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Modeling of heat and mass transfer processes in phase transformation cycle of sprayed water into gas:
2. Phase transformation peculiarities of a droplet heated up by convection in humid gas flow

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Nomenclature

a – thermal diffusivity, m^2/s; B – Spalding transfer number; C_l–droplet drag coefficient; c_p – mass specific heat, J/(kg K); Fo – Fourier number; g – evaporation velocity, kg/s; $k+r$ – conduction and radiation; L – latent heat of evaporation, J/kg; m – vapour mass flux, kg/(m^{2}s); Nu – Nusselt number; p – pressure, Pa; P – symbol of free parameter in heat-mass transfer; q – heat flux, W/m^2; r – radial coordinate, m; T – temperature, K; η – non-dimensional radial coordinate; λ – thermal conductivity, W/(m K); μ – molecular mass, kg/kmol; ρ – density, kg/m^3; τ – time, w–velocity.

Subscripts: C – droplet centre; co – condensation; e – equilibrium evaporation; f – phase change; g – gas; i – time index in a digital scheme; it – number of iteration; I – index of control time; j – index of radial coordinate; J – index of droplet surface; k – conduction; $k+r$ – conduction and radiation; l – liquid; m – mass average; r – radiation; R – droplet surface; v – vapor; vg – gas-vapor mixture; 0 – initial state; ∞ – far from a droplet.

Superscripts: + – external side of a droplet surface; - – internal side of a droplet surface.

1. Introduction

The fluid spraying technologies improvement and creation requires a deep knowledge of transfer processes regularities. Conditions of these processes are often complicated, experiments are difficult and expensive, therefore theoretical research are widely used [1]. Efficiency of spayed liquid technologies depends from transfer processes speed in them. It can be defined according to heat and mass transfer intensity between gas and droplets. Therefore, investigations that proceed in transfer processes of gas and droplet flows are called by general name – „droplet“ task, and processes that proceed in them can be combined by a droplet „external“ and „internal“ tasks. Heat transfer and liquid vapour flow intensity between liquid and gaseous phases are defined by solutions of „external“ task. Therefore, it considered to be important and was widely studied [2]. „External“ task is defined when droplet temperature is known. Boundary conditions in thermal technology are often changing and for a droplet thermal state description fails in „external“ task framework. Then, a heat transfer intensity that process inside a droplet should be taken into account. Hence, it is „internal“ task solution. Therefore, these two tasks are closely related. They considered to be relatively independent, when the next task solution is known. This is possible, when numerical iterative methods are applied for a „droplet“ task solving.

In general case, in pure semi-transparent droplets heat spreads by radiation and convection. At multicomponent liquid case components mass transfer are going together. Fundamental equations system, which describes compound heat transfer processes at droplet convection case does not have analytical solution, and its direct numerical analysis is complicated [1, 2]. Combined analytical–numerical research methods gives solutions [3-5] when in droplet a compound heat spread by radiation − conduction is analysed analytically, and heat convection input for complex heat transfer balance is evaluated by effective parameter according to [5] methodology. „Droplet“ task speedily [4] and deep [3] solving approaches is bright in integral type analytical solutions and numerical method combinations. In the first case asymptotic type solutions is defined by boundary conditions, that are easily integrate towards complicated numerical models of sprayed combustion liquid, but requires additional dependability control. The latter can be ensured by the aim to get closer near unknown strict analytical „droplet“ task solutions by using iterative methods. This requires a strict verification of numerical schemes that are applied to calculate for a droplet transfer parameters in different phase transformation modes.

Methodology of a pure liquid phase transformation cycle with universal time scale for condensation, unsteady and equilibrium evaporation modes were developed [6]. According to this, numerical schemes peculiarities of a droplet phase transformation parameters were assessed in detail [7]. In cases of water droplet heating up by conductivity and its compound heating by conductivity − radiation a modelling results of phase transformation parameters change in cycle determines an assumption application limitation of droplet diameter stability $R_{i,it} \equiv R_{i-1}$.

This article deals with a problem of simulation specifics of convective heat exchange when water droplet slips in humid air

2. Research method

Droplets moves with a speed w_l in gas flow that flowing at speed w_g. These speed difference defines a velocity of droplet slip in gas flow $\Delta w = \left| w_l - w_g \right|$. The droplet movement in gas flow is described by equation:

$$\frac{dw_l}{d\tau} = \frac{3}{8}\frac{C_l}{R}\frac{\rho_g}{\rho_l}\frac{\left|w_l - w_g\right|}{\left(w_l - w_g\right)^{-1}}, \tag{1}$$

where resistance that is caused by friction and pressure forces, for a droplet movement in gas flow is evaluated by full friction drag coefficient [8]

$$C_l = \frac{24}{(1+B_T)^{0,2}\,\mathrm{Re}}\left(1 + 0.2\,\mathrm{Re}^{0.63}\right). \tag{2}$$

With Spolding transfer number B_T :

$$B_T = c_p\,\frac{T_g - T_R}{L - (q/m_v^+)} \tag{3}$$

the droplet phase transformation impact for its movement impeding forces in gas, is taken into account. Reynolds number in Eq. (2) is defined by a droplet diameter, slip velocity, gas density and gas dynamic velocity of the gas mixture:

$$\mathrm{Re} \equiv \frac{2R\Delta w_l \rho_g}{\mu_{vg}}. \tag{4}$$

In Eq. (4) a gas density is defined by gas temperature: $\rho \equiv \rho(T_g)$ when dynamic viscosity of the gas mixture $\mu_{vg} \equiv \mu(T_{vg})$ is selected for liquid vapour and gas mixture, where its temperature is $T_{vg} \equiv T_{vg,R} + (T_g - T_{vg,R})/3$ at phase transformation mode, while for condensing vapour $p_v = p_{v,R} + (p_{v,\infty} - p_{v,R})/3$ and for evaporating droplet $p_v = p_{v,R} - (p_{v,R} - p_{v,\infty})/3$.

Evaporating droplet is heated up less by convection than a solid particle in similar terms. The heating weakening is taken into account by parameter B_T functions:

$$Nu_f = Nu\;f\left(B_T\right). \tag{5}$$

A classic [9], an experimental correlation [10] and Abramzon-Sirignano [5] parameter B_T functions models are the the most popular for heat exchange of „droplet“ convection description. Empirical expressions for a spherical solid particle of Nusselt criterion description are well known [5].

Eq. (3) of parameter B_T is formal. A parameter q must be concretized for individual phase transformation cycle modes. In general case, parameter q represents a heat flow that is involved in phase transformation process without any external heat convection contribution [11]. In different phase transformation modes of a cycle its physical interpretation is varying. Modified Eq. (3) expression allows to take into account the peculiarities of parameter q variation in phase transformation cycle [12]:

$$B_T = \frac{c_p\left(T_g - T_R\right)}{L}\left(1 + \frac{q_c^-}{q_c^+}\right). \tag{6}$$

In Eq. (6) a density of convectional heat flow from the gas:

$$q_c^+ = \lambda_{vg}\frac{Nu_f}{2R}\left(T_g - T_R\right), \tag{7}$$

while a convective heat flow in droplet is described by a modified Fourier law:

$$q_c^- = -\lambda_l k_c^- \,gradT_{r\equiv R}, \tag{8}$$

therefore interface of external heating and thermal state of the droplet is obvious. The effective thermal conductivity parameter in Eq. (8) is described by Peclet number $Pe_l = Re_l Pr_l = 2wR/a_l$ function [5]:

$$k_c^- = 1.86 + 0.86\,tanh\left[2.225\,log_{10}\left(Pe_l/30\right)\right]. \tag{9}$$

In the influence of the friction forces on the droplet surface the flowing liquid maximum speed w_R depends from fluid nature and is defined by friction drag coefficient, droplet slip speed and Reynolds criterion that evaluates gas flowing round mode [5].

A numerical scheme to define the droplet dynamics and convective heating intensity according to mathematical model (1-9) is created by time grid $\tau_i (I \equiv 1 \div I)$ that was formulated in methodology [7]:

$$\begin{aligned} q_{c,i,it}^+ &= \lambda_{vg,i,it}\frac{T_g - T_{R,it}}{2R_{i,it}} + \\ &+ \left[2\frac{\ln\left(1 + B_{T,i,it}\right)}{B_{T,i,it}} + 0.57\frac{\mathrm{Re}_{i,it}^{1/2}\,\mathrm{Pr}_{i,it}^{1/3}}{\left(1 + B_{T,i,it}\right)^{0.7}}\right], \end{aligned} \tag{10}$$

$$\mathrm{Re}_{i,it} = 2R_{i,it}\Delta w_{l,i,it}\rho_g/\mu_{vg,i,it},\quad \mathrm{Pr}_{i,it} = \nu_{vg,i,it}/a_{vg,i,it}, \tag{11}$$

$$B_{T,i,it} = \frac{c_{p,vg,i,it}\left(T_g - T_{R,i,it}\right)}{L_{i,it}}\left(1 + \frac{q_{c,i,it}^-}{q_{c,i,it}^+}\right), \tag{12}$$

$$q_c^- = -\lambda_{l,i,it}k_{c,i,it}^-\left.\frac{\partial T\left(r,\tau_i\right)}{\partial r}\right|_{r=R_{i,it}}, \tag{13}$$

$$k_{c,i,it}^- = 1.86 + 0.86\tanh\left(2.225\log_{10}\frac{Pe_{l,i,it}}{30}\right), \tag{14}$$

$$w_{l,i,it} = w_{l,i-1} + \frac{3}{8}\frac{\overline{C}_{l,i}\rho_g\Delta\overline{w}_{l,i}\left|\Delta\overline{w}_{l,i}\right|}{\overline{R}_i\overline{\rho}_{l,i}}\left(\tau_i - \tau_{i-1}\right), \tag{15}$$

$$\Delta\overline{w}_{l,i} = 0.5\left(w_{l,i-1} + w_{l,it}\right) - w_g,\quad \overline{C}_{l,i} = 0.5\left(C_{l,i-1} + C_{l,it}\right), \tag{16}$$

$$\overline{R}_i = 0.5\left(R_{i-1} + R_{i,it}\right),\quad \overline{\rho}_{l,i} = 0.5\left(\rho_{l,i-1} + \rho_{l,i,it}\right), \tag{17}$$

The droplet thermal parameters is described by a compound heat spread model in them [3]. A model discussed in [7] work is applicate for phase transitions parameters. A condition defining energy balance on the droplet surface for heat flows $q_{c,i}^+$, $q_{c,i}^-$ and $q_{f,i}^+$:

$$\begin{aligned} &\lambda_{vg,i,IT}\frac{T_g - T_{R,i,IT}}{2R_{i,IT}} + \left[2\frac{ln\left(1 + B_{T,i,IT}\right)}{B_{T,i,IT}} + 0.57\frac{\mathrm{Re}_{i,IT}^{1/2}\,Pr_{i,IT}^{1/3}}{\left(1 + B_{T,i,IT}\right)^{0.7}}\right] = \\ &= \lambda_{l,i.IT}k_{c,i,IT}^-\,gradT_{r\equiv R,i,IT} + m_{v,i,IT}^+L_{i,IT}. \end{aligned} \tag{18}$$

It requires matching of heat flows that flows in and flows down from the droplet surface. In iterative cycle $it \equiv 1 \div IT$ for time moment τ_i the droplet surface temperature $T_{R,i} \equiv T_{R,i,IT}$ is defined with provided requirement Eq. (18). Droplet thermal P_T, phase transitions P_f, dynamic P_d and energetic P_q parameters are calculated in parallel. In droplet parameters $P_{i,it}$ numerical schemes a condition of $R_{i,it} \equiv R_{i,it\text{-}1}$ was maintained [7] and accepted $q_{r,I} \equiv 0$. For transfer parameters $P_{i,it}$, which are not sufficient to define temperature $T_{R,i,it}$ selected for *it* iteration, a condition $P_{i,it} \equiv P_{i,it\text{-}1}$ is applied. Volume change of warming droplet was calculated according to scheme Eq. (9) submitted in work [7].

3. Numerical simulation results and discussion

Water droplet heating phase transformation cycle was modeled at the initial conditions applied in [7] work: $T_g = 500$ K, $p = 0.1$ MPa, $\rho_{v,\infty}/\rho = 0.3$, $T_0 = 278$ K, $2R_0 = 150 \cdot 10^{-6}$ m , when $G_{l,0}/G_{d,0} \to 0$. A droplet heating is defined by Reynolds number values of 0, 20 and 50 in aspect of air flow with velocity on 10 m/s. $\mathrm{Re}_0 \equiv 0$ case suited a heat transfer conditions for droplet heating by conductivity "*k*". The other two modelled cases matched convection heat transfer conditions "*c*". In iterative cycles $it = 1 \div IT$ a condition Eq. (18) satisfaction has been controlled. For all modelled droplet heat transfer cases a lower than 0.03% heat flow disbalance of heat fluxes that flow in and down from the droplet surface was ensured (Fig. 1).

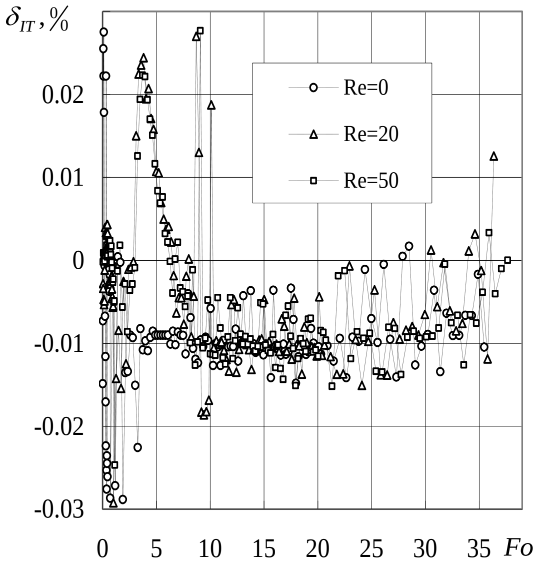

Fig. 1 Heat fluxes disbalance on the surface of a droplet Eq. (18) conditions satisfaction in modelled phase transformation modes

For modelled cases in condensation phase transformation mode a droplet surface heats up to dew point temperature (Fig 2, a, 1 point), in unsteady evaporation mode droplets heat up to state where equilibrium evaporation temperature $T_e \equiv T_{R,e}$, describes isothermal state. Temperature $T_{e,\text{"}k\text{"}} \equiv T_{R,e,\text{"}k\text{"}} \equiv 346.306$ K ensures conditions of equilibrium evaporation when droplet is heated by conductivity, while in unsteady phase transformations mode droplet heats up to higher $T_{e,\text{"}c\text{"},Re=20} \equiv T_{R,e,Re=20} \equiv 347.121$ K and $T_{e,\text{"}c\text{"},Re=50} \equiv T_{R,e,Re=50} \equiv 347.155$ K temperature (Fig. 2, 2 point). The droplet surface temperature for isothermal droplet defines an average mass temperature at the beginning of equilibrium evaporation $T_{m,e,\text{"}k\text{"}} \equiv T_{R,e,\text{"}k\text{"}}$ and $T_{m,e,\text{"c"}} \equiv T_{R,e,\text{"c"}}$. In equilibrium evaporation mode a temperature of a droplet heated up by conduction does not change, while a droplet heated up conventionally cools down (Fig. 2, *b*). In phase transformation cycle a droplet thermal state is related with droplet energy state, which change is reflected by heat flows dynamics on the surface of the droplet (Fig. 3).

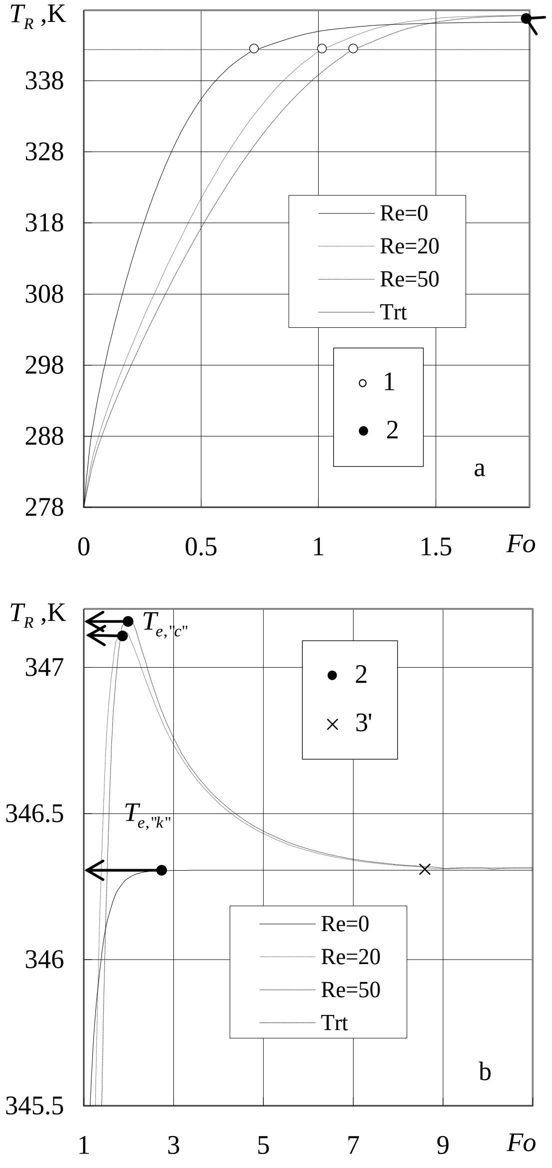

Fig. 2 Heating influence for a droplet surface temperature in unsteady phase transformation mode (a) and at the initial stage of equilibrium evaporation mode (b)

In condensation phase transformation mode a droplet heated up by external heat convection and by phase transformation heat that is being released during vapour condensation. Internal heat convection provides heating in the droplet. This convection intensity is defined by heat flow density q_c^-. In condensation mode $q_{c,0-1}^- = q_c^+ + q_{f\equiv ko}^+$. At the end of condensation mode $q_f^+ (Fo \equiv Fo_{\mathrm{ko}}) = 0$ therefore $q_c^- (Fo \equiv Fo_{\mathrm{ko}}) = q_c^+ (Fo \equiv Fo_{\mathrm{ko}})$ (Fig. 3, 1 point). In unsteady evaporation mode a heat of external convection heats up the droplet and evaporates water from its surface, therefore in cycle range defined by points 1 and 2

$q^-_{c,1-2} = q^+_c - q^+_{f\equiv ng}$. In the end of unsteady evaporation $q^-_c(Fo \equiv Fo_{nf}) = 0$, therefore $q^-_f(Fo \equiv Fo_{nf}) = q^+_c(Fo \equiv \equiv Fo_{nf})$ (Fig. 3, 2 point). Convectional heating intensity is consistently weakening in unsteady phase transformation mode (Fig. 3). This is influenced by weakening external heating driving force that is expressed by temperature difference $\Delta T(\tau) \equiv T_g - T_R(\tau)$ and by receding droplet slip in air flow (Fig. 4).

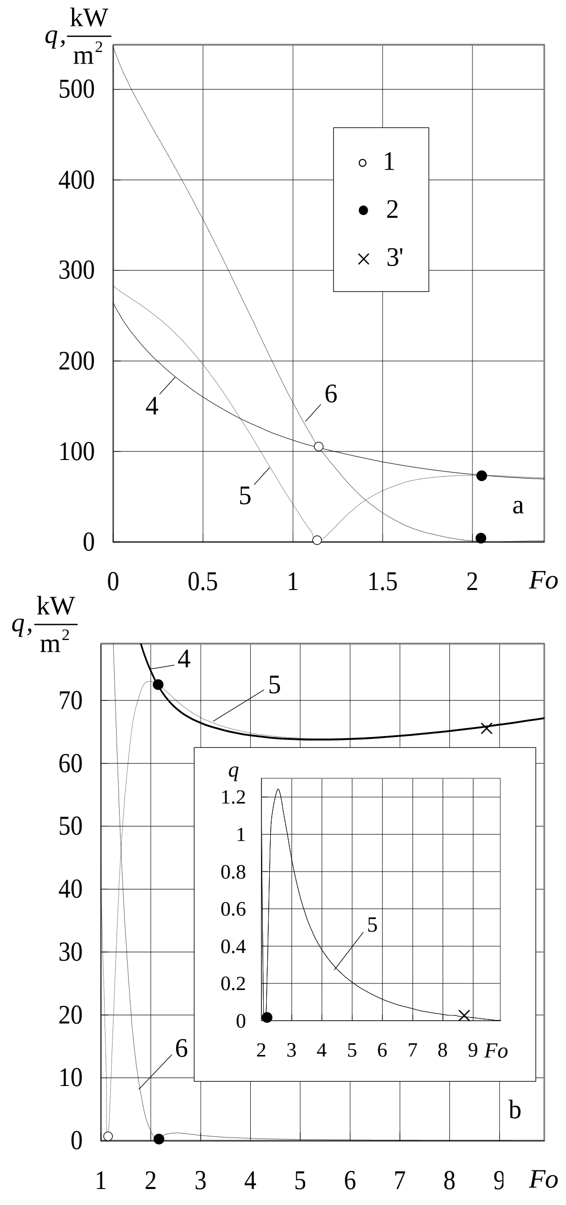

Fig. 3 Heat flows density change of slipping droplet in unsteady phase transformation mode (a) and at the initial period of equilibrium evaporation mode (b) $Re_0 = 50$. Heat flows (4) q^+_c, (5) q^-_c, (6) q^+_f

