Modeling of heat and mass transfer processes in phase transformation cycle of sprayed water into gas:

1. The calculation peculiarities of droplet phase transformation parameters

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Nomenclature

- \( a \) – thermal diffusivity, \( \text{m}^2/\text{s} \);
- \( B \) – Spalding transfer number;
- \( \bar{c}_p \) – mass specific heat, \( \text{J/(kg K)} \);
- \( D \) – mass diffusivity, \( \text{m}^2/\text{s} \);
- \( F_0 \) – Fourier number;
- \( G \) – mass flow rate, \( \text{kg/s} \);
- \( L \) – latent heat of evaporation, \( \text{J/kg} \);
- \( m \) – vapour mass flux, \( \text{kg/(m}^2\text{s)} \);
- \( p \) – pressure, \( \text{Pa} \);
- \( P \) – symbol of free parameter in heat-mass transfer;
- \( \bar{P} \) – droplet dimensionless parameter in heat-mass transfer;
- \( q \) – heat flux, \( \text{W/m}^2 \);
- \( R \) – universal gas constant \( \text{J/(kmol K)} \);
- \( T \) – temperature, \( \text{K} \);
- \( \eta \) – non-dimensional radial coordinate;
- \( \lambda \) – thermal conductivity, \( \text{W/(m K)} \);
- \( \mu \) – molecular mass, \( \text{kg/kmol} \);
- \( \rho \) – density, \( \text{kg/m}^3 \);
- \( \tau \) – time.

Superscripts:

- \(^c\) – droplet centre;
- \(^c\) – convective;
- \(^e\) – equilibrium evaporation;
- \(^f\) – phase change;
- \(^g\) – gas;
- \(^i\) – time index in a digital scheme;
- \(^it\) – number of iteration;
- \(^l\) – index of control time;
- \(^j\) – index of radial coordinate;
- \(^k\) – conduction;
- \(^l\) – liquid;
- \(^m\) – mass average;
- \(^r\) – radiation;
- \(^v\) – vapor;
- \(^0\) – initial state;
- \( \infty\) – far from a droplet;
- \( \Sigma\) – total.

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1. Introduction

Water is widely used in industry and energy sector. Water spraying is the first step towards a modern micro-systems, by which technologies of transfer processes are based on. In these technologies contact area is strongly developed between one-piece carrier (often gas) and dis-cretionary (often liquid droplets or solid particles) medium. Fast change of heat and mass transfer between phases can be organized. The latter is defined by intensity of transfer processes. Therefore, a management of water sprayed technologies requires a deep-knowledge in droplets and in gas two-phase flow transformation processes. Heat and mass transfer processes are closely linked and interact with each other. This interaction is operated by conditions of heat and mass transfer \([1]\). Primary parameters of gas and water are important to define these conditions, because parameters concretizes droplets phase transformation cycle. Droplet phase transformation cycle of pure liquid includes condensation, unsteady evaporation and equilibrium evaporation modes \([2]\). For a condensing phase transformation mode proceeding, the most important water vapor component must be \( \bar{P}_{\infty} = p_{\infty}/(p > 0) \) in carrier gas mixture, and a droplet surface temperature must be lower than a dew point temperature \( T_d = T_v/T_p < 1 \). At condensing phase transformation mode, droplet is heated up by the warmth from the gas in heat exchange process (case \( T_d > T_v \)) and by the warmth of phase transitions, which is released at water vapor condensation time. Therefore, droplet surface layers heats up rapidly. When they heat up till temperature of dew point, phase transformation regime on a surface of the droplet changes into unsteady evaporation. This happens at time moment, when parameter is \( \bar{P}_d = 1 \). At unsteady evaporation mode a part of warmth, which is provided for a droplet by a heat transfer, is used for heating. The other part of warmth participates in process of water evaporation. A droplet which evaporates unsteady heats up till temperature \( T_v \), which describes equilibrium evaporation conditions. Equilibrium evaporation is comprehensible phase transformation case, when all warmth, which is given to a droplet at heat transfer process, evaporates water. Temperature of equilibrium evaporation mode is defined by gas parameters \( T_d \) and \( \bar{P}_{\infty} \) as well as droplet heating conditions \([3]\). In condensating and unsteady evaporation modes a droplet is non-isothermal, and its thermal state at equilibrium evaporation mode is influenced by peculiarities of heat transfer between gas flux and a droplet \([4]\).

