On radiation absorption effects and air humidity influence on evaporating water droplets and vapour condensation intensity

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Abstract

This paper discusses modelling of water droplet heating and evaporation in humid air. The effect of black body spectral radiation of the air temperature on the combined heat transfer in the water droplet has been evaluated. A combined analytical and numerical method of investigation is applied. Securing the balance of energy fluxes in the droplet with a confidence of one hundredth of a percent, the method of fastest descent has been used to determine the droplet surface temperature. Thermal state and phase transformation dynamics for the warming droplets heated in a humid air environment are modelled under conductive and combined conductive-radiative heating.
Keywords: humid air, water droplet, combined heat and mass transfer, droplet heating and evaporation, condensation.

1   Introduction

The research of water droplet heat and mass transfer is connected with application of sprayed water technology in power energy and other industries. The problem of droplet evaporation has been researched for more than a hundred years [1]. Demand to improve technology which employs liquids in the sprayed form requires further understanding of combined heat and mass transfer processes in liquid droplets under wide range of conditions. Applied methods for investigation of heat and mass transfer in liquid droplet are systematically reviewed in [2]. There has been an objective for particular consideration of unsteady combined heat and mass transfer processes in recent years [3–9]. The methods developed for analytical and numerical investigation of droplet combined heat and mass transfer allows modelling of more complex processes and their interactions.

The above mentioned phenomenon is relevant to nuclear industry and specifically to durability of boiler tubes. Hence, understanding of factors affecting tube metal degradation is significant to nuclear safety of the plant. The relevant degradation mechanism depends on tube wall metal and the environment properties it operates in. The risk of stress corrosion cracking is applicable to stainless steel tubes, which normally operate with superheated steam, but under certain operational conditions have likelihood of droplet carryover into that section of the boiler.

Water droplet heating and evaporation can be modelled in different ways. Various aspects of heat and mass transfer can be considered: droplet slipping in steam flow will affect convection, droplets in steam are also heated by convection, but radiation of the surroundings determines if heating is combined heating. Sprayed droplet initial temperature and dispersity are also very important factors affecting heat and mass transfer. The condensation process requires the presence of vapour in the droplet surroundings. The initial droplet temperature affects if heat and mass transfer on the droplet surface will be for condensation or evaporation. For small droplets of diameter of microns range it is necessary to evaluate the influence of Knudsen layer to droplet evaporation. In the case when droplets are large the influence of surroundings radiation must be evaluated. Each of these factors contributes essential peculiarities for heat and mass transfer modelling [9–11].

The results of analysis of heating and phase transformation for larger droplets on their surface in humid air are presented in this paper.

2   Formulation of the problