



INFLUENCE OF SPRAYED WATER TEMPERATURE ON HEAT AND MASS TRANSFER PROCESSES IN THE HUMID GAS

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Abstract. *The paper discusses modelling of water droplets combined heat and mass transfer in a humid gas. Combined analytical and numerical method of investigation is applied. Securing balance of energy fluxes in the droplet with confidence of one hundredth of percent and using the method of fastest descent the droplet surface temperature is selected. The influence of sprayed water temperature and black body spectral radiation of gas temperature on droplets heating and evaporating are evaluated. The effect of sprayed water temperature has been highlighted.*

Keywords: *humid gas, water droplet, evaporation and condensation, combined heat and mass transfer, modelling*

1. INTRODUCTION

Humid flue gas is generated in the fuel combustion process. Humidity can be accumulated in gas artificially, when water vapour is used in liquid fuel spray technologies, and when water is sprayed into a furnace due to ecological considerations aiming to reduce nitrogen oxide emissions into the atmosphere using a regulation of a combustion torch temperature. Water vapour in products of biofuel combustion can dominate. The more humid gas is, the more significant part of its enthalpy is constituted by the component related to water phase transformations that can be exerted from flue gas in the water vapor condensation process only. Traditionally, heat from flue gas is utilized in the expensive recuperative heat exchangers. Application of exhaust flue gas utilization technologies based on direct injection of water is perspective (Miliauskas and Sinkunas, 2010). Two phase water droplets-humid gas flows are also met in important thermal processes such as precipitant cooling of high temperature gas flow; waste heat utilization in ventilation; heat exchangers of building HVAC systems; air humidifying and drying in evaporation chambers of air conditioning systems; fire extinguishing in fire fighting, etc.

Conditions of water droplets heating and evaporation in the humidity gas can be different: droplets slipping in the gas flow will be heated by convection, droplets flowing in gas will be heated by conduction and surrounding radiation determines the case of combined heating. Direct experiment for investigation of complex heat transfer in droplets is complicated. Applied research methods discussed in detail (Sazhin, 2006). Droplets initial temperature and dispersity are very important aspects. The initial droplet temperature determines peculiarities of vapour flow on the droplet surface and can establish assumptions for vapour condensation process in the initial stage of droplet heating and determine phase change variation in the following stage of droplet heating. For the smallest droplets with diameter of microns it is necessary to evaluate the influence of Knudsen layer for droplet evaporation. In the case of largest droplets the influence of surroundings radiation must be evaluated. Each of these factors contributes essential peculiarities for heat and mass transfer modelling (Miliauskas, 2001; Miliauskas and Garmus, 2009). Modelling results of larger droplets heating and phase change on their surface in humid gas are presented in this paper.

2. NUMERICAL RESEARCH METHOD

The combined analytical and numerical research method for the droplet heating and evaporation is applied (Miliauskas, 2001). In this method the digital scheme of non-stationary temperature field in semitransparent evaporating droplet for combined radiative-conductive heat transfer is constructed not for the primary systems of differential and integral equations, but for its solutions – the system of algebraic and integral equations. Avoidance of indeterminacies, related to selection of time and coordinate steps, and reliable control of research scheme's convergence are main advantages of this method. The droplet surface temperature is determined by heat flow interaction at the surface. This temperature must secure the heat flux in-flow and out-flow balance. Assumption of heat and mass transfer process quasi-stacionarity enables to describe the heat flow balance by the condition:

$$\bar{q}_k^+ + \bar{q}_k^- + \bar{q}_f^+ \equiv 0; \frac{\lambda_{vg}}{R} (T_g - T_R) \cdot \ln \frac{1+B_r}{B_r} - \lambda \frac{\partial T(r, \tau)}{\partial r} \Big|_{r=R^-} = m_v^+ L \quad (1)$$

Logarithmic function of Spalding heat transfer number

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$$B_T = \frac{c_{p,v,g}(T_g - T_R)}{L} \left(1 + \frac{q_k^-}{q_k^+} \right) \quad (2)$$

in the Eq. (1) takes into account the effect of Stefan hydrodynamic flow on the intensity of convective heating of evaporating droplet. It is assumed that there is no phase slippage in humid gas flow carrying water droplets and semitransparent droplet surface does not absorb radiation. Water circulation in the droplet has not been considered. The temperature gradient in the droplet is described by expression:

$$\frac{\partial T(r, \tau)}{\partial r} \Big|_{r=R^-} = \frac{2\pi}{R^2} \sum_{n=1}^{\infty} n(-1)^n \int_0^{\tau} \left[(-1)^n \frac{R}{n\pi} \frac{dT_R}{d\tau_*} + \frac{1}{R\rho c_p} \int_0^R (\sin n\pi\eta - n\pi\eta \cdot \cos n\pi\eta) q_r dr \right] \exp \left[-a \left(\frac{n\pi}{R} \right)^2 (\tau - \tau_*) \right] d\tau_* \quad (3)$$

