INTERACTION OF HEAT AND MASS TRANSFER PROCESSES OF WATER DROPLETS SLIPPING IN HUMID GAS

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ABSTRACT

This paper presents the transformation cycle of condensation and transit evaporation regimes of sprayed water droplet phase in humid gas in the context of heat utilization from removed biofuel combustion products.

A mathematical model based on the heat flow balance on the droplet surface was applied. It combines droplet internal heat transfer and external heat transfer and phase transformation problem solutions. The unsteady temperature field gradient of the droplet is described according to analytical model of heat spread by conduction and radiation in a droplet, while the influence of heat convection is evaluated by the effective heat conductivity parameter. In the droplet, local radiation flow is defined based on spectral radiation absorption in a semi-transparent sphere model. Variation of droplet heat and mass transfer parameters is defined by droplet surface instantaneous temperature that is selected according to iterative numerical scheme operated by the fastest descent method. For this scheme, the requirement is raised that relative error between instantaneous calculated heat flows that flow in and from the surface should not exceed five-hundredths percent. The essential role of the droplet slipping factor upon interaction of transfer processes in transformation regime of the condensation phase in gas flow was highlighted.

INTRODUCTION

A lot of modern technologies [1-6] are based on sprayed water heat and mass transfer processes; they are also important in atmospheric events [7]. Water spray technologies are combined by droplet link that allows envisaging a consistent variation of phase transformation regimes and presenting it by typical phase transformation cycle ongoing on the droplet surface that combines condensation, transit and equilibrium evaporation regimes [8]. The droplet phase transformation cycle allows evaluating the influence of successfully boundary conditions on transfer process regularities and revealing essential factors that affect compound process interaction. Optimal boundary conditions can be defined when separate water spraying technologies are taken into account. At the current stage of humankind, the development of the need of usage of rational energy resources and nature conservation is very strong. Therefore, the practice of using renewable energy sources, including biofuel burning, is rapidly developing. Heat recovery from removed humid gas becomes relevant for economic and environmental aspects [9].

NOMENCLATURE

a	[m^2/s]	thermal diffusivity
B_T	[-]	Spalding transfer number
c_p	[J/(kg K)]	mass specific heat
D	[m^2/s]	mass diffusivity
k	[W/mK]	thermal conductivity
Fo	[-]	Fourier number
L	[J/kg]	latent heat of evaporation
m	[kg/(m^{2}s)]	vapour mass flow
M	[kg]	mass
n	[-]	number of the term in the infinite sum
p	[Pa]	pressure
Pr	[-]	Prandtl number
q	[W/m^2]	heat flow
r	[m]	coordinate of the droplet
R	[m]	radius of the droplet
Pe	[-]	Peclet number
Re	[-]	Reynolds number
R_μ	[J/(kmol·K)]	universal gas constant
T	[K]	temperature
w	[m/s]	velocity

Special characters

η	[-]	non-dimensional coordinate
λ	[W/(m K);]	thermal conductivity
μ	[kg/kmol]	molecular mass
ρ	[kg/m^3]	density
τ	[s]	time

Subscripts

+	external side of a droplet surface
-	internal side of a droplet surface
c	convective
co	condensation
"c"	heating by convection
"c+r"	heating by radiation
ee	equilibrium evaporation
f	phase change
g	gas
i	time index in a digital scheme
I	index of control time
J	index of droplet surface
l	liquid
rt	Dew point
uf	transit evaporation
vg	vapour-gas mixture
Σ	total
0	initial state
∞	far from droplet

Transformation heat of water vapour phase from biofuel flue gas is recovered in condensing economizers. In these technologies, water spraying is important: at contact-type heat

exchangers, vapour condenses directly to sprayed water droplets, while in tube-type recuperative heat exchangers, water is sprayed to improve hydrodynamics of gravity condensate film that flows along the tube surface. In the first case, transformation regime of the condensation droplet phase is important, while in the second case, droplet evaporation regime becomes essential. Regularities of these regimes are analysed in this study.

PROBLEM FORMULATION

The beginning of water phase transformation cycle $\tau \equiv 0 \div \tau_{co} \div \tau_{uf} \div \tau_f$ is fixed by water spraying moment $\tau=0$, while the end is defined by droplet life duration τ_f. At time moment $\tau=\tau_{co}$, on the droplet surface, phase transformation regime changes from water vapour condensation to water evaporation. In condensation regime $\tau \equiv 0 \div \tau_{co}$, droplet is heated up by the warmth that is supplied by external heat transfer and by phase transformation heat that by internal heat transfer is leaded within the droplet, separated from water vapour in the process of condensation:

$$q_{\Sigma,0\div\tau_{co}}^- = q_\Sigma^+(\tau) + q_{co}^-(\tau).$$ (1)

In condensation regime, the droplet surface is intensively heated up and warmed to the dew point temperature T_{rt}. In the transit evaporation regime, a part of heat supplied for droplet still warms water:

$$q_{\Sigma,\tau_{co}\div\tau_{uf}}^- = q_\Sigma^+(\tau) - q_{ue}^-(\tau).$$ (2)

At time moment $\tau=\tau_{uf}$, droplet heats up to temperature T_e that ensures equilibrium evaporation. Equilibrium evaporation is such a phase transformation case, when all heat supplied to droplet only evaporates the water; therefore:

$$q_{ee}(\tau=\tau_{uf}) \equiv q_\Sigma^+(\tau=\tau_{uf}) \text{ ir } q_\Sigma^-(\tau=\tau_{uf}) = 0.$$ (3).

Thermal state variation of equilibrium evaporating the droplet is influenced by the way of heating [10]. Interaction of heat and mass transfer processes defines function $T_R(\tau)$. It describes the variation of droplet surface temperature in the phase transformation cycle. This function ensures instantaneous equivalence of heat flows that flow in and from the droplet surface and in the quasi-steady state, the assumption is defined by condition:

$$\vec{q}_\Sigma^+(\tau) + \vec{q}_\Sigma^-(\tau) + \vec{q}_f^+(\tau) \equiv 0.$$ (4)

Expression (4) is formal; therefore, for numerical scheme formulation, mathematical model of heat flows are concretized. Total heat flow on both droplet surface sides is defined according to components of radiation and convection $q_\Sigma = q_r + q_c$. After estimating peculiarities of water complex spectral index of refraction [11], radiation absorption by water droplet surface is denied: $q_r^- \equiv q_r^+$. For radiation component definition, an integral radiation model of local radiation flow $q_r(r)$ in a semi-transparent sphere is applied [12]. It demands already known temperature field function $T(r,\tau)$ in the droplet, but enables to take into account peculiarities of spectral optical peculiarities and evaluate spectral optical effects on the droplet surface. Droplet heating by

convection is described according to Ambramzom-Sirignano model [13]:

$$q_{"c"}^+ = \lambda_{vg}\frac{T_g - T_R}{2R}\cdot\left[2\frac{\ln(1+B_T)}{B_T} + 0.57\frac{Re^{1/2}Pr^{1/3}}{(1+B_T)^{0.7}}\right].$$ (5)

In expression (5), a modified form of Reynolds criterion is applied $Re \equiv 2R\Delta w_l \rho_g / \mu_{vg}$ for flue gas and vapour mixture $Y_{vg} \equiv Y_{vg,R} + (Y_{vg,\infty} - Y_{vg,R})/3$ and $T_{vg} \equiv T_{vg,R} + (T_g - T_{vg,R})/3$. A universal form for the entire cycle of phase transformation [9] is applied to describe the Spalding heat transfer parameter B_T:

$$B_T(\tau) = c_{vg}(\tau)\frac{T_g(\tau) - T_R(\tau)}{L(\tau)}\cdot\frac{q_f^+(\tau)}{q_c^+(\tau)}.$$ (6)

By expression (6), Stefan hydrodynamic flow impact on peculiarities of convection heating intensity in the transformation cycle regime of droplet phase is evaluated.

Convection component of total heat flow in the droplet is described according to the heat spread integral model therein [12].

$$q_c^-(\tau) = -k_c^-(\tau)\lambda_{l(\tau)}\frac{\partial T(r,\tau)}{\partial r}\bigg|_{r=R} = -2k_c^-\frac{\lambda_l}{R^2}\sum_{n=1}^{\infty}n(-1)^n \times$$
$$\times \int_0^\tau f_n(r,\tau)\exp\left[-a_l\left(\frac{n\pi}{R}\right)^2(\tau - \tau_*)\right]d\tau_*.$$ (7)

In expression (7), by function

$$f_n = \frac{(-1)^n R}{n\pi}\frac{dT_R}{d\tau} + \frac{R^{-1}}{\rho_l c_{p,l}}\int_0^R\left(\sin\frac{n\pi r}{R} - \frac{n\pi r}{R}\cos\frac{n\pi r}{R}\right)dr$$ (8).

Heating rate of the droplet surface and peculiarities of the local flow radiation are taken into account [12], while the impact of forced heat convection in water on heat spread in droplet slipping at flue gas is evaluated by effective heat conductivity parameter $k_c^- = f(Pe_l)$ [13]. Droplet slipping in fume is defined by movement equation [14]

$$\frac{dw_l}{d\tau} = \frac{3}{8}\frac{\rho_g}{\rho_l}\frac{|w_l - w_g|}{(w_l - w_g)^{-1}}\frac{24 + 4.8Re^{0.63}}{(1+B_T)^{0.2}R\,Re}.$$ (9)

Droplet mass variation in case of sphericity assumptions is defined based on Shorin-Kuzikovsky model [15, 16]:

$$\frac{dM_l(\tau)}{d\tau} = -4\pi R^2(\tau)m_v^+(\tau) = -4\pi R\frac{D_{vg}\mu_v}{T_R R_\mu} \times$$
$$\times\left[p_{v,R} - p_{v,\infty} + \frac{\mu_v}{\mu_g}\cdot\left(p\ln\frac{p - p_{v,\infty}}{p - p_{v,R}} - p_{v,R} + p_{v,\infty}\right)\right].$$ (10)

Droplet phase transformation heat flow is defined according to dynamics of vapour flow density on the droplet surface:

$$q_f^+(\tau) = m_v^+(\tau)\cdot L(\tau).$$ (11)

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When water vapour flow in condensation regime is provided to be negative, while in the evaporation regime, spread of water vapour flow from the droplet is positive, integral and algebraic equation system (1-11) defines droplet heat and mass transfer in the entire phase transformation cycle, when initial and boundary conditions are defined:

$$T(r,\tau=0)=T_{l,0},\ R(\tau=0)=R_0,\ \Delta w_l(\tau=0)=\Delta w_{l,0},$$
$$T_g(\tau)=T_{g,0},\ p_{v,\infty}(\tau)=p_{v,\infty,0};\ T(r=R,\tau)=T_R(\tau). \quad (12)$$

NUMERICAL METHOD

Heat and mass transfer processes in droplet phase transformation cycle described by equation system (1)-(12) are numerically solved by an iterative algorithm. The need of iterative numerical scheme is defined by the demand to know the function of unsteady temperature field $T(r,\tau)$ of the droplet in order to calculate local radiation flow in the droplet. Also, in boundary conditions of expressions (11), a known function of droplet surface temperature $T_R(\tau)$ is provided. This function is necessary to form integral heat spread model by conduction and radiation [12]. Based on heat flow expressions (5-7) and (11), the condition of heat flow balance (4) is concretized. Time moments τ_i are assumed, and dimensionless radial coordinate $\eta=r/R_i$ is introduced, which provides unchanging uniform radius of the droplet $\eta(r\equiv R_i)=1$ in the droplet phase transformation cycle, also, mediate radial coordinate η_j is defined:

$$\sum_{i=2}^{I}(\tau_i-\tau_{i-1})=\tau_f \ \ \text{ir}\ \ \sum_{j=2}^{J}(\eta_i-\eta_{i-1})=1. \quad (13)$$

In each provided time moment τ_i, an iterative cycle $it_i \equiv 1\div IT$ is executed to define instantaneous droplet surface temperature $T_{R,i}$: temperature $T_{R,i}\equiv T_{J,i,it\equiv IT}$ is selected by fastest descent method that ensures fulfilment of the requirement

$$1-\cfrac{m_{v,i,iT}^{+}L_{i,IT}+k_{c,i,IT}^{-}\lambda_{l,i,IT}R_{i,IT-1}\left.\dfrac{\partial T_{i,j,IT}}{\partial\eta}\right|_{j\equiv J}}{\lambda_{vg,i,IT}\dfrac{T_g-T_{J,i,IT}}{2R_{i,IT-1}}\cdot\left[2\dfrac{\ln(1+B_{T,i,IT})}{B_{T,i,IT}}+0.57\dfrac{\mathrm{Re}_{i,IT}^{1/2}\,\mathrm{Pr}_{i,IT}^{1/3}}{(1+B_{T,i,IT})^{0.7}}\right]}<\dfrac{Pa}{100\%}, \quad (14)$$

when $Pa=0.05\%$.

Individual durations of different regimes of droplet phase transformation cycle may significantly differ. Therefore, a problem of time $\Delta\tau_i=\tau_{i+1}-\tau_i$ determination arises. When solving it, it is worth remembering that at the moment of change of phase transformation regime, vapour flow from condensation to evaporation on the droplet surface gets zero value. Consequently, the final iterative $it_{i\equiv I_{co}}$ cycle of condensing regime may become indeterminate. To avoid that, condensation phase transformation regime is considered to be supporting in selected $\Delta\tau_i$. A linear time step grid is provided for it. The experiment is defined by Fourier number $Fo=a_0\tau/R_0^2$, based on the universal time scale. The main advantage of this time scale

will be discussed later: according to Reynolds number in grouped droplet clouds, functions of heat and mass exchange parameters $P(\tau)$ in dimensionless form are insensitive to droplet dispersity in case, described by parameters $T_{l,0}$, T_g and $\bar{p}_{v,\infty}=p_{v,\infty}/p$. Therefore, in case of selected boundary conditions, it is sufficient for Re_0 to model condensation phase transition $Fo\equiv 0\div Fo_{co}$ regime of a freely chosen diameter, when $\Delta Fo_{i,co}=Fo_{co}/(I_{co}-1)$. The duration of condensation phase transformation regime Fo_{co} is defined by a separate numerical experiment by consistent approximation method for time grid case $I_{co}=31$, when for final iteration $it_{i=I_{co}}$, a requirement $T_{rt}-T_{J,i=I_{co},IT}\equiv\Delta T_{\min}>0$ is raised. The latter requirement aims to ensure heating of the droplet surface as close to dew point temperature as possible, but without exceeding it, and to ensure reliable convergence of final iterative cycle of condensation regime.
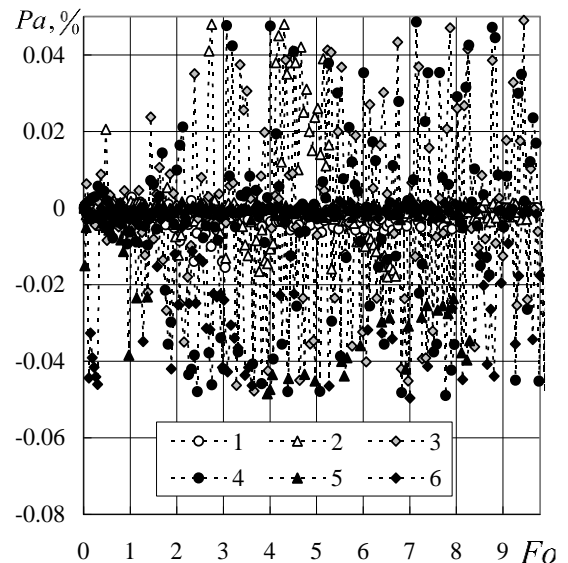

Figure 1 Control of heat flow imbalance on the droplet surface. T_g, K: (1-4) 370, (5, 6) 500; $\bar{p}_{g,\infty}$: (1, 2) 0.1, (3, 4) 0.5, (5, 6) 0.3; Re_0: (1) 0, (2, 4, 6) 50, (3) 20, (5) 10

When universal time step $\Delta Fo_{i,co}$ is determined for droplet cloud defined by specific Re_0 criterion, which provides individual time grid $\Delta\tau_{i,co}=R_0^2\Delta Fo_{i,co}/a_0$ for specific droplet dispersity R_0, transit droplet phase transformation regime is numerically modelled. For its condensation regime a step $\Delta Fo_{i,co}$ is kept, while in transit evaporation regime, there is an opportunity to increase this step: $\Delta Fo_{i>Ico}=N_{ue}\cdot\Delta Fo_{i,co}$. In the studies presented in this work, $N_{ue}=2$. At the second stage of numerical modelling, universal Fo_{uf} duration of droplet transit phase transformation regime is defined, and individual durations $\tau_{uf}=\tau_{co}+\tau_{ue}$ for desirable droplet dispersity are provided. Should full droplet phase transformation cycle be of interest, the third numerical experiment stage would be necessary, where already defined steps $\Delta Fo_{i,co}$ and $\Delta Fo_{i,ue}$ are kept for transit phase transformation regime, while for equilibrium evaporation, there

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is an opportunity to select optimal $\Delta Fo_{i,ee} = N_{ee} \cdot \Delta Fo_{i,ue}$ step. In the numeric scheme of expression (7), evaluation of infinite sum 101 member was accepted as the optimal, while droplet radial coordinate was calibrated for $J=41$ case. During numerical experiment, the fulfilment of requirement (1 Fig.) was controlled (14).

RESULTS AND DISCUSSIONS

Transit phase transformation regime was numerically modelled at T_g=370 and 500 K temperature $\overline{p}_{g,\infty} = 0.1$, 0.3 and 0.5 humid air, when slipping water droplets at temperature T_0=278 K have Re$_0$=0, 10, 20 and 50.
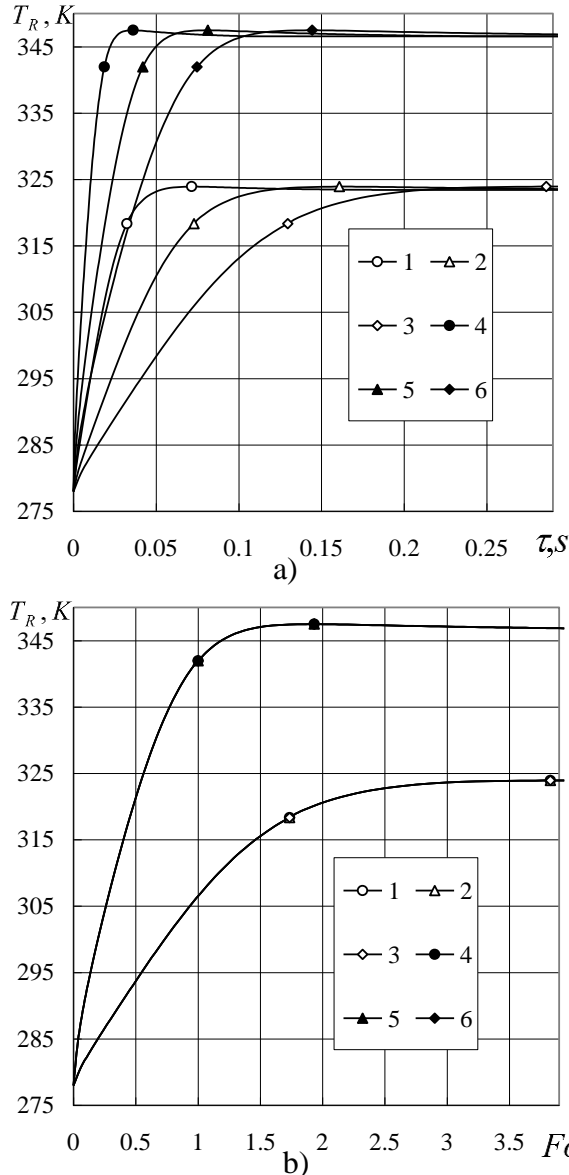
Figure 2 Peculiarities of droplet surface temperature functions $T_R(\tau)$ (a) and $T_R(Fo)$ (b). T_g, K: (1-3) 370, (4-6) 500; $\overline{p}_{g,\infty}$: (1-3) 0.1, (4-6) 0.3; Re_0: (1-3) 50, (4-6) 20; $R_0 \cdot 10^6$, m: (1, 4) 50, (2, 5) 75, (3, 6) 100
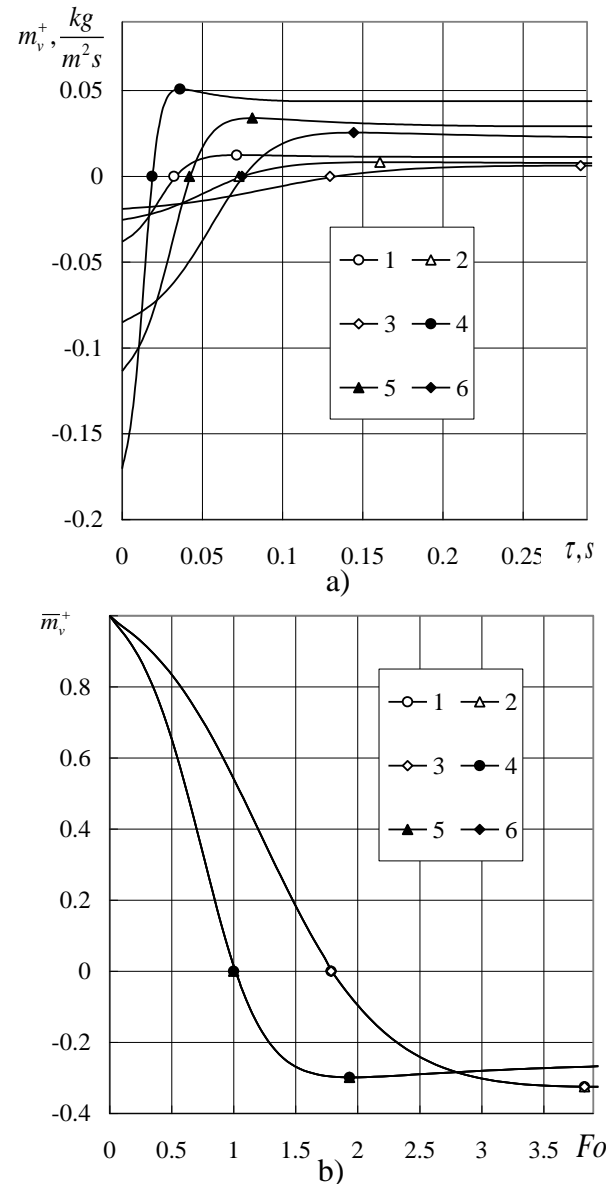