Droplet initial and air flow velocities difference $\Delta w_0 = |w_{l,0} - w_{g,0}|$ defines a slip intensity of generated droplets. For modelled lonely droplet heat exchange cases $w_g(\tau) \equiv w_{g,0}$=10 m/s. Initial droplet velocity $w_{l,0}$ is defined by Reynolds criterion and depends from droplet size dispersity. For a droplet, with diameter $2R_0 = 150\cdot10^{-6}$ m, velocities are $w_{l,0,Re=20} \equiv 14$ m/s and $w_{l,0,Re=50} \equiv 21$ m/s. Due to influence of friction and pressure forces the droplet slip suffocates in air flow drops and droplet velocity approaching asymptotically to the air flow velocity (Fig. 4). At a starting point of unsteady evaporation moment the droplet is maximally heated up (Fig. 2, 2 point), and its convective heating intensity drops continuously (Fig. 3). Therefore the droplet surface layers starts to cool down. A negative temperature field‘s gradient forms in a droplet. This creates assumptions of cooling down droplet enthalpy to participate in water evaporation process, where its contribution is reflected by heat flow intensity:

$$q^-_c \equiv -\rho_{l.m} c_{p,l,m} \left(dT_{l.m} / d\tau \right) / 3 .$$

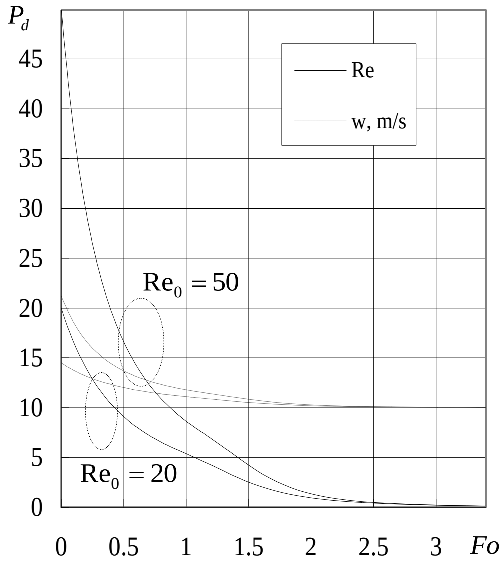

Fig. 4 A droplet velocity change in unsteady phase transformation mode and at the initial state of equilibrium evaporation. $w_g = 10$ m/s

Heat flow $q^+_{f\equiv eg,2-3'} = q^+_c + q^-_c$ of phase transformation defined by points 2 and 3' in equilibrium evaporation mode, exceeds external heating intensity (Fig. 3, b, 5 curve). Therefore in equilibrium evaporation mode periods of initial and final heating can be distinguished. At initial period a droplet temperature decreases from $T_{m,e,\text{"c"}}$ to equilibrium evaporation temperature $T_{m,e,\text{"k"}}$ when droplet is heated up by conductivity (Fig. 2, b). In the final period droplet is already heated up by conduction, and its temperature does not change $q^+_{f\equiv eg,3'-3} = q^+_c \equiv q^+_k$, where $q^-_k = 0$. Point 3 defines a droplet evaporation moment.

A primary droplet slip velocity in air has a sensible impact for convective heating (Fig. 5) and its transfer processes (Fig. 6). In condensation phase transformation mode droplet is being heated up intensively from analogous convective heating case for solid particle: $Nu_{f,0,Re=0} = 2.37$, when $Nu_{Re=0} = 2$; $Nu_{f,0,Re=20} = 4.62$, and $Nu_{0,Re=20} = 4.19$; $Nu_{f,0,Re=50} = 5.9$, while $Nu_{0,Re=50} = 5.46$. In condensing mode a droplet heating intensity drops and are coincident with solid particle heating case intensities at the moment of phase transformation nature change. Therefore $Nu_f(Fo \equiv Fo_{ko}) \equiv Nu(Fo \equiv Fo_{ko})$ 2, 3.13 and 3.33, respectively. At the evaporation mode droplet by convection is being heated up less than analogous solid heating case. An equal intensity that reflects heating case by conduction $Nu_{f,\text{"c"}} \equiv Nu_{f,\text{"k"}} = 1.92$ sets in at initial period of equilibrium evaporation, independently from the Re_0 value.

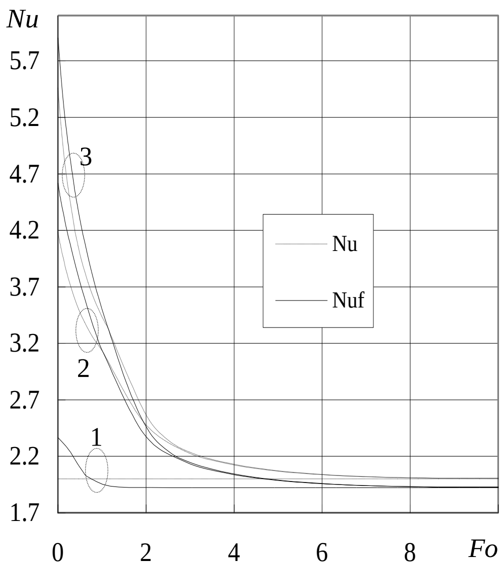

Fig. 5 A convective heating intensity change in droplet phase transformation cycle Re_0: (1) 0, (2) 20, (3) 50

