* = 300$ K/m, and $A_* = 400$ K/m, respectively).

For better visualization (Figure 1, 3, 5, 6) the first and second components of the liquid and gas velocities have been multiplied by factors 100 and 10, respectively. The flows of the liquids (lower layers) can be characterized as a rotational motion of a smaller intensity than in the gas layers (upper layers).

**Figure 1.** Stream lines and trajectories in ethanol – nitrogen system at $A = 0.1, Gr = 470$: $h_l = 0.25$ (left); $h_l = 0.1$ (right).

**Figure 2.** Distribution of the temperature in ethanol – nitrogen system at $A = 0.1; Gr = 470$: $h_l = 0.25$ (left); $h_l = 0.1$ (right).

Under low gravity the flows in both phases are characterized by clearly marked symmetric two-vortex structure at $A = 0.1$ both for $h_l = 0.1$ and $h_l = 0.25$ (Figure 1). Vortices in the
liquid have the thermocapillary nature and vortex centers are located close to the interface in the “corners”. Such topology of the flow arises due to liquid spreading on the interface from hot central thermal roll to the lateral walls (see thermal pattern in Figure 2). Two longitudinal shafts with the opposite circulation of the liquid are generated by the Marangoni effect. With changing the gravitational influence the qualitative structure of the velocity and temperature fields is not modified; the two-vortex structure is kept in the media and the thermal billow is formed. Only the quantitative variations of hydrodynamical, temperature and concentration characteristics are observed. But in the thin layer the rotational motion component becomes more significant due to action of the thermocapillary effect, which generates in the thin layer more intensive liquid spreading from the center of the thermal billow to the periphery (to walls).

Figure 3. Stream lines and trajectories in ethanol–nitrogen system at $A = 0.3$: $Gr = 470$, $h_l = 0.25$ (left); $Gr = 47000$, $h_l = 0.1$ (right).

Figure 4. Distribution of the temperature in ethanol–nitrogen system at $A = 0.3$: $Gr = 470$, $h_l = 0.25$ (left); $Gr = 47000$, $h_l = 0.1$ (right).

At the same time the bright qualitative differences are found by simulation of the HFE-7100–nitrogen flows (Figure 5). At $A = 0.1$ we observe the two-vortex structure in the gas layer and “quadruple” flow in the liquid layer under microgravity (such flow topology with formation of four longitudinal thermocapillary rolls is typical for both considered geometrical configuration).
In the system with $h_l = 0.25$ two additional small corner vortices appear in the liquid layer in the case of normal gravity. Formation of the extra vortexes is explained by weaker viscous effects in HFE-7100 in comparison with ethanol. Furthermore, in the terrestrial condition near-bottom-wall reverse flows in HFE-7100 appear (see trajectories in right picture of Figure 5). Thermal pattern is similar to structure, presented in Figure 2. But transversal size of arising thermal rolls is more than in ethanol–nitrogen system; cold “spots” arise near the lateral walls.

More complicated vortex patterns in fluids are observed in the case with more intensive thermal load (at $A = 0.3$, see Figure 3, 6). Splitting two big vortex into four asymmetrical swirls in the liquid layer occurs in the ethanol–nitrogen system in microgravity conditions. Two of the vortices are deformed into “angled” vortexes, their cores are located in “corners” near the lateral walls and stay close to the interface (left picture of Figure 3). Liquid particles move on the interface from the hot spots formed in “corners” (Figure 4) to center zone due to the Marangoni effect and go down because of unstable thermal stratification. Thus, the upper part of the “angled” vortex is generated by thermocapillary effect. In microgravity conditions in ethanol the thermal “horns” appears (left picture in Figure 4). Formation of such inhomogeneities of the temperature field is induced by condensation supplying the heat inflow in the liquid layer. Under weak gravity the thermal stratification in the system is less prominent. Thermoclines (in the form of the thermal “horns” in the liquid layer) arise due to condensation and are supported by the thermal properties of the working liquid (see Table 1). In the terrestrial conditions vortex structures in the liquid layer are weakly distorted and keep “dipolar” pattern (right picture in Figure 3) for both values of $h_l$, but a localization of the vortex cores is changed, they moves from the surface into the interior of liquid layer. In the layer with $h_l = 0.25$ the second core appears inside the vortex. The temperature regime differs sufficiently with changing thickness of the liquid layer: at smaller $h_l$ a sufficiently homogeneous hot near-surface layer is formed (a surface hot film, see right picture in Figure 4), in the gas-vapor layer the thermal billow falls apart two small “shafts”.

![Figure 5](image-url). Stream lines and trajectories in HFE-7100–nitrogen system at $A = 0.1$: $Gr = 12200$, $h_l = 0.1$ (left); $Gr = 1220000$, $h_l = 0.25$ (right).

In HFE-7100–nitrogen system in the case with more intensive longitudinal temperature regime (Figure 6) the liquid flows are characterized by four separate vortices under microgravity and six swirls in the terrestrial conditions for both values of $h_l$. Note, that the transverse size of the “inner” vortexes, which appear in the central part of the channel, decreases. At $g = g_0$ and $h_l = 0.25$ near-bottom-wall reverse flow is observed and the additional vortexes in the corners are generated (see right picture in Figure 6). In the thin layer the similar flow picture is not observed. For the system the flow regimes differ only in the liquid layers (compare Figure 5...
Figure 6. Stream lines and trajectories in HFE-7100 – nitrogen system; $A = 0.3$: $Gr = 12200$, $h_l = 0.1$ (left); $Gr = 1220000$, $h_l = 0.25$ (right).

and 6), whereas the fluid flow structures are rebuilt in both upper and lower layers in ethanol–nitrogen system (Figure 1 and 3). In the case of more intensive thermal load the temperature field in HFE-7100 – nitrogen system is not changed, we observe only variation of the transversal size of the thermal roll formed in the central part of the channel (like to pattern in Figure 3).

