


Modeling of heat and mass transfer processes in phase transformation cycle of sprayed water into gas: 3. Energy and thermal states analysis of slipping droplet in a humid air flow

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Nomenclature

B_T - Spalding transfer number; D - mass diffusivity, m^2/s ; Fo - Fourier number; g - evaporation velocity, kg/s ; k_c^- - effective thermal conductivity parameter; L - latent heat of evaporation, J/kg ; m - vapour mass flux, $kg/(m^2s)$; Nu - Nusselt number; p - pressure, Pa ; P - symbol of free parameter in heat-mass transfer; \bar{P} - dimensionless parameter in heat-mass transfer; \hat{P} - average parameter in heat-mass transfer; Pe - Peclet number; Pr - Prandtl number; q - heat flux, W/m^2 ; r - radial coordinate, m ; Re - Reynolds number; S - area, m^2 ; T - temperature, K ; η - non-dimensional radial coordinate; λ - thermal conductivity, $W/(mK)$; μ - molecular mass, $kg/kmol$; ρ - density, kg/m^3 ; τ - time, s ;

subscripts –

c - convection; " c " - convective heating; " $c+r$ " - convective-radiative heating; C - droplet centre; co - condensation; e - equilibrium evaporation; f - phase change; g - gas; i - time index in a digital scheme; it - number of iteration; IT - index of closing iteration; I - index of control time; j - index of radial coordinate; J - index of droplet surface; k - conduction; " k " - conductive heating; l - liquid; m - mass average; r - radiation; rt - dew point; R - droplet surface; v - vapor; vg - vapor-gas mixture; 0 - initial state; Σ - total; ∞ - far from a droplet;

superscripts –

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

1. Introduction

Many thermal technologies are based on by droplets heat transfer and phase transformations. Therefore, researchers' attention for water heat transfer processes and for heat exchange and phase transformations of hydrocarbon and other liquids dispersed into droplets do not decrease [1-6]. A liquid droplets phase transformation cycle combines condensing, unsteady and equilibrium evaporation modes $\tau \equiv 0 \div \tau_{co} \div \tau_{nf} \div \tau_f$. An intensive interaction of heat and mass transfer processes sets when a heat supplying conditions for droplets are rapidly changing. Droplet environment provides thermal energy by processes of heat exchange and liquid vapour condensation on the surface of the droplet. In condensation mode a supplying heat warmth the liquid in a droplet. At unsteady evaporation mode heat is being provided by heat transfer, where a part of heat vaporizes a liquid. At equilibrium evaporation mode all heat that is provided for the droplet participates in liquid

evaporation. Peculiarities of interaction between phases determine the droplet thermal state, which has a reversible impact for a droplet energy state variation in phase transformation cycle.

Droplets phase transformation cycle is determined by sprayed liquid and carrier gas flow parameters. Liquid spray dispersity, a two - phase flow velocity and a temperature can be considered the essential parameters of sprayed liquid. Parameter of liquid vapour condensation in gas mixture is very important for heat and mass transfer intensity. A phase transformation cycle starts with condensing phase transformation mode, when sprayed pure liquid temperature is lower than a dew point temperature $\bar{T}_0 \equiv T_r/T_0 > 1$. In condensing phase mode a droplet is heated up and therefore grows rapidly. In condensing mode droplet heats up to dew point temperature and in unsteady evaporation mode droplets dispersity is defined. A droplet slipping in gas flow has a bright effect for condensing phase transformation mode that causes a longer term of liquid vapour condensation on a droplet surface by enhanced convective heating conditions [5]. A longer duration of condensing phase transformation means extended droplet surface heating to dew point temperature. A bit more liquid vapour condenses on the droplet surface therefore a droplet is larger at the end of condensing mode. Peculiarity of slipping droplet in condensing phase transformation mode can be based by intensive inner layers warming, compared with the case of a stable liquid, which is caused by fluid circulation. This requires assessment of droplet energy state in phase transformation cycle. It necessitate analysis of heat and mass flows on the droplet surface by conditions of a complex transfer processes. A problem of temperature gradient in a droplet rises when defining the intensity of the processes. This gradient is highly dependent from a droplet definition methodology. When a liquid is stable in a droplet, then temperature gradient in a droplet can be defined by integral type model that is convenient for numerical research [7]. Integral type model combines heat spread in droplet by conduction and radiation.

However, liquid can circulate in a droplet. These presumptions are made by non-isothermal in a droplet and by friction forces that arises on the droplet surface [1, 8, 9]. Archimedes forces rises in non-isothermal droplet. Their effect for liquid stability depends from droplet dispersity. In common occurring technologies such as liquid fuel burning, fireplaces or air conditioning systems droplets are quite small. Rising Archimedes forces in droplets are week and do not cause a fluid circulation [7]. A forced fluid circulation is arising in a slipping droplet. This circulation is

described by Navier-Stokes equation system. It is impossible to solve this system analytically. Its numerical solution was analyzed in work [10]. This solution is receptive for machine counting and is difficult to apply for iterative scheme.