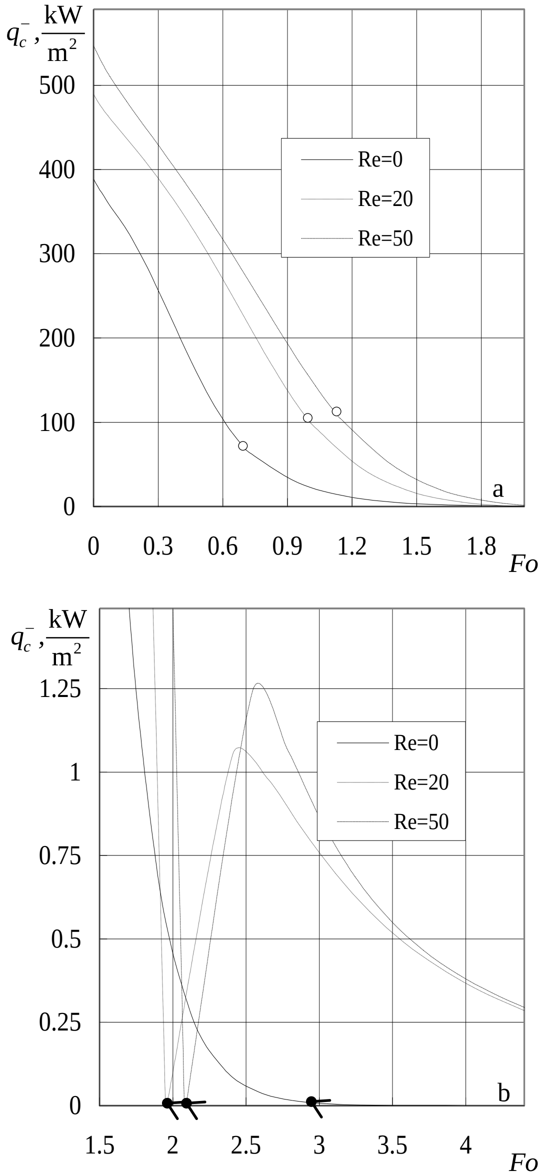

Fig. 6 Heat transfer intensity in unsteady phase transformation mode (a) and at the initial state of equilibrium evaporation (b)

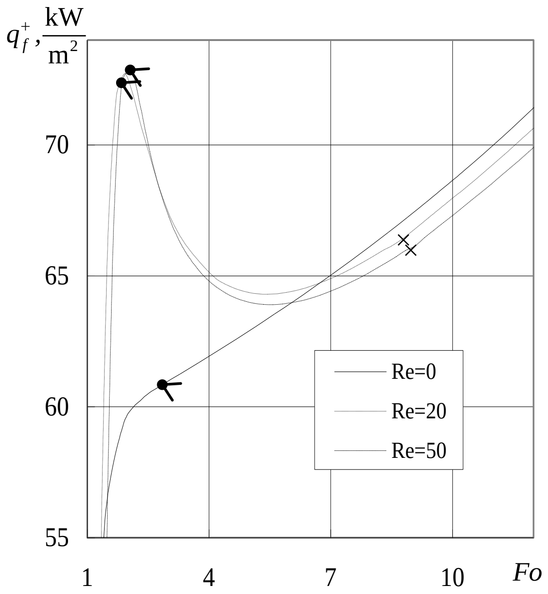

Fig. 7 Influence of external heating for droplet phase transformation heat flow change

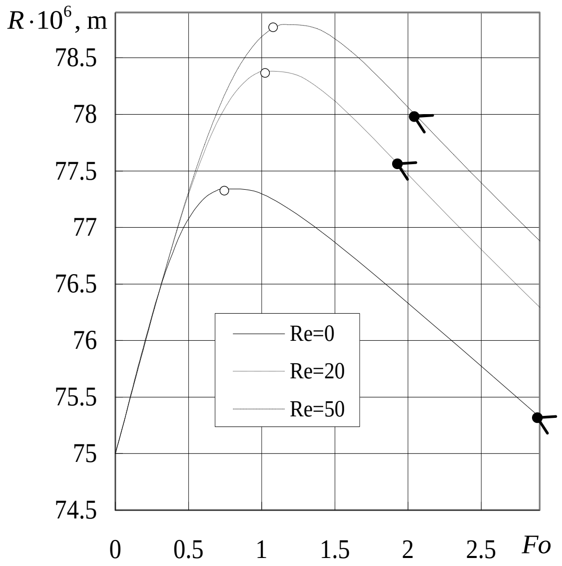

Fig. 8 Influence of external heating for droplet diameter change in unsteady phase transformation mode