Flux of radiation in Eq. (3) is calculated according to methodology (Miliauskas, 2001) and the complex refractive index of water is used in accordance with (Hale and Querry, 1973) recommendations. The water vapour flux intensity at the droplet surface is described by expression (Kuzikovskij, 1970):

$$m_v^+ = \frac{D_{vg} \mu_v}{T_R R_\mu R} \left[p_{v,R} - p_{v,\infty} + \frac{\mu_v}{\mu_g} \left(p \ln \frac{p - p_{v,\infty}}{p - p_{v,R}} + p_{v,\infty} - p_{v,R} \right) \right] \quad (4)$$

The droplet surface temperature determines the regime of phase transformations – when it is below the dew point temperature the water vapour of humid gas condenses on the droplet surface. When heated droplet surface temperature exceeds the dew point temperature the regime of phase transformation changes and droplet starts to evaporate. Gas humidity is defined as $\bar{p}_v = p_{v,\infty} / p$. The volume change of spherical droplet is determined by:

$$\frac{4}{3} \pi \frac{\partial(\rho R^3)}{\partial \tau} = -g_v^+ = -4\pi R^2 m_v^+ \quad (5)$$

The thermal state of droplet is predicted to calculate for the optional moment of time τ . For the time of interval $0 \div \tau$ finite whole number I of intermediate time moments τ_i is selected: $\tau_i = 0$ when $i = 1$, and $\tau_i = \tau$, when $i = I$. In the droplet, a finite whole number J of control droplet cross-sections is selected freely and the position of the cross-sections in variable volume of the droplet is defined by dimensionless universal $\eta = r/R$ coordinate: $\eta_j = 0$ when $j = 1$ and $\eta = 1$, when $j = J$. The temperature of warming and evaporating droplet at chosen fixed time τ_j is selected according to the numerical scheme of the expression (1) by iterative calculations, which is performed using the method of fastest descent assigned for finding the value of droplets surface temperature $T_{R,I}$, that would guarantee iterative minimal energy fluxes imbalance on the droplet surface $\delta < 0.01\%$.

3. RESULTS AND DISCUSSION

The analysis has been conducted for water droplets of various initial temperatures in the humid gas (flue gas) of 873 K and 0.1MPa. Conductive heating has been modeled assuming that droplets in gas are stagnant. In the case of combined heating by conduction and radiation the external black body radiative source with gas temperature has been assumed. Gas temperature and composition of gas mixture does not change due to warming and evaporation of droplets. The Gerry empirical equation was applied for definition of water saturated vapour on the droplet surface.

Thermal state of droplet varies during phase transformation process (Fig. 1-2). One can notice qualitatively common tendencies temperature field $T(r, \tau)$ of evaporating droplets. When defining thermal state of a warming droplet, the following functions of characteristic temperature variation are important: surface temperature $T_r(\tau)$, centre temperature $T_c(\tau)$ and mean mass temperature of the droplet $T_m(\tau)$. Surface temperature of droplets is important for heat and mass transfer between droplets and gas flow; temperature difference between droplet centre and surface defines non-isothermality of the droplet, which can cause natural circulation inside it. The rate of change of the mean mass temperature indicates the intensity of heat flow, which warms the droplet. Variation of thermal state of evaporating droplet is very active during the mode of unsteady phase transformation. At the beginning surface layers of the droplets warm rapidly, later the rate of their warming decreases and, as central layers of the droplets warm rapidly, non-isothermality of the droplets decreases. The thermal state of equilibrium evaporating droplets is close to isothermal and independent of size of the conductively heated droplets (Fig. 1a). Smaller droplets have already reached equilibrium evaporation conditions; bigger droplets are still warming intensively. Though the change of temperature field in droplets and the duration of unsteady phase transformations significantly depend on size of droplets, dynamics of

warming of droplets of various diameters is identical in the time scale, expressed by Fourier number (Fig. 1b). This conclusion is confirmed in all modelled cases of thermal state change of different – size conductively heated droplets, as boundary conditions regarding sprayed liquid temperature and gas parameters are identical for droplets of various sizes. Hence, in Fourier numbers based scale the characteristic centre, surface and mean mass temperatures curves indicate warming dynamics of infinite set of water droplets. It is important to note that all heat and mass transfer parameter changes can be described by some characteristic curves when the droplets are heated conductively. It is necessary to express the desired parameter in normalized form in correspondence to the Fourier number. Usually, for parameter normalization, the initial state and equilibrium evaporation values are used (Miliauskas; et. all, 2008). To compile specific parameter characteristic curves for the conductively heated droplet it is sufficient to model the evaporation process of a freely chosen droplet. Because of this, the extent of the initial numerical experiment can be significantly reduced. After the characteristic curves are calculated, all that remains is to model evaporation of the droplet in randomly chosen boundary conditions of heat exchange and to use the comparative method in order to evaluate the influence of more complicated heat transfer conditions in terms of their impact on the transfer processes interaction (Fig. 2-3).

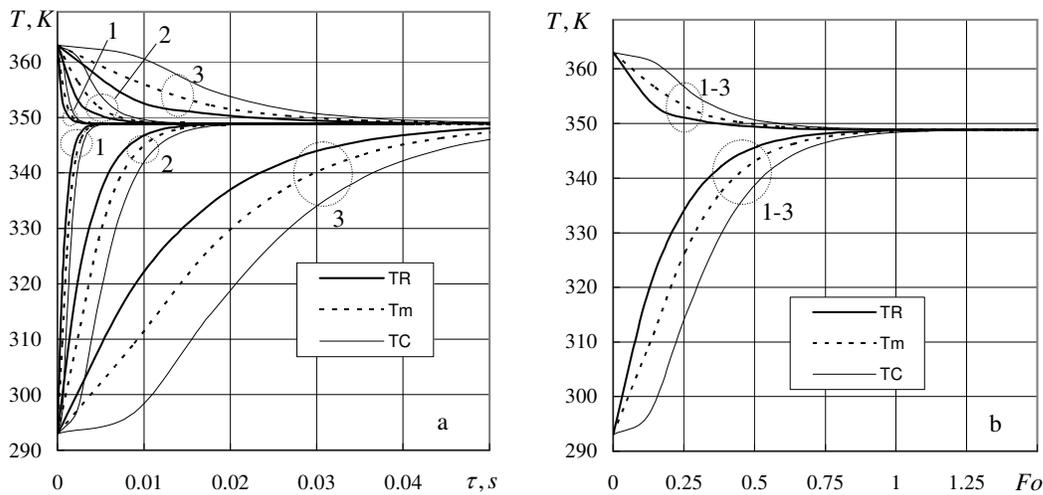


Figure 1. Variation of characteristic temperatures of an unsteady temperature field in conductively heated water droplets in real time (a) and Fourier number (b) scales. $\bar{p} = .25$; $R \cdot 10^{-6}$, m: (1) 25, (2) 50, (3) 100.

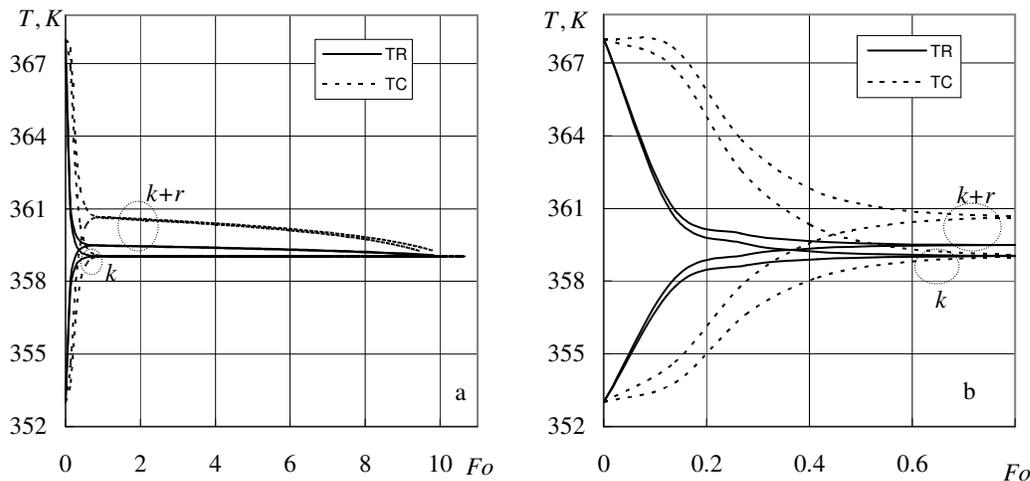


Figure 2. The influence of initial water temperature and droplets heating manner on droplets thermal state: (a) phase transformation regime; (b) unsteady phase transformation regime. $R_0 = .0001$ m; $\bar{p} = .5$.

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The droplet evaporation process strongly depends on sprayed water temperature (Fig. 3). Radius of the low initial temperature droplets increases during the primary stage of phase transformations (Fig. 3a) due to vapour condensation on their surfaces (Fig. 3b) and expansion of warming water. The droplet radius is increasing for certain duration due to expansion of warming water during the initial stage of the droplet evaporation regime. The evaporating droplet radius starts to decrease when the process of water evaporation exceeds water expansion process. The effects of above mentioned competing processes to the dynamics of droplet radius reach equality and are visible on the radius dynamics curve as an extreme point (Fig. 3a). The droplet radius of high initial water temperature does not have volume expansion stage and its volume starts to decrease immediately. Rapid radius decrease is caused by intensive evaporation process and shrinkage of cooling water. Water droplets quite quickly reach equilibrium evaporation regime (Fig. 2).

The equilibrium evaporation temperature is reached by intensive droplet heating for low initial temperature droplets and intensive cooling for high initial temperature droplets (Fig. 1-2). Intensive heating of low initial temperature droplets up to dew point temperature is caused by intensive vapour condensation process (Fig. 3b).

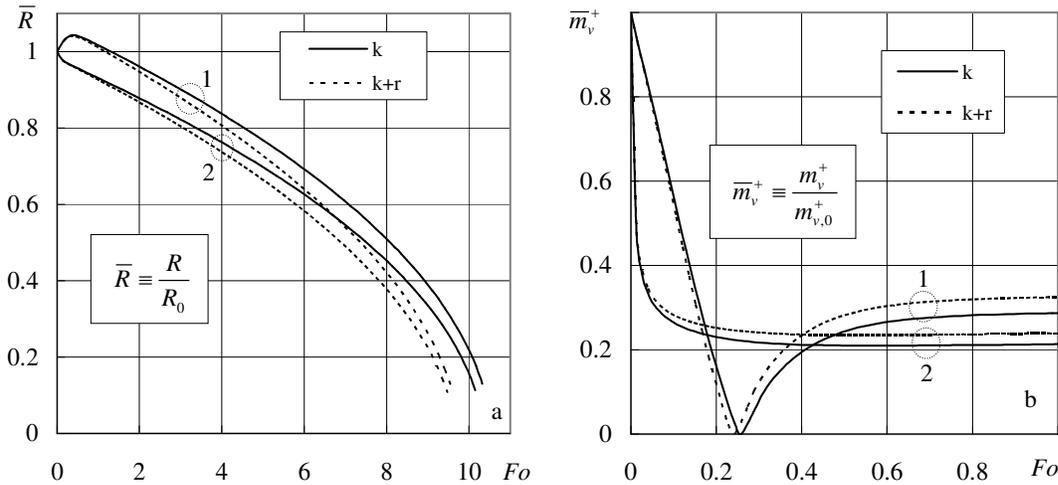


Figure 3. The influence of initial water temperature and droplets heating manner on droplets evaporation (a) and vapour flux (b). T_0 , K: (1) 293, (2) 368; $m_{v,0}^+$, kg/m²s: (1) .2796, (2) .3875; $R_0 = .0001$ m; $\bar{p} = .5$.