This article presents an energy state balance assessment methodology of sliding droplet in gas. In humid air slipping water droplet case is analyzed as well as energy and thermal states need for complex analysis is justified.

2. Research method

Energy state change is defined by connection of droplet internal and external heat transfer and by phase transformation processes that is ongoing on its surface. In case of condition $T_g > T_l$ a droplet external heat transfer ensures continuous heat supply for a droplet in all phase transformation cycle. Heating intensity is described by density function of total heat flow on a droplet surface external side:

$$q_{\Sigma, c+r}^+(\tau) = q_r^+(\tau) + q_c^+(\tau). \quad (1)$$

In non-radiant environment for warming droplet case $q_r = 0$, so $q_{\Sigma}^+ \equiv q_c^+$. In droplet phase transformation cycle a convective heating heat flow is described by expression:

$$q_c^+ = \lambda_{vg} \frac{T_g - T_R}{2R} + \left[2 \frac{\ln(1 + B_T)}{B_T} + 0.57 \frac{Re^{1/2} Pr^{1/3}}{(1 + B_T)^{0.7}} \right], \quad (2)$$

where phase transformation impact for convective heating is taken into account by the Spalding transfer parameter B_T [5]. A droplet slip velocity $\Delta w_l = w_l - w_g$ defines a convection heating intensity, that determines Reynolds number $Re = 2R |\Delta w| \rho_g / \mu_{vg}$, where a gas density is chosen according to temperature T_d , and liquid vapor and gas mixture dynamic viscosity coefficient is selected by temperature according to "1/3" rule: $T_{vg} \equiv T_R + (T_g - T_R) / 3$.

A combination of empirical model [11] for effective thermal conductivity and integral model of heat spread in droplet by conductivity-radiation [7] are adapted to define the heat exchange in a droplet. A heat flow that is leaded to the droplet is described by modified Fourier law of heat spread:

$$q_c^-(\tau) = -k_c^-(\tau) \lambda_l(\tau) \left. \frac{\partial T_l(\eta, \tau)}{\partial \eta} \right|_{\eta=1}. \quad (3)$$

A forced liquid circulation influence for heat spread in a droplet is evaluated by effective thermal conductivity parameter, which is defined by methodology [11] as function $k_c^- = f(Pe_l)$ of Peclet number. The temperature gradient in equation (3) is defined by methodology [7].

Heat flow which participates in phase transformations is calculated by water vapor flow density on the surface of a droplet:

$$q_f^-(\tau) = m_v^+(\tau) L(\tau). \quad (4)$$

On a droplet surface, expressions (2) – (4) is applied to concretize an energy balance condition $\bar{q}_{\Sigma}^+ + \bar{q}_{\Sigma}^- + \bar{q}_f^+ \equiv 0$ for all modeled droplet heating cases. A balance condition requires matching of heat flows that flows in and flows from the surface of the droplet. In outspread form a balance condition becomes a transcendental system of algebraic and integral equations, because its solutions are unambiguous only then, when the droplet surface temperature function of time $T_R(\tau)$ is defined. This function is defined by iterative technique according to method [5]. However, the temperature distribution inside the droplet $T(r < R, \tau)$, can only be defined by case assumptions of non-circulating fluid. At numerical experiment attention is taken into account to phase transformation in technologies of heat recovery from humid combustion products. Water injection takes an important place for gas mixture cleaning and for additional irrigation [7]. Peculiarities of convective heating was highlight by modeling a water droplets of 278 K temperature at unsteady phase transformation mode in 500 K temperature humid gas flow ($\bar{p}_{v,\infty} = 0.3$, when $p = 0.1$ MPa). Droplets primary slipping is defined by Reynolds number values 0, 5, 10, 20, 40, and 80 for $2R_0 = 150 \cdot 10^{-6}$ m droplet diameter, when a gas flow velocity is $w_g \equiv 10$ m/s. These Re_0 number values were ensured by primaries velocities $w_{l,0}$ m/s: 10, 11.12, 12.25, 14.49, 18.98 and 27.97, respectively. Fourier number application in time scale was carried out in numerical experiment. The main attention is laid on for unsteady phase transformation mode $0 \div Fo_{of}$. In numeric control scheme for condensing mode 21 control time moments are provided for time grid formation. Condensing mode duration Fo_{co} is defined $Fo \equiv 0 \div Fo_{co}$ (Fig. 1).