Figure 3 Peculiarities of functions of vapour flow density on the droplet surface $m_v^+(Fo)$ (a) and $\overline{m}_v^+(Fo) = m_v^+(Fo)/m_{v,0}^+$ (b). Boundary conditions correspond to those in Figure 2.

When analysing regularities of droplet phase transformation cycle, droplet heat and mass transfer process parameters P are combined in thermal P_T, energetic P_q, dynamics P_D and phase transformation P_f parameter groups. Thermal parameters are related to function $T(r,\tau)$ of unsteady temperature field of the droplet, energetic are associated with heat flows, dynamics with droplet movement, while phase – with vapour flow and droplet radius and mass. Time function $T_R(\tau) \equiv T(r=R,\tau)$ that describes variation of droplet surface temperature is important for definition of droplet phase transformation cycle. This function defines variation of phase transformation regimes in the droplet phase transformation cycle and is sensitive to droplet dispersity (Figure 2 a). Peculiarities of function of thermal parameters $P_T(Fo)$ of the droplet in time scale defined by Fourier number are

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highlighted: sprayed water temperature and gas temperature, also in cases defined by humidity, they are insensitive to droplet dispersity combined in droplet clouds with the same Reynolds number (Figure 2 b). Points in figures show variation of phase transformation regimes. Condensation regime ends when droplet surface heats up to the dew point $T_{rt}=T_s(p_{v,\infty})$ temperature. It is convenient to define the duration of condensation phase transformation regime graphically according to $m_v^+(\tau=\tau_{co})=0$ condition (Figure 3 a). Volume of the numerical experiment can be significantly reduced by the fact that function graphs of phase transformation parameters $\overline{P}_f(Fo)=P_f(Fo)/P_{f,0}$ provided in normed form are insensitive to droplet dispersity (Figure 3 b). Because droplet phase transformation parameters are defined by totality of droplet thermal, energetic and dynamic parameters, it can be stated that $\overline{P}(Fo)$ function graphs of all parameters are insensitive to droplet dispersity in conditions discussed above.