A liquid vapor flux intensity factor, is very important in sprayed liquid technologies. This factor describes efficiency of phase transformation. At liquid fuel case vapor flux that spreads from droplets defines a combustion process. Peculiarities of water sprayed technology defines a vapor flux that is required for a water case. Cases of air conditioning, sudden gas cooling and heat recovering of phase transformation from removed smoke can be distinguished. Droplet evaporation process defines efficiency of irrigation and cooling, while a vapor condensation process in smoke determines a heat recovery. Phase transformations that occur on droplets surface raise a structural change of two-phase flow. In order to define them, dynamics of droplets phase transformation should be taken into account, linking warming and weight change of droplet.

This article presents a defining specifics of phase transformation in droplet lifetime cycle, when droplet warms in different gas conditions.

2. Research method

Droplet mass dynamics is defined by vapor flux function on droplet surface:
\[
\frac{dM(\tau)}{dt} = -g^i_\tau(\tau).
\] (1)

In Eq. (1) vapor flux is positive at liquid evaporation mode, when droplet mass decreases. In condensing phase transformation mode a vapor flux, that flows condensates on the surface of the droplet, considered to be negative, then mass of droplet grows. Liquid vapor flux density can be described by analytical model [5]:

\[
m^i_\tau = \frac{D_{\alpha R}}{T^2 R (p_{v,\tau} - p_{v,\infty}) + \mu_s \left( p \ln \frac{p - p_{v,\infty}}{p - p_{v,\tau}} + p_{v,\tau} - p_{v,\infty} \right)}
\] (2)

Then vapor flux function can be defined spherically:

\[
g^i_\tau(\tau) = 4\pi R^3(\tau) m^i_\tau(\tau).
\] (3)

Vapor flux function density \(m^i_\tau(\tau)\) calculation according Eq. (2) is directly related with functions definition and describes the change of droplet surface temperature \(T_d(\tau)\) and its dimension \(R(\tau)\) in a droplet phase transformation. Droplet warming and ongoing phase transformation processes on its surface are closely related and influence one to another. This impact is indirect and reveals through function \(T_d(\tau), R(\tau)\) as well \(m^i_\tau(\tau)\) influence for heat fluxes dynamics on the surface of a droplet.

In droplet phase transformation process, heat flux intensity is defined by a vapor flux density on the droplet surface:

\[q^i_\tau(\tau) = m^i_\tau(\tau) L(\tau).\]

Surrounded energy impact for a droplet is defined by compound heat transfer of a total heat flux density \(q^i_\tau(\tau) = q^i_2(\tau) + q^i_1(\tau)\) in thermal technology at a common case, when \(T_d > T_R\). Total heat flux of convective and radiative components impact for a droplet thermal state have a different mechanisms: convection warmth is given for a surface of a droplet and in radiation heat flux is absorbed in semitransparent droplet [6-8]. The radiation heat flux directly warmth droplet inner layers, but practically has no direct effect for a droplet phase surface temperature function \(T_d(\tau)\). A convective heat flux impact for a droplet surface temperature is direct, but for internal thermal state it is only based on by a partial spreading in a droplet by inner heat transfer. The rest of external convection heat flux participates directly in liquid evaporation process on the surface of a droplet. Heat radiation, that is absorbed by a droplet, can only participate in evaporation process when is leaded out to the surface on the droplet by internal heat transfer. This is possible when a negative temperature gradient field forms [7].

Heat fluxes, that interact on the surface of a droplet, defines function \(T_d(\tau)\). Its description is a key for heat and mass transfer problem, which is known as a "droplet" problem. For that droplet internal and external heat transfer and heat fluxes \(q^i_2(\tau), q^i_2(\tau)\) as well \(q^i_1(\tau)\), that describes intensity of phase transformation are combined by energy flow balance on the droplet surface according to request of transfer processes in quasi-steady state:

\[q^i_2(\tau) + q^i_2(\tau) + q^i_1(\tau) = 0.\] (4)