In unsteady phase transformation mode water heating at the droplet decreases and becomes zero at initial moment of equilibrium evaporation (Fig. 6). At droplet heating case by conduction ($Re_0 = 0$), at equilibrium evaporation mode $q_c^-(Fo > Fo_{nf}) \equiv 0$ (Fig. 6), therefore a thermal state in droplet does not change.

As mentioned, in case of convection heating ($Re_0 > 0$) at initial state of equilibrium evaporation mode a part of enthalpy from cooling down droplet participates in water evaporation process. The bigger is primary slip of the droplet in air, the more intense is a part of droplet enthalpy withdrawal to the surface by conduction (Fig. 6, b) and its contribution to energy balance of equilibrium evaporation is more significant (Fig. 7). A droplet energy state transformation is related with dispersity of droplet that defines a surface area of heat transfer, change in cycle of phase transformation. In condensing mode a droplet dimension grows up due to warming water expansion and for the condensing vapour on the droplet surface. It is interesting that the droplet growing up process is influenced by heat transfer conditions (Fig. 8).

In condensation phase transformation mode a diameter of the droplet heated up by conduction grows up to $2R_{ko,Re=0} = 154.68 \cdot 10^{-6}$ m, while in convection heating case to $2R_{ko,Re=20} = 156.76 \cdot 10^{-6}$ m and $2R_{ko,Re=50} = 157.58 \cdot 10^{-6}$ m. In unstedy evaporation mode droplets heats up slightly (Fig. 2.), therefore a water expansion effect is over weighted by surface water evaporation so droplets starts to decrease (Fig. 8.).

In unsteady evaporation mode droplets decreases to $2R_{ko,Re=0} = 105.3 \cdot 10^{-6}$ m, $2R_{ko,Re=20} = 155.1 \cdot 10^{-6}$m and $2R_{ko,Re=50} = 155.92 \cdot 10^{-6}$m, respectively. Remembering, that a droplet thermal state at the end of unsteady phase transformation mode also depends from heat transfer conditions, it can be said that in droplets unsteady phase transformation mode heat transfer conditions defines a peculiarities of droplet equilibrium evaporation mode.

4. Conclusions

A droplet phase transformation cycle is defined by numerical experiment for each heating case (Table 1).

Table 1

Modelled droplet phase transformation cycles

Re_0	Fo_{ko}	Fo_{ng}	Fo_{nf}	$Fo_{eg,1}$	Fo_{eg}	Fo_f
0	0.72	1.86	2.9	2.9	33.48	36.06
20	1.01	0.92	1.93	8.5	34.87	36.8
50	1.15	0.95	2.1	8.7	35.1	37.2

Analysing an information provided in the table it was unexpected that at intensive external heating case duration of condensing phase transformation mode increases. This means that in air flow slipping a droplet surface heats up longer to the dew point and its dimension increases more in condensing mode. A balance analysis of complex droplet energy state change in cycle of phase transformation is necessary for physical explanation of this effect. This is the purpose of further research.

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MODELING OF HEAT AND MASS TRANSFER PROCESSES IN PHASE TRANSFORMATION CYCLE OF SPRAYED WATER INTO GAS. 2. PHASE TRANSFORMATION PECULIARITIES OF A DROPLET HEATED UP CONVECTION IN HUMID GAS FLOW

Summary

Heat and mass transfer mathematical model of slipping in humid air droplet was provided, its solution algorithm was discussed and numerical scheme of iterative solution for a droplet transfer parameters calculation was created. Water droplet convective heating cases are defined by initial conditions $T_g = 500$ K, $w_g = 10$ m/s, $p = 0.1$ MPa, $p_{v,\infty}/p = 0.3$, T_0=278 K and $2R_0 = 150 \cdot 10^{-6}$m, when Reynolds number is 0, 20 and 50. A droplet phase transformation cycle expressed by Fourier time scale was modelled. It was based on, that in unsteady phase transformation mode a heat transfer conditions has essential influence for a droplet thermal and energy states consistent pattern change at phase transformation cycle.

Keywords: water droplets, convective heating, phase transformation cycle, thermal and energy state.

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