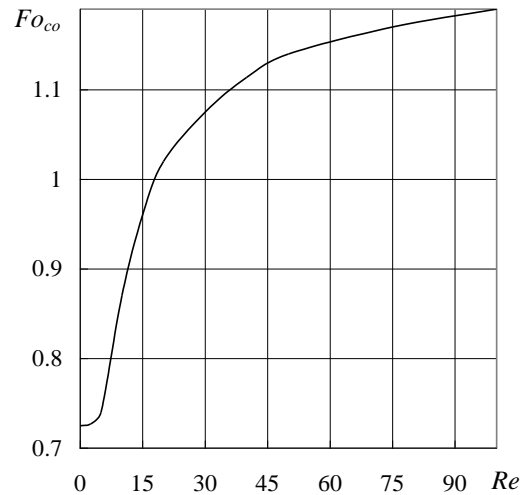


Fig. 1 A slipping droplet in gas flow impact for duration of condensing phase transformation mode

Unchanging individual time step $\Delta Fo_i = Fo_{co} / (I_{co} - 1)$, when $I_{co} = 21$ was kept in each modeled cycle. A droplet surface temperature function $T_R(Fo)$ is defined according to (10) - (18) schemes in work [5]. Other parameters functions $P(Fo)$ of heat and mass transfer are defined in parallel. At numerical experiment process a condition matching of heat flows that flows in and flows from a droplet surface is satisfied (Fig. 2.) by a strict requirement:

$$\left| 1 - \frac{q_c^-(Fo) + q_f^+(Fo)}{q_c^+(Fo)} \right| \cdot 100\% < \delta_R \equiv 0.01\% \quad (5)$$

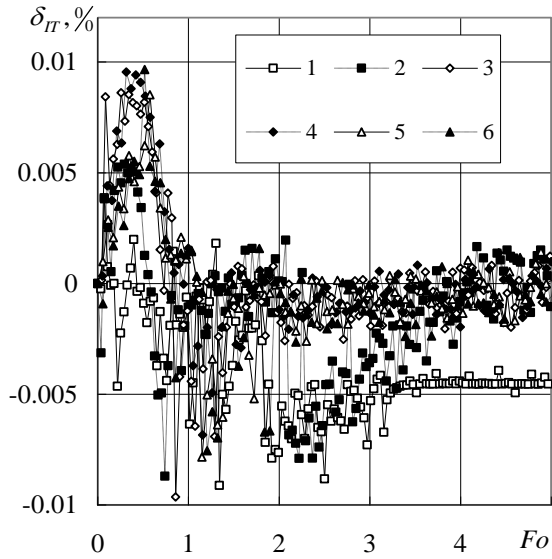


Fig. 2 Heat fluxes disbalance on the surface of a droplet (5) conditions satisfaction in modelled unsteady phase transformation regimes. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

In phase transformation cycle a gas surrounding gives the heat for a droplet by heat transfer (together with condensing heat or without a heat that is necessary for evaporation process):

$$Q_{J,co}^+ + Q_{J,ng}^+ + Q_{J,eg}^+ = Q_J^+ \quad (6)$$

According to expression (6) described heat quantity can be defined according to heat flow density average values $\hat{q}_{c,i}^-$ in a droplet that is distinguish at time intervals

$$Q_J^+ = \sum_{i=2}^l 4\pi\hat{R}_i^2 \hat{q}_{c,i}^- \Delta\tau_i, \text{ when } \hat{q}_{c,i}^- \equiv \frac{q_{c,i}^- + q_{c,i-1}^-}{2} \quad (7)$$

Because of physical nature change in phase transformation modes at heat flow in a droplet [7], peculiarities of phase transformation cycle modes should be taken into account when defining $\hat{q}_{c,i}^-$. At condensing phase transformation mode a gas surrounding gives thermal energy in heat transfer process together with vapour phase transformation heat that condensates on the surface of a droplet. At unsteady evaporation mode a convective heat warmth and evaporates a droplet. In equilibrium evaporation mode a convectional heat can only evaporates the droplet and enthalpy of cooling down droplet can participate in evaporation:

$$\left. \begin{aligned} \hat{q}_{c,i}^- &= \hat{q}_{c,i}^+ + \hat{q}_{f,i}^+, \text{ when } Fo \equiv 0 \div Fo_{co}; \\ \hat{q}_{c,i}^- &= \hat{q}_{c,i}^+ - \hat{q}_{f,i}^+, \text{ when } Fo_{co} < Fo \equiv < Fo_{nf}; \\ \hat{q}_{c,i}^- &= \hat{q}_{f,i}^+ - \hat{q}_{c,i}^+, \text{ when } Fo \geq Fo_{nf}. \end{aligned} \right\} \quad (9)$$