Eq. (4) requires matching of heat fluxes that flows in and flows out from a droplet surface. But Eq. (4) is a formal expression, therefore it is necessary to specify expression in order to make a "droplet" task numerical solution algorithm. This requires analysis of four droplet heat and mass transfer tasks: 1) case of compound heat exchange in semitransparent droplet; 2) spectral radiation absorption in semitransparent droplet; 3) phase transformation that are set on the surface of a droplet; 4) droplet heating by external convection in phase transitions movement conditions. The first problem solution are functions of unsteady temperature field \(T(\tau, \tau)\) and total heat flux \(q^i_2(\tau), \text{respectively; for the second} a local radiation flux function \(q^i(\tau)\) in a droplet at defined time moments \(\tau\); the third – vapor flux on the surface of a droplet, vapor flux density and heat flux of phase transformations functions \(g^i(\tau), m^i(\tau), q^i(\tau)\); the fourth – a heat flux density function of external convection \(q^e(\tau)\). Each solution of discussed problem requires for already defined answers of remaining problems. This is taken into account during unambiguity boundary conditions formulating. This provides only conditionally independent solutions of separate tasks. At case of combined heat transfer by conduction-radiation in a droplet (4) expression integral - mathematical model is developed in [7] work. It is solved numerically. Initial conditions are defined by parameters \(T_i, R, p, p_{v,\infty}\), heating time \(\tau_i\) of droplet is provided, and in time change interval 0 - \(\tau_i\) index of control time \(l\) is selected that meets condition:

\[
\sum_{i=2}^{l} (r_i - r_{i-1}) = \tau_1.
\] (5)

For each time moment \(\tau_i\) in iterative cycle \(il = 1 - IT\) a droplet surface temperature \(T_{R,i} \equiv T_{R,i,d} = T_{R,i,\tau} = IT\) is selected. Whole number \(IT\) defines the end of iterative cycle. This number provides (4) condition requiring accuracy of the balance \(\delta_q\) iterative cycle is exercised in fastest descent method [2-4, 7, 9]. Rising a high requiring accuracy \(\delta_q < 0.1\%,\) a droplet surface temperature changes of hundredth row must be taken into account [9]. Condition (4) sensitivity for a droplet surface temperature is defined by Eq. (2), which is described as vapor flux logarithmic dependence from generated saturated water vapor pressure on the surface of droplet (in case of condensation from saturated vapor pressure). The latter is a droplet surface function \(p_{v,R} = p(T_R)\). Therefore, water droplet phase transformation cycle is modeled by applying a strict Gerry empirical correlation between saturated water vapor and temperature [10].

Defining heat fluxes in Eq. (4) at selected time moments \(\tau_i\) it is necessary to dispose with dimension of droplet size. At spherical assumptions case, this is droplet diameter \(2R\) defined by droplet rays \(R\). An inconvenience of numerical scheme formation is that droplet volume, in rigorous assessment, can only be defined when iterative cycle ends by modified expression (6):
A problem of droplet dimension definition in common iteration is solved by making assumptions. It is necessary to avoid potential iterative cycle instability problem. The latter is related with hardly programmed by (2) expression vapor flux values, when random temperatures \( T_{R,i,j} \) are selected at each iterative cycle initial state. When \( R_{i+1} = R_0 \) and in \( j > 1 \) cases \( R_{j,i} \) are defined in previous iterative cycles, it is popular to apply a droplet dimension stability assumption \( R_{j,i} = R_{j-1} \). Then a change of droplet diameter is calculated just before next iterative cycle. When droplet surface temperature \( T_{R,i,j} \) and radius \( R_{j,i} \) parameter are selected for ordinary iteration, then heat fluxes in Eq. (4) are described by defined functions [3, 7, 11]:

\[
\begin{align*}
q_{v,j,i}^+ &= f_v \left( m_{R,j,i}^+, \tau_{j,i}^+ \right) , \\
q_{v,j,i}^- &= f_v \left( T_{R,i,j} , R_{j,i}^0 , N_{u,j,i} , B_{j,i} \right) , \\
q_{c,j,i}^- &= f_{c_k} \left( \frac{\partial T_{v,j,i}}{\partial r} , \tau_{j,i}^+ , \rho_{j,i} , \eta , \rho_{j,i}^0 \right) , \\
q_{v,j,i}^- &= f_{c_k} \left( \frac{\partial T_{v,j,i}}{\partial r} , \tau_{j,i}^+ , \rho_{j,i} , \eta , \rho_{j,i}^0 \right) ,
\end{align*}
\]

(7)

Phase transformation heat fluxes and external convection intensity of heat fluxes are inversely proportional to radius of spherical droplet, when translucent droplet decreases a radiation absorption sulphocare in them [3, 7, 12]. Therefore, in "droplet" studies for assessment of assumption of droplet dimension stability requires for comprehensive numerical research of phase transformation cycle and systematic evaluation of results. Droplet heat transfer and phase transformation parameters are appropriate to combine in groups of thermal \( P_T \), energetic \( P_v \), dynamic \( P_d \) and phase transition \( P_I \) [13]. Different impact of assumption \( R_{j,i} = R_{j,i-1} \) is expected for each group parameters. In order to highlight this impact a consistent way of evaluation is suppositional, when \( R_{j,i} = R_{j-1} \) assumption is applied in numeric scheme calculating for selected group parameters, and in other groups a condition \( R_{j,i} = R_{j,i-1} \) remains the same. Phase transformation parameters are often important in thermal technologies of water spraying. A liquid vapor flux on the surface of the droplet \( g_v^+ \) and its density \( m_v^+ \) are assigned for them, as well they defining a droplet mass \( M \), volume \( V \) and radius \( R \) dynamics in droplet phase transformation cycle. A ray dynamics numerical scheme is formed in Eq. (6) basis:

\[
\begin{align*}
\frac{d[R(t)V(t)]}{dt} = \frac{4}{3} \pi \frac{d[R(t)R^3(t)]}{dt} = -g_v^+ (t) ;
\end{align*}
\]

\[
\begin{align*}
\frac{d[R(t)]}{dt} &= -\frac{1}{\rho_v(t)} \left[ m_V^+ + \frac{R(t)}{3} \frac{d[R(t)]}{dt} \right] .
\end{align*}
\]

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\]
Because of valid condition $T_0/T_\infty < 1$, therefore water droplet phase transformation cycle begins at condensing mode, which will be consistently replaced by unsteady and equilibrium evaporation modes. The time scale is formed for phase transformation modes in numeric schemes cycle $\tau = 0 - \tau_{i0} - \tau_{io} - \tau_i$. They are taken into account individually, but equivalent modes importance in cycle treatment principle is applied. Time scale is expressed by Fourier number $Fo = \left(\alpha_0 / R_0^2\right) \tau_i$ and unsteady phase transformation cycle is $F_0 = 0 - F_{o0}, R_0 - F_{oi}, R_0$ modelled. Heat transfer cycle in "k" case is considered to be supporting for affect evaluation of droplets heat transfer conditions

$$F_{o_k} = 0 - F_{o0_k} - F_{o_k} - F_{oi_k}.$$  

(14)

It is important, because sprayed water temperature $T_0$ and gas parameters $T_d$ as well $\overline{\rho}, \overline{c_v}$ in defined cases are independent from a droplet dispersity. Here impact of Knudsen layer for heat transfer and phase transformation can be denied [9]. $F_{o_k}$ criteria determines time of phase transformation mode cycle and serves for creation of unit time phase transformation cycle $\overline{F}_{o_k} = 0 - 1 - 2 - 3$, where $\overline{F}_{o_k} = f(Fo, F_{o_k})$ [2]. Modeled phase transition mode values of $\overline{F}_{o_k} = (i-1)/(I-1)$ are defined by whole number $I$ of control time index, where $\overline{F}_{o_0} = 0$ describes the beginning of phase transformation mode and $\overline{F}_{o_1} = 1$ refers its end. Condensing and unsteady evaporation modes are modelled for case $I = 41$. Individual time grid for each mode are defined according to scheme $\overline{F}_{o_k} \rightarrow \overline{F}_{oi_k} \rightarrow \tau_i$. Necessary values of numbers $F_{o_k}$ were guessed. They can be selected according to [14, 15] recommendations.

$$\Delta_T = T_{R,B} - T_{R,B,IT}$$

In iterative cycles for ensuring Eq. (4) conditions requirement by accuracy of $\Delta_T = \pm 0.04\%$ (Fig. 1, 2), a droplet surface temperature change at hundredth degree
series must be taken into account (Fig. 3). In primary stage of condensing phase mode \( F_{o} ≡ 0 - 4 \) a calculated intensity of droplet warming heat flux \( q_{i} = q_{i}^{+} + q_{i}^{-} \) is higher in case \( R_{i,\alpha} ≡ R_{i,\alpha - 1} \), while in final stage this intensity is higher at \( R_{i,\alpha} ≡ R_{i - 1} \) case (Fig. 4, a). This initial phase stage for energy assessment is more significant in condensing mode, therefore in case \( R_{i,\alpha} ≡ R_{i,\alpha - 1} \) a droplet surface warmth first up to dew point temperature (Fig. 4, b). Durations of condensing phase transformation mode were qualified by additional numerical research:

\[
F_{o,b}^{k}, k = 0.722, \quad R_{i,\alpha} ≡ R_{i,\alpha - 1} \quad \text{and} \quad F_{o,b}^{k}, k = 0.771 \quad \text{when} \quad R_{i,\alpha} ≡ R_{i - 1}.
\]