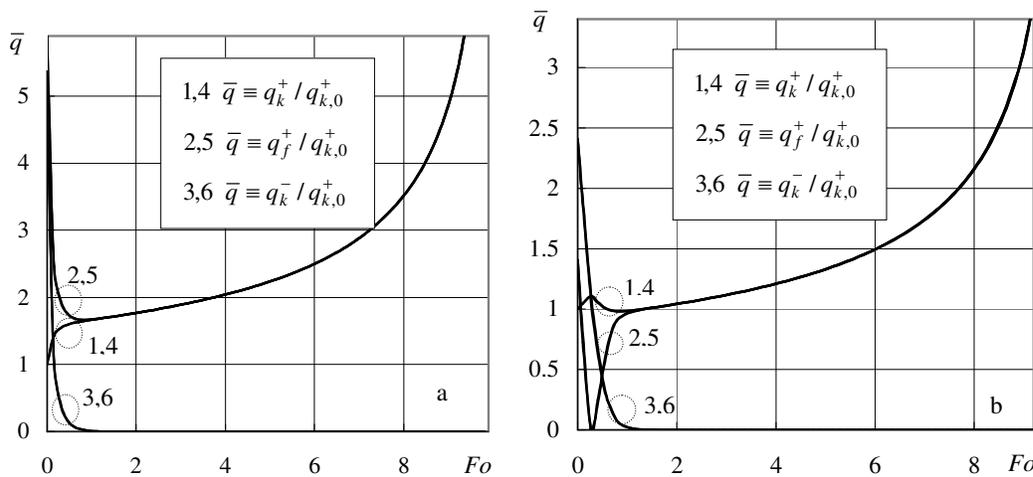


Figure 4. Variation of heat fluxes in surface conductively heated high (a) and low (b) initial temperature water droplets in Fourier number scale. $R \cdot 10^6$, m: (1-3) 50, (4-6) 75; $\bar{p} = .25$; T_0 , K: (a) 363, 293.

When the droplet is heated conductively, then the intensity of water warming is determined by conductive heat flux on the internal side of the droplet surface (Fig. 4), and in the case of combined heating – by the total heat flux (Fig. 5, 6). During the unsteady phase transformations not only the droplet temperature changes rapidly, but also the

heat fluxes at the droplet surface change significantly. This is caused by the initial water droplets temperature and by the way of heating.

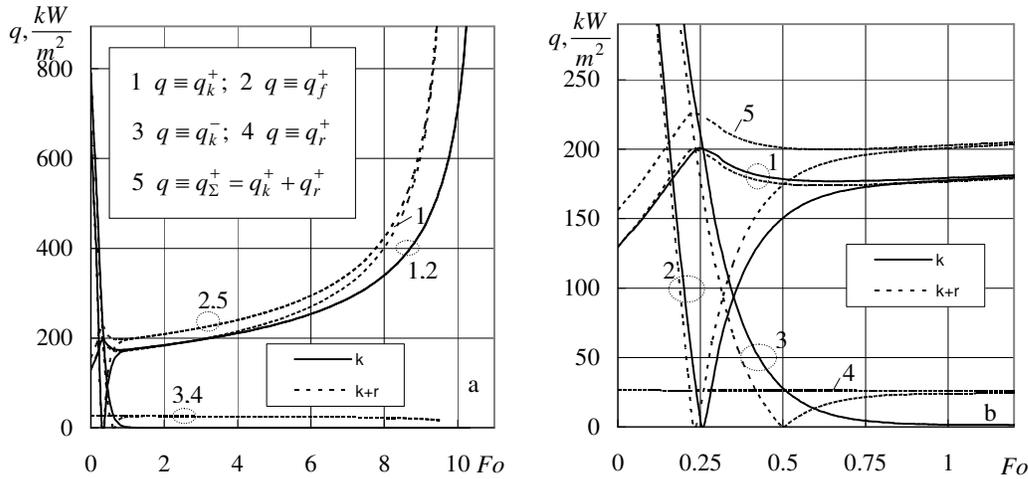


Figure 5. The influence of droplets heating manner on heat fluxes dynamics in surface of low initial temperature water droplets: (a) phase transformation regime; (b) unsteady phase transformation regime.