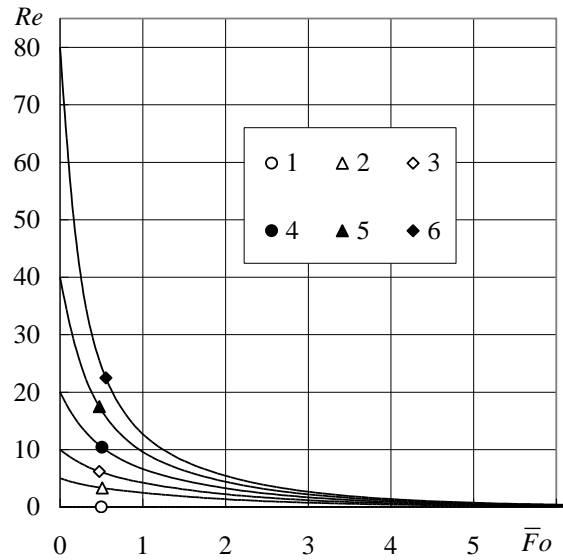


Fig. 3 A change of droplet slipping intensity in gas flow. $\bar{Fo} \equiv Fo/Fo_{co}, "k"$; $Fo_{co}, "k" = 0.725$; Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

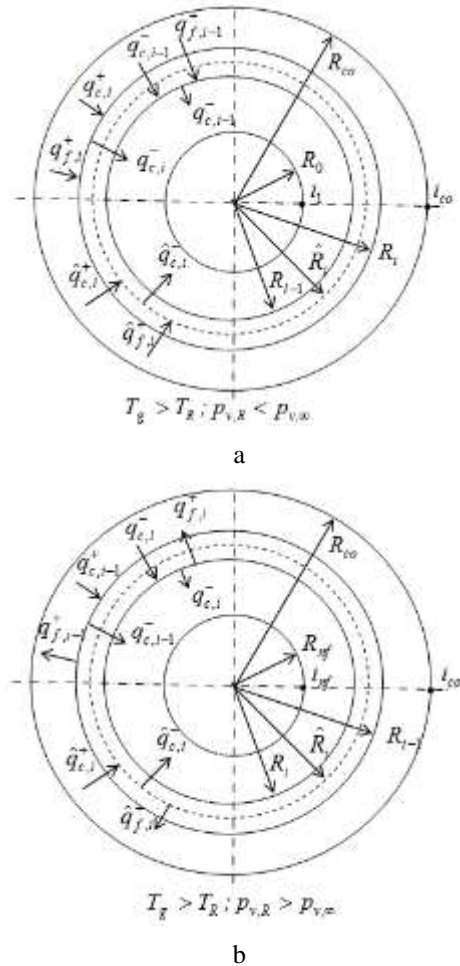


Fig. 4 A droplet energy interpretation in condensation (a) and in unsteady evaporation (b) phase transformation regimes

A droplet slipping in gas flow is decreasing because of the impact of resistance forces. The fastest droplet velocity change is in condensing phase transformation mode, while in evaporation mode a droplet slipping be-

comes negligible in term $\approx 5 \cdot \bar{Fo}_{co}$ (Fig. 3). Then a case of heating by conductivity approach in practice. Therefore at a droplet energy state analysis the main attention is given for condensing and unsteady evaporation modes.

3. Energy evaluation of unsteady phase transformation mode

A droplet energy state graphical interpretation, in freely chosen time $\Delta\tau_i$ intervals at condensing and unsteady evaporation modes is reflected in Fig 4. In condensation phase transformation mode a droplet diameter increases from $2R_0$ to $2R_{co}$, therefore $R_i > R_{i-1}$. At evaporation mode a droplet diameter decreases from $2R_{co}$ to zero, therefore $R_i < R_{i-1}$.

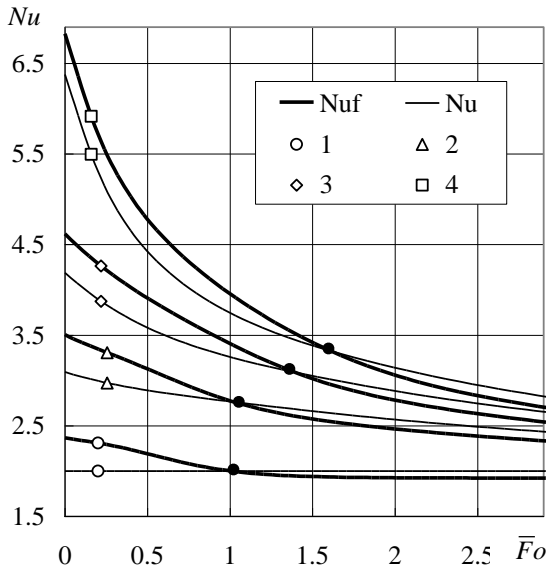


Fig. 5 In gas flow slipping droplet impact for convective heating intensity. Re_0 : (1) 0, (2) 5, (3) 20, (4) 80