In both cases a droplet central and surface layers warming dynamics is different: a droplet surface layers warming rate rapidly suffocates, while central layers warming rate grows at the beginning of condensing mode and at the moment \( F_{o} ≡ 0.2 \) it reaches maximum (Fig. 5). Then gradually suffocates, remaining greater than surface warming rate. Therefore a bright non-isothermal observes at condensation mode in a droplet (Fig. 4, b). Droplet heating (Fig. 5) and phase transformation (Fig. 6) speed dependence from droplet dimension selection method in iterative cycle causes a bright calculated droplet diameter changes for assumptions \( R_{i,\alpha} ≡ R_{i,\alpha - 1} \) and \( R_{i,\alpha} ≡ R_{i - 1} \) cases. (Fig. 7).

Unsteady phase transformation mode \( 0 - 1 - 2 \) is modeled in its numeric scheme for condensing mode maintaining the previous time grid, and for nonstationary evaporation time grid is formed in whole number \( I = 30 \) basis. Value \( \tau_{i - 1} \) represents the end of condensation mode, which coincides with the beginning of unsteady evaporation regime. By equilibrium evaporation conditions approaching asymptotically.

\[
\frac{dT}{dF_{o}} = \frac{T - T_{r}}{F_{o} - F_{o,i - 1}}; \quad i > 1
\]

\[
3 \quad T = T_{r}; \quad 4 \quad T = T_{c}
\]

![Fig. 4 Change of heat fluxes (a) and droplet thermal state (b) in condensation mode at "k" case of heat transfer: 1 - \( R_{i,\alpha} ≡ R_{i - 1} \), 2 - \( R_{i,\alpha} ≡ R_{i,\alpha - 1} \)]

![Fig. 5 Change of droplets surface and central layers warming rate in condensation mode]

![Fig. 6 Change of vapor fluxes and its density on a droplet surface in condensation phase transformation mode]

\[
g_{v,0}^{*} = 8.03 \cdot 10^{-9} \quad \text{kg/s}; \quad m_{\nu,0}^{*} = 0.1136 \quad \text{kg/(m}^{2}\text{s})
\]

Therefore a beginning of equilibrium evaporation definition requires for agreement of remaining condition.
When this condition is being satisfied evaporation is considered to be equilibrium. This condition can be defined according calculated droplet surface temperature deviation from theoretical temperature, that ensures equilibrium evaporation $T_{R,e} - T_e < \Delta T_{R,e}^{\text{iso}}$ or by permissible non-isothermally $T_{R,e} - T_C < \Delta T_{R,e}^{\text{iso}}$ [15]. At discussed primary conditions droplets that are heated by conductivity in unsteady phase transition mode warmth to $T_{m,e} = T_{R,e} \approx 348.565$ K. Condition $\Delta T_{R,e}^{\text{iso}} = 0.01$ K. is provided for equilibrium evaporation. For guessed $F_{o,y}^{eq,rho} \equiv 3$ the duration of unsteady phase transformation $Fo_{eq,rho}$ is defined graphically (Fig. 8): 2.27 and 2.07 for conditions $R_{o,\beta} \equiv R_{o,1}$ and $R_{o,\beta} \equiv R_{o,1-1}$, respectively. Then unsteady evaporation duration $Fo_{eq,rho}^{eq,rho} = Fo_{eq,rho}^{eq,rho} - Fo_{eq,rho}^{eq,rho}$ is defined: 1.5 and 1.35, respectively.

$$\Delta T_{R,e}, K$$

![Fig. 7 Influence of assumptions $R_{o,\beta} \equiv R_{o,1-1}$ and $R_{o,\beta} \equiv R_{o,1}$ for calculated droplet diameter dynamics in condensation phase transition mode](image)

Droplet phase transformation cycle 0 – 1 – 2 - 3 is modeled in numeric scheme for condensing and unsteady evaporation mode maintaining the previous time grid. For equilibrium evaporation mode a time grid is formed in base of whole number $I = 50$. Here $\tau_{1,1}$ represents the beginning of equilibrium evaporation mode, which matches with the end of unsteady phase transformation mode. The duration of equilibrium evaporation $Fo_{eq,rho}^{eq,rho}$ is 23.53 for $R_{o,\beta} \equiv R_{o,1}$ and 34.63 for $R_{o,\beta} \equiv R_{o,1-1}$, respectively. These durations were selected in numerical research in order that in $i = 121$ iterative cycle must ensure a droplet evaporation.