$$R_0 = .0001 \text{ m}; \bar{p} = .5; T_0 = 293 \text{ K}.$$

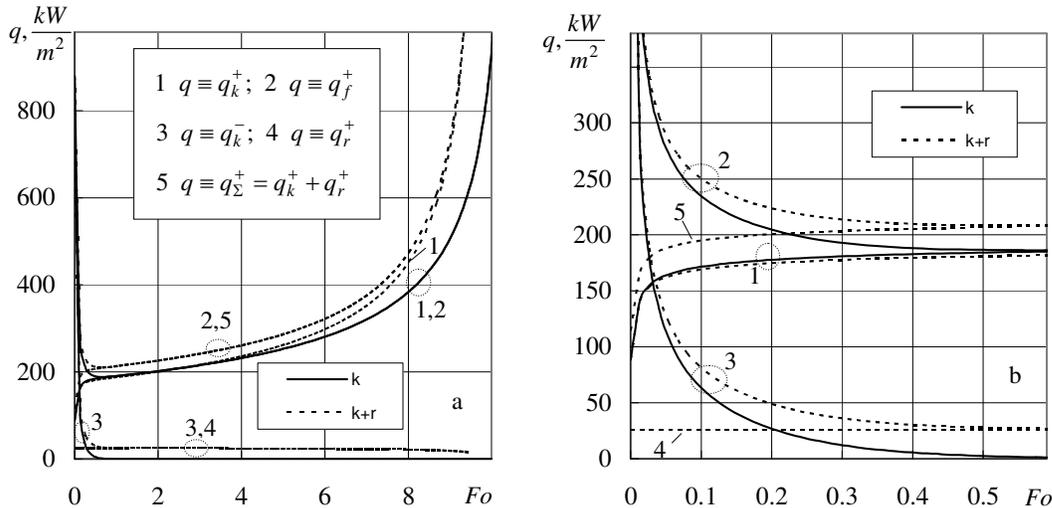


Figure 6. The influence of droplets heating manner on heat fluxes dynamics in surface of high initial temperature water droplets: (a) phase transformation regime; (b) unsteady phase transformation regime.

$$R_0 = .0001 \text{ m}; \bar{p} = .5; T_0 = 368 \text{ K}.$$

The initial water temperature determines peculiarities of heat fluxes change on the droplet surface. Function of radiation heat flux $q_r(Fo)$ for high low initial temperature water droplets and high initial temperature water droplets differs only quantitatively (Fig. 5, 6). Comparison of heat flux functions $q_k^+(Fo)$, $q_k^-(Fo)$ and $q_f^+(Fo)$ for low initial temperature water droplets and high initial temperature water droplets in unsteady evaporation process differs quantitatively and qualitatively. For conduction heat flux q_k^- such difference is very obvious. Value of q_k^- for high initial temperature water droplets during unsteady evaporation reduces to radiation heat flux value q_r (Fig. 6) For the low initial temperature water droplets value q_k^- during unsteady phase change regime (condensation and evaporation regimes) initially reduces to zero, but later enhances up to value q_r (Fig. 5). Heat flux q_f^+ of high initial temperature

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water droplets continuously increases during evaporation process (Fig. 4a, 6). For low initial temperature water droplets value q_f^+ initially during condensation regime reduces to zero (Fig. 4b, 5), but later during unsteady evaporation regime enhances up to value q_k^+ (Fig. 4) or enhances up to value q_Σ^+ (Fig. 5) and later continuously increases during equilibrium evaporation process. During the equilibrium evaporation regime the influence of sprayed water temperature is only quantitative.

4. CONCLUSIONS

The regime of unsteady phase transformations for interaction of heat and mass transfer processes in sprayed water systems is very significant. The way of droplet heating, water initial temperature and gas humidity have an important role during this phase transformation regime. Nonetheless, the initial water droplet temperature does not influence heat transfer processes during the equilibrium evaporation regime.

The process of water vapour condensation causes rapid warming of low initial temperature droplets to the equilibrium evaporation temperature. The participation of droplet internal energy in the evaporation process determines rapid cooling of high initial temperature droplets.

The influence of radiation flux absorbed by sub cooled and sub heated water droplets for their thermal state change is different.

5. NOMENCLATURE

a thermal diffusivity, m^2/s ; B_T Spalding transfer number; c_p mass specific heat, $J/(kg\ K)$; D mass diffusivity, m^2/s ; Fo Fourier number; g evaporation velocity, kg/s ; k conduction; $k+r$ conduction and radiation; L latent heat of evaporation, J/kg ; m vapour mass flux, $kg/(m^2s)$; n number of the term in infinite sum; q heat flux, W/m^2 ; r radial coordinate, m ; R radius of a droplet, m ; R_u universal gas constant $J/(kmol\ K)$; T temperature, K . *Greek symbols*: η non-dimensional radial coordinate; λ thermal conductivity, $W/(m\ K)$; μ molecular mass, $kg/kmol$; ρ density, kg/m^3 ; τ time, s ; *Subscripts*: C droplet centre; f phase change; g gas; i time index in a digital scheme; I control time; j index of radial coordinate; J droplet surface; k conduction; m mass average; r radiation; R droplet surface; v vapor; vg gas-vapor mixture; $*$ variable; 0 initial state; ∞ far from a droplet. *Superscripts*: $+$ external side of a droplet surface; $-$ internal side of a droplet surface.

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