In transit evaporation regime, droplet heats up to the highest $T_{R,ee}$ temperature (Figure 4); therefore the beginning of equilibrium evaporation is defined by $T_{R,ee} \equiv T_{R,i}^{max}$ condition. Temperature $T_{R,ee}$ depends on the conditions of droplet heat transfer that define peculiarities of interaction of transfer processes. In case of marginal "c" heat transfer $Re_0=0$, the droplet asymptotically approaches to equilibrium evaporation conditions; therefore, an assumption $T_{R,ee}-T_{R,i}<0.01$ K is made for equilibrium evaporation.
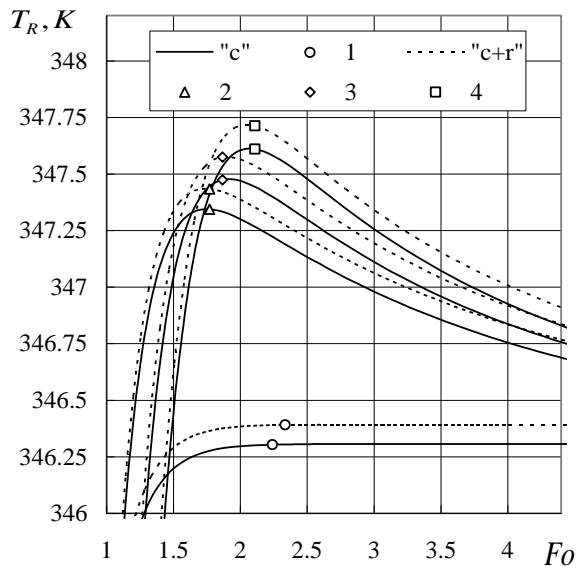

Figure 4 Variation of droplet surface temperature with the changing evaporation regime. T_g=500K; $\overline{p}_{g,\infty}=0.3$; Re_0: (1) 0, (2) 10, (3) 20, (4) 50; R_0=75·10⁻⁶m

It has been observed that droplet phase transformation cycle is sensitive to factor determining convection heating of a droplet in slipping gas flow, while radiation impact is not essential. A faster droplet slipping provides more intensive external heating (Figure 5 a) and together defines droplet internal heat transfer (Figure 5 b). Droplet slipping reduces the impact of resistance forces; therefore, slipping factor is the most significant in condensation phase transformation regime.
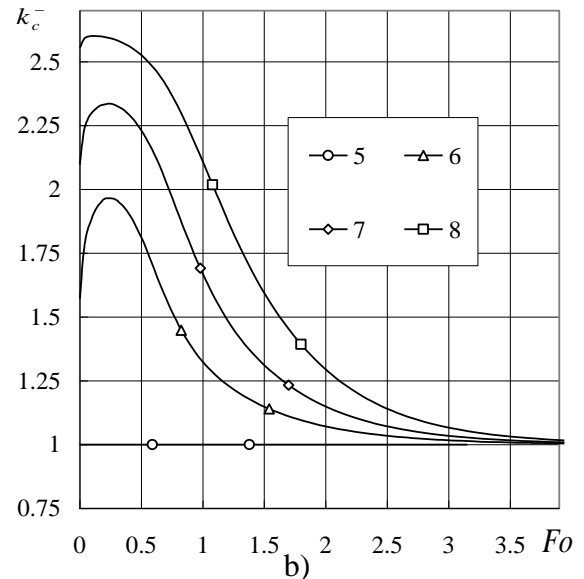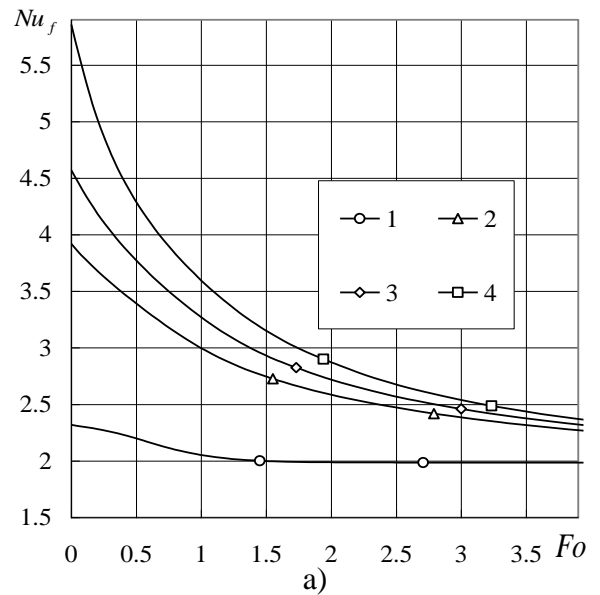

a)

b)

Figure 5 Intensity variation of convective heating of the droplet (a) and convection heat transfer in it (b) T_g, K: (1-4) 370, (5-8) 500; $\overline{p}_{g,\infty}$: (1-4) 0.3, (5-8) 0.5; Re_0: (1, 5) 0, (2, 6) 10, (3, 7) 20, (4, 8) 50

Forced water circulation accelerates heating of central layers in the first part of condensation regime in a more intensively slipping droplet, while it slows down heating of surface layers (Figure 6). Since in the beginning, water vapour condensation on the droplet surface is intensive (Figure 3 a), then mass of a more intensively slipping droplet at the condensation regime grows more distinctively (Figure 7). It is influenced by the increased duration of condensation regime of a more intensively slipping droplet.