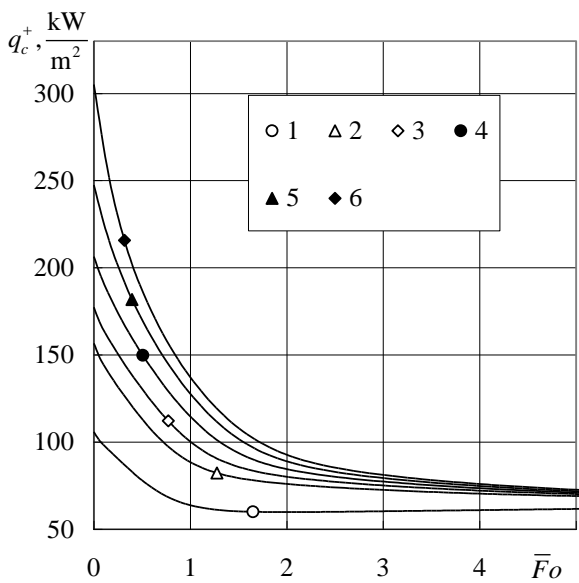


Fig. 6 In gas flow slipping droplet impact for convective heat flow. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

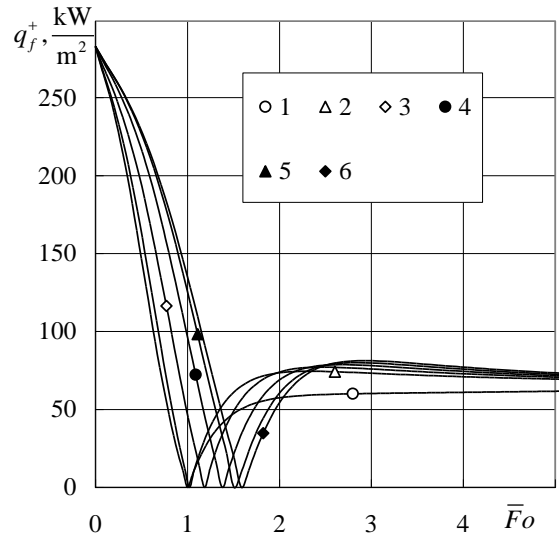


Fig. 7 In gas flow slipping droplet impact for phase transformation heat flow. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

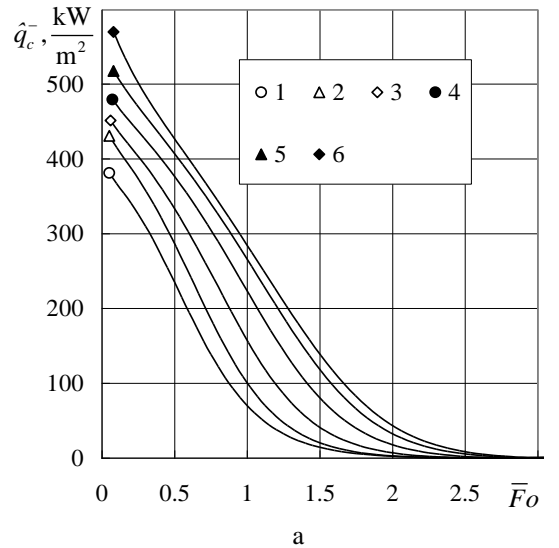


Fig. 8 In gas flow slipping droplet impact for liquid droplet average heating intensity: a - at unsteady phase transformation mode; b - at initial state of equilibrium evaporation mode. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

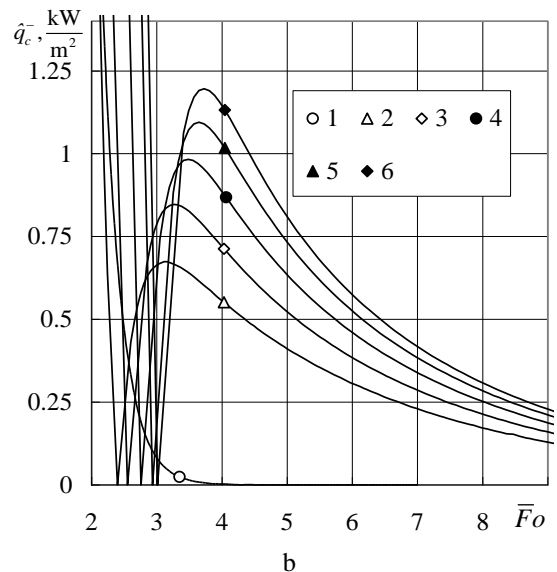


Fig. 8 In gas flow slipping droplet impact for liquid droplet average heating intensity: a - at unsteady phase transformation mode; b - at initial state of equilibrium evaporation mode. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

At condensation phase transformation mode droplet convective heating intensity exceeds analogous solid particle heating case, when phase transformation does not expose on its surface. In unsteady evaporation mode a droplet heating intensity is weaker than solid particle, while in regime change moment, matches it black points (Fig. 5). Droplet slipping in gas flow has a bright impact for convective heat flow that warmth a droplet (Fig. 6), and also has an impact for phase transformation heat flow (Fig. 7). In unsteady phase transformation mode at a droplet liquid is heated up intensively (8 Fig. a), its surface temperature increases, and temperature difference $\Delta T = T_g - T_R$ that reflects external heat exchange driving force, decreases (Fig. 9). Therefore convective heating intensity suffocates in unsteady condensing and evaporation phase transformation modes (Fig. 6).

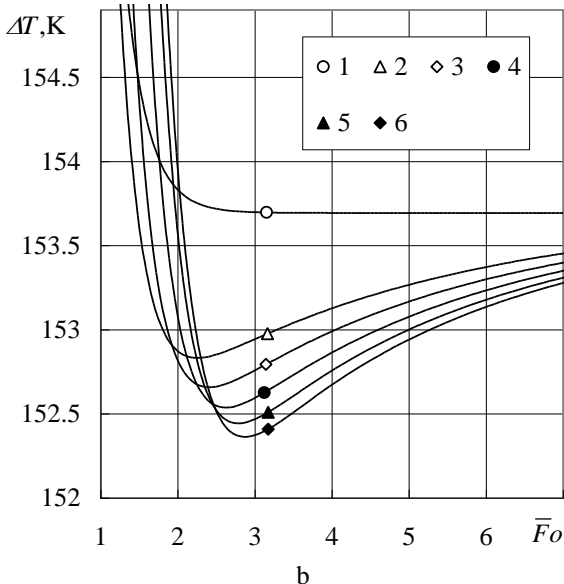
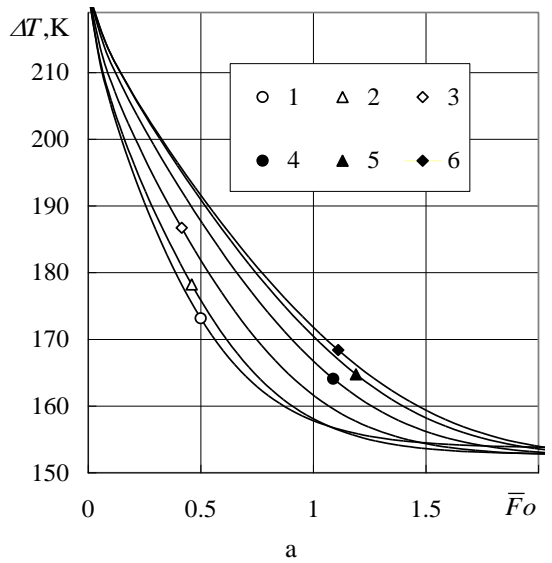


Fig. 9 In gas flow slipping droplet impact for driving force change of heat transfer: a - unsteady phase transformation mode; b - initial state of equilibrium evaporation mode. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

In condensation mode a growing heat exchange area has a bright impact for convective heat flow density that is provided for a droplet (Fig. 10.). A warming liquid

expansion and liquid vapour condensation on the surface causes a droplet surface area growth in condensation mode. Surface water evaporation compensates liquid expansion in unsteady evaporation mode. At balance moment of these factors extreme point forms in droplet surface variation curve therefore a droplet surface area start to decrease.

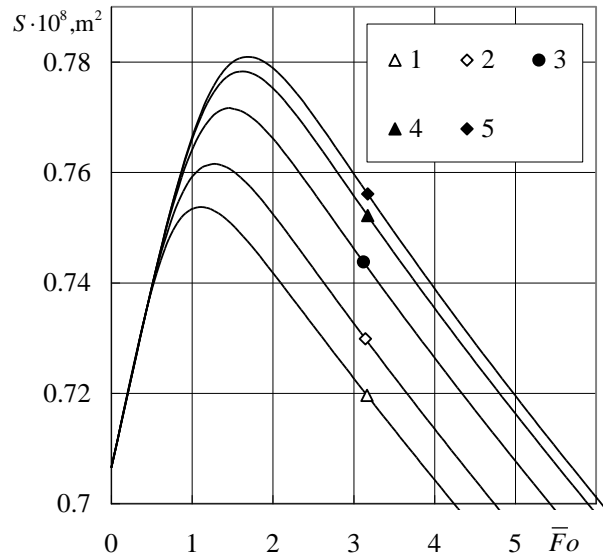


Fig. 10 In gas flow slipping droplet impact for area variation of heat exchange. Re_0 : (1) 5, (2) 10, (3) 20, (4) 40, (5) 80

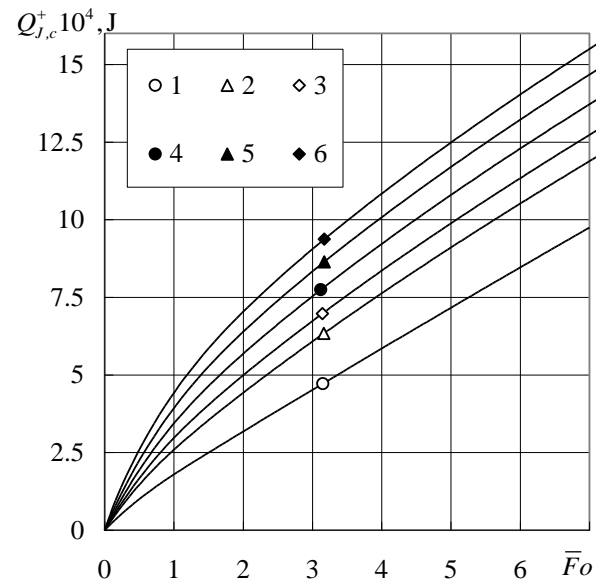


Fig. 11 In gas flow slipping droplet impact for heat change that is provided for a droplet by convection. Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

At equilibrium evaporation mode a droplet surface decreases linearly and satisfies a well known law D^2 [12]. For a more extensive evaluation of droplet phase transformation peculiarities needs to make a broader numerical research. Gas humidity and temperature, as well temperature of sprayed water and heat transfer of a droplet would be angular aspects. This is one of the future research topics. In unsteady phase transformation mode a heat that is provided for a droplet by convection from a gas surrounding is reflected in Fig. 11, while heat change that participates in phase transformation process is presented in Fig. 12.

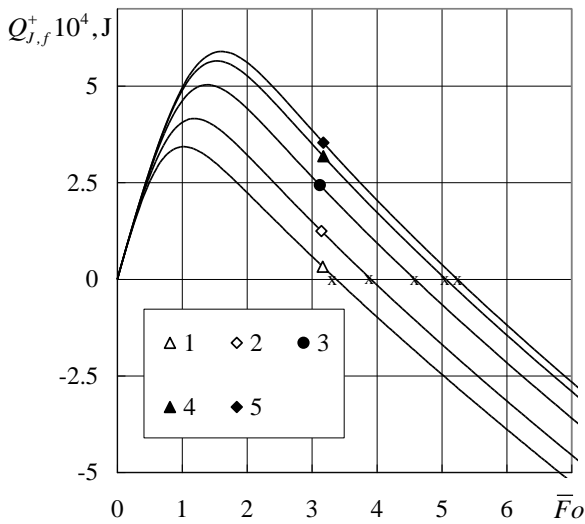


Fig. 12 In gas flow sliding droplet impact for change of provided heat during phase transformation. Re_0 : (1) 5, (2) 10, (3) 20, (4) 40, (5) 80

Heat is being provided for a droplet by convection in whole phase transformation cycle, therefore a provided heat amount is consistently growing. In phase transformation balance assessment the evolved heat considered to be positive in condensation process, while a heat that is required for water evaporation considered to be negative. Therefore at the end of condensation mode in curve $Q_{J,f}^+(Fo)$ of phase transformation heat dynamics an extreme point observes. Liquid evaporation starts from this point. Evaporation process continues due to a part of heat that is provided by convection. In condensation process, a released heat of phase transformation gets a bright effect from droplet slipping in gas: $Q_{J,f}^+(Re_0, Fo \equiv Fo_{co}) \cdot 10^4, J$ is 3.195, 3.433, 4.159, 5.033, 5.649, 5.893, when Re is 0, 5, 10, 20, 40 and 80, respectively. The same heat amount is used at initial state of unsteady evaporation, that is defined by time moment $Q_{J,f}^+(Re_0, Fo) \equiv 0$ (Fig. 12 points x).

Therefore in condensation phase transformation mode a heat amount that is provided for a droplet is $Q_{J,c}^+(Re_0, Fo_{co}) + Q_{J,f}^+(Re_0, Fo_{co})$. It is led to droplet by internal heat convection $Q_{J,c}^-(Re_0, Fo_{co}) \cdot 10^4, J$: 4.985, 6.063, 7.546, 9.403, 10.933, and 11.962 when Re is 0, 5, 10, 20, 40 and 80, respectively. In a droplet water is heated from $T_{l,0} = 278$ to $T_{l,m}(Fo \equiv Fo_{co})$. Heat amount that is led to a droplet by internal heat convection (Fig. 13) is defined by condition $Q_{J,c}^-(Fo) \equiv Q_{J,c}^-(Fo \equiv Fo_{nf})$, which enables to define unsteady phase transformation duration $Fo_{nf}(Re_0)$ from scientific assessment: 2.68, 1.739, 1.849, 1.999, 2.128, 2.186, when Re is 0, 5, 10, 20, 40 and 80, respectively (Fig. 13, b). In equilibrium evaporation mode a liquid in a droplet is not heated anymore. For droplet that is heated up by conductively this is reflected by condition $\bar{Q}_{J,c}^-(Fo > Fo_{nf}) = 1$.

Internal heat convection in slipping droplet can still going on, but convection leads out heat from cooling down droplet to its surface and stimulates an evaporation process. This is reflected by the condition $\bar{Q}_{J,c}^-(Fo > Fo_{nf}) < 1$.