A phase transformation cycle is defined according to "k" heat transfer modeling results: 0 - 0.771 - 2.27 - 25.8 when $R_{o,\beta} \equiv R_{o,1}$ and 0 - 0.722 - 2.07-36.7, when $R_{o,\beta} \equiv R_{o,1-1}$. Droplet dimension selection method influence for comparative evaluation of the main phase transformation parameters for $R_{o,\beta} \equiv R_{o,1}$ and $R_{o,\beta} \equiv R_{o,1-1}$ cases are given in (Table). Nonvalidity of assumption $R_{o,\beta} \equiv R_{o,1}$ application for droplet phase transformation cycle in "k" heat transfer case modeling is highlight.

<table>
<thead>
<tr>
<th>Table</th>
<th>Comparative evaluation of the main phase transformation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{o,\beta} \equiv R_{o,1-1}$</td>
</tr>
<tr>
<td>$R_{o,1} \cdot 10^{-6}$, m</td>
<td>83.31</td>
</tr>
<tr>
<td>$M_{ho,rho} \cdot 10^{0}$, kg</td>
<td>19.078</td>
</tr>
<tr>
<td>$F_{o,y}^{eq,rho}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$R_{o,1} \cdot 10^{-6}$, m</td>
<td>82.3</td>
</tr>
<tr>
<td>$m_{ho,rho}^{eq,rho}$, kg/(m²·s):</td>
<td>0.02388</td>
</tr>
<tr>
<td>$g_{ho,rho}^{eq,rho} \cdot 10^{-7}$, kg/s</td>
<td>0.0203</td>
</tr>
<tr>
<td>$M_{ho,rho} \cdot 10^{0}$,kg</td>
<td>18.008</td>
</tr>
<tr>
<td>$F_{o,y}^{eq,rho}$</td>
<td>23.53</td>
</tr>
</tbody>
</table>

It was state that in combined droplet heating case by conductivity-radiation, absolutely black body radiation source radiates air temperature. Due to peculiarities of radiant flux absorption in droplets, at combined heat transfer case a droplet phase transformation cycle depends from droplets dispersity. A quantitative indicators of the cycle that are listed below valid only for modeled $2R_{o,1} = 150 \cdot 10^{-6}$ m droplet diameter. A comparative analysis of modeled "k" and "k+\rho" cases gives a qualitative assessment. For combined heat transfer case a time grid of individual phase transformation in numerical schemes formulation methodology was kept the same as for conduction heating.

Due to additional heat flux from radiation source a condensing mode becomes shorter in "k+\rho" case: $Fo_{ho,rho}^{eq,rho}$ = 0.764 when $R_{o,\beta} \equiv R_{o,1}$ and $Fo_{ho,rho}^{eq,rho}$ = 0.713 when $R_{o,\beta} \equiv R_{o,1-1}$. Because of intense surface layers warming, bright non-isothermally is proper for droplet in condensation mode. Peculiarities of droplet surface and central layers warming rate (Fig. 5) causes a formation of non-isothermal peak at the beginning of unsteady evaporation (Fig. 9). It observes in all heat transfer modes and is the same at qualitative assessment. At compound heat transformation case a radiation heat flux that is absorbed in a droplet thermal more droplet central layers (Fig. 10). This
forms assumptions for the second non-isothermal peak (Fig. 10). In case of "k+r" droplet begins to evaporate equilibrium at the second non-isothermal peak formation time, when \( \Delta T_{k+r}(\tau \equiv \tau_0) \equiv \Delta T_{\text{max},2} \). According to that Fourier number \( F_{\text{o},k+r} \) is defined: 3.16, when \( R_{i,1} \equiv R_{i-1} \) and 2.91, when \( R_{i,1} \equiv R_{i-1} \). Then time of unsteady evaporation mode \( F_{\text{o},k+r} \equiv F_{\text{o},k+r} - F_{\text{o},k+r} \) is 2.396 and 2.197, respectively.

In the end of unsteady evaporation a temperature gradient inside a droplet provides full heat that is absorbed by radiation output to droplet surface by conductivity; therefore all external compound heat flux, starts participate in evaporation process whose intensivity is reflected by its density \( q_\Sigma = q_i + q_r \) (Fig. 11).

Phase transformation cycle duration \( F_{\text{o},k+r} \) is defined by numerical research: 23.53, when \( R_{i,1} \equiv R_{i-1} \) and 34.63, when \( R_{i,1} \equiv R_{i-1} \). Then equilibrium evaporation mode \( F_{\text{o},k+r} \equiv F_{\text{o},k+r} - F_{\text{o},k+r} \) lasts 22.86 and 34, respectively. At equilibrium evaporation mode droplets decreases rapidly (Fig. 12), therefore the influence of radiation source fades away and non-isotermality suffocates at a droplet.

According to generalized "k+r" heat transfer modeling results, as well in case "k", a weakness of assumption \( R_{i,1} \equiv R_{i-1} \) application for phase cycle modeling, was highlight. The results were confirmed by different calculating methods of droplet mass dynamics in Fig. 12, curves 4 and 5: curves 4 are formed by numerical scheme that is based on by a model of droplet mass change Eq. (13) and curves 5 are based on by linking droplet mass and volume of non-isothermal droplet mass medium density \( M_l \equiv V_l \rho_{l,m} \).
Water density is selected by expression (11), which describes temperature \( \rho_{in} = \rho_{i}(T_{in}) \). Functions \( M(Fo) \) graphs match on assumptions \( R_{i,it} = R_{i,it-1} \) case and for \( R_{i-it} = R_{i-it-1} \) case are markedly different (Fig. 12).

4. Conclusions

A droplet diameter selection method in iterative cycle importance at humid air sprayed water phase transformation cycle impact for modeling results of droplet heating by conduction and combined heating by conduction-radiation, was highlighted.

Assumption \( R_{i-it} = R_{i-it-1} \) that was applied in numeric schemes for phase transformation parameters \( P_{i} \) can be extended in thermal \( P_{i} \), energy \( P_{i} \), and dynamic \( P_{i} \) droplet parameters at numerical calculation algorithms.

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ŠILUMOKAITOS IR MASĖS PERNASOS PROCESŲ MODELIAVIMAS DUJOSE IŠPURKŠTO VANDENS FAZINIU VIRŠMU CIKLE. 1. LAŠĖLIO FAZINIU VIRŠMU PARAMETRŲ APSKAIČIAVIMO SAVITUMAI

Re ziumė

Skaitiskai sumodeliuotas drėgname ore išpurkšto vandens lašelių nestacionarųjų fazinių viršmių ciklas, apjungiantis kondensacijin ir nestacionarajį garavimo režimus. Įvertinta lašelio skersmo kirimo iteraciniame cikle būdo įtaką apskaičiuojuosi lašelio fazinių viršmių parametrams. Atliekta palyginimo analizė, kai iteraciniame cikle pritaikoma lašelio stambumo pastovumo sąlyga arba eilinėje iteracijoje naudojamas buvusioje iteracijoje apibrėžtas lašelio skersmuo. Fazinių viršmių ciklas sumodeliuotas lašėliams bei jų sudėtiniu šildymu laidumui ir spinduliuvo atvejais. Pagrįstas lašelio stambumo pastovumo iteraciniame cikelio prielaidos netinkamumas „lašo“ uždavinio skaitinio sprendimo algoritme.
An unsteady phase transformation cycle of sprayed water droplets was numerically modelled in humid air. This cycle combines condensing and unsteady evaporation modes. Method influence of droplet diameter selection in iterative cycle was estimated for calculated droplet phase transformation parameters. A comparative analysis of modeling results was performed, when a droplet coarseness stability condition is applied in iterative cycle or droplet diameter is used in ordinary iteration, when it was defined in former iteration. Phase transformation cycle was modelled for droplets in combined conduction-radiation case. Assumption of droplet size stability in iterative cycle inadequacy at ‘droplet’ task numerical solution algorithms.

Keywords: water droplets, phase transformation cycle, condensation, evaporation.

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