In high humidity gas, the mass of intensively slipping droplets can increase up to 25 percent in condensation phase transformation regime, while its increment for droplets carried without slipping accounts for merely 10 percent.
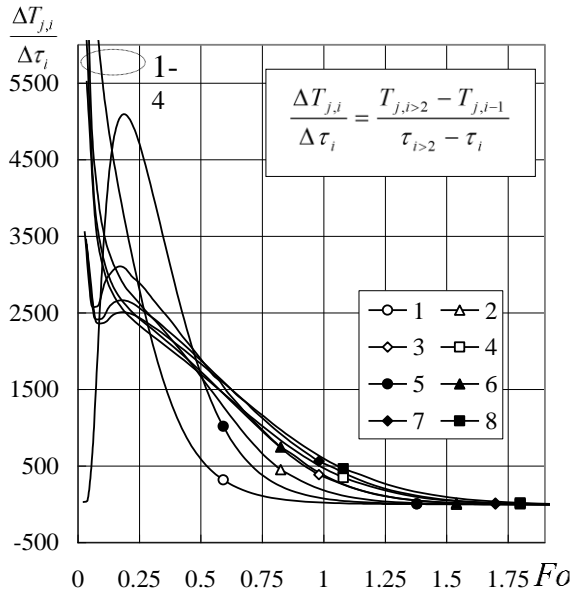
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$$\frac{\Delta T_{j,i}}{\Delta \tau_i} = \frac{T_{j,i>2} - T_{j,i-1}}{\tau_{i>2} - \tau_i}$$

Figure 6 The impact of droplet slipping on heating of its central $(T_{j,i}{=}T_{j=1,i})$ and surface $(T_{j,i}{=}T_{j=J,i})$ layers. T_g=500K ; $\overline{p}_{g,\infty} = 0.5$; Re_0: (1, 5) 0, (2, 6) 10, (3, 7) 20, (4, 8) 50
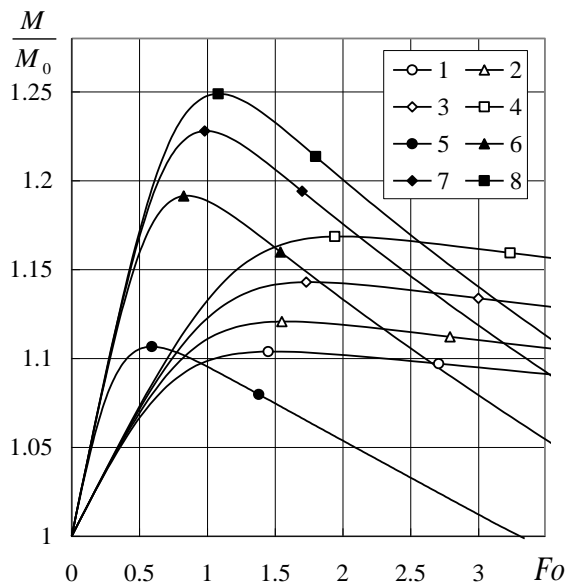
Figure 7 The impact of droplet slipping on its mass growth in condensation regime T_g, K: (1-4) 370, (5-8) 500; $\overline{p}_{g,\infty}$: (1-4) 0.3, (5-8) 0.5; Re_0: (1, 5) 0, (2, 6) 10, (3, 7) 20, (4, 8) 50

CONCLUSION

In humid gas sprayed water compound, interaction of heat transfer processes in transit droplet phase transformation regime is defined by droplet heat transfer and is influenced by gas flow parameters: higher temperature provides intensive droplet heating and leads to higher equilibrium evaporation temperature, while higher humidity defines higher dew point temperature and provides intensive water vapour condensation at the initial stage of condensation regime. Friction forces occurring on the droplet surface that is slipping in gas cause a forced water circulation. This may result in prolonged duration of condensation regime. This is a very important factor for organizing effective heat recovery from humid flue gas of disposal biofuel in contact condensing economizers.

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