For integrated droplet energy and thermal state change analysis it is required to define a droplet warming dynamics in all phase transformation cycle. A thermal state analysis of circulating water in a droplet is quite complicated and would extend this work. It would be one of the future research topics.

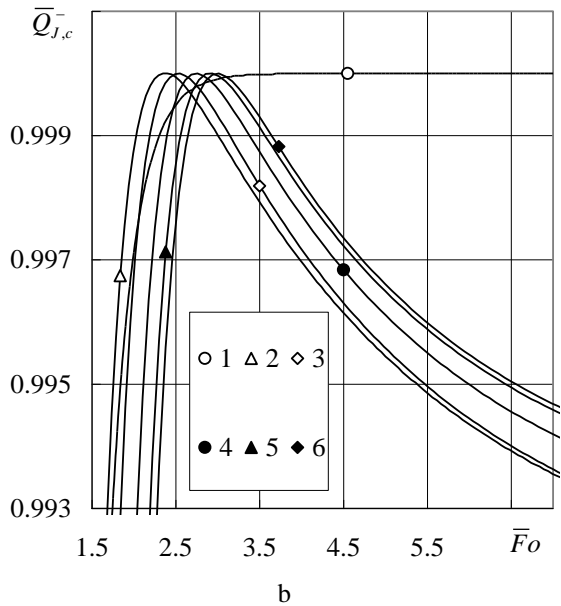
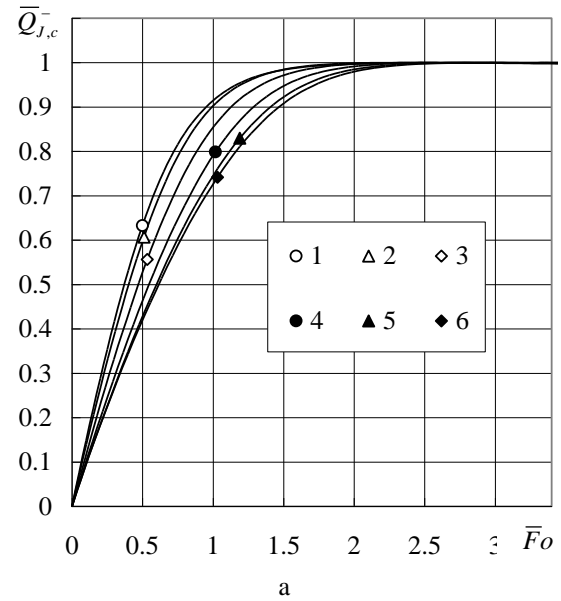


Fig. 13 In gas flow a slipping droplet impact for heat amount that is led to a droplet by convection $\bar{Q}_{J,c}^-(Fo) \equiv Q_{J,c}^-(Fo) / Q_{J,c}^-(Fo \equiv Fo_{nf})$, $Q_{J,c}^-(Fo \equiv Fo_{nf}), J$: (1) 5.45, (2) 6.67, (3) 8.23, (4) 10.18, (5) 11.83, (6) 12.91; Re_0 : (1) 0, (2) 5, (3) 10, (4) 20, (5) 40, (6) 80

4. Conclusions

Water droplets slipping have a maximum impact for droplets heat transfer in humid gas at condensation phase transformation mode. A set analysis of energy state balance for different speeds moving droplets shows, that essential role falls far liquid circulation that is caused by friction forces that arises on the surface of the slipping

droplet. For this reason, heat is led out to central layers of the droplet more intensively. Therefore droplet heats up gradually; a temperature gradient in surface layers is lower than at conductivity heating case and droplet surface heats up till a dew point longer. On the surface of a droplet slipping in humid gas liquid vapor condenses more intensively therefore a droplet diameter grows in condensation mode.

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MODELING OF HEAT AND MASS TRANSFER PROCESSES IN PHASE TRANSFORMATION CYCLE OF SPRAYED WATER INTO GAS:
3. ENERGY AND THERMAL STATES ANALYSIS OF SLIPPING DROPLET IN A HUMID AIR FLOW

Summary

In this work an unsteady phase transformation mode for droplets that are slipping in humid air was numerically simulated. Initial slipping for droplet of 150 micrometer diameter is defined by Reynolds number values of 0, 5, 10, 20, 40 and 80. Warming droplet energy state is evaluated by balance method according to average heat flow density values in distinguished Fourier number time intervals at condensing and unsteady evaporation modes. At numerical experiment a balance control of heat flow on droplet surface was carried out, when allowable imbalance is defined by less than hundredth percentage point. Bright water slipping in humid gas impact for their heat transfer in condensation phase transformation mode was based on. This impact reveals due to reactivation of led heat to central layers as well as an equal droplet warming and duration grow of condensing mode.

Keywords: humid gas, water droplets, convection heating, condensation, unsteady evaporation, numerical simulation, energy analysis.

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