Further increasing the temperature gradient leads to formation the thermal shafts in the liquid layer and to growth of number of the longitudinal thermocapillary rolls in the thin layer of HFE-7100 liquid (Figure 7).

Figure 7. Stream lines and trajectories (left) and distribution of the temperature (right) in HFE-7100 – nitrogen system at $A = 0.4$, $h_l = 0.1$, $Gr = 12200$.

In all the cases flow patterns are symmetric with respect to the plane $y = 0.5$ in both phases. Thus, we have different flow topology and essentially varied temperature patterns for the various gas–liquid systems. More intensive rotational flow has been observed under normal gravity. It is explained by the more significant influence of the temperature stratification.
5. Conclusions

The stationary coupled problem of the gravitational and thermocapillary convection with respect to evaporation is formulated in the paper. The exact solution is constructed in the three-dimensional case to describe the convective flows in an infinite channel of a rectilinear cross section, it means without assumption of axial symmetry of the flow domains. This solution is the analogue of the Ostroumov – Birikh solution of the convection equations which additionally include the Dufour and Soret effects in the gas phase. The flows of both fluids (of a liquid and gas–vapor mixture) modeled with the help of the exact solution can be characterized as a translational motion and progressively rotational flows and be realized in the various forms. The qualitative and quantitative differences are confirmed for the flows of various working fluids (ethanol–nitrogen and HFE-7100–nitrogen systems). The numerical investigations allow one to analyze the possible flow structure with respect to the intensity of the gravitation field and longitudinal temperature gradients created on the interface. Intensity and structure of the liquid flows depends on intensity of the gravitation field and on interface temperature regime. Topologically various structures of flows (double, quadruple or sextuple vortex patterns) are formed due to combined influence of the thermocapillary and convective mechanisms and evaporation/condensation process, affecting the thermal pattern of the flows.

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References

[1] Bekezhanova V B and Goncharova O N 2017 Problems of the evaporative convection (Review) Journal of Applied Mathematics and Mechanics (accepted for publication)

[2] Shliomis M I and Yakushin V I 1972 Convection in a two-layers binary system with an evaporation, Collected papers: Uchenye zapiski Permskogo Gosuniversiteta, seriya Gidrodinamika 4 129-40

[3] Goncharova O N and Rezanova E V 2014 Example of an exact solution of the stationary problem of two-layer flows with evaporation at the interface Journal of Applied Mechanics and Technical Physics 55(2) 247-57

[4] Goncharova O N, Rezanova E V, Lyulin Yu V and Kabov O A 2015 Modeling of two-layer liquid-gas flow with account for evaporation Thermophysics and Aeromechanics 22(5) 655-61

[5] Bekezhanova V B and Goncharova O N 2016 Stability of the exact solutions describing the two-layer flows with evaporation at interface Fluid Dynamics Research Journal 48(6) 061408

[6] Ostroumov G A 1952 Free convection under the conditions of an internal problem (Moscow-Leningrad: Gostehizdat Press)

[7] Birikh R V 1969 Thermocapillary convection in a horizontal layer of liquid Journal of Applied Mechanics and Technical Physics 3 43-5

[8] Andreev V K, Gaponenko Yu A, Goncharova O N and Pukhnachov V V 2012 Mathematical models of convection (de Gruyter Studies in Mathematical Physics) (Berlin/Boston: De Gruyter)

[9] Pukhnachov V V 2000 Group-theoretical nature of the Birikh’s solution and its generalizations (Krasnoyarsk: Book of Proc. Symmetry and differential equations) pp 180-3

[10] Goncharova O N, Kabov O A and Pukhnachov V V 2012 Solutions of special type describing the three dimensional thermocapillary flows with an interface Int. J. Heat Mass Transfer 55 715-25

[11] Goncharova O N and Kabov O A 2016 Investigation of the two-layer fluid flows with evaporation at interface on the basis of the exact solutions of the 3D problems of convection Journal of Physics: Conference Series 754 032008(1-6)

[12] Landau L D and Lifshitz E M 1987 Fluid Mechanics vol 6 (Butterworth – Heinemann)

[13] Roache P J 1976 Computational Fluid Dynamics (Albuquerque: Hermosa Publishers)

[14] Bekezhanova V B, Goncharova O N and Shefer I A 2017 Problems of the evaporative convection (Review). Part II. Three-dimensional flows Journal of Siberian Federal University, Mathematics & Physics (submitted for publication)

[15] Weast C R C 1979 Handbook of Chemistry and Physics (Boca Raton: CRC Press Inc)

[16] Lyulin Y, Kabov O, Iorio C S, Chikov S, Glushchuk A, Marchuk I and Queeckers P 2009 Liquids – candidates for CIMEX-1 experiments on ISS (Manuscript: CIMEX Meeting, Bruxelles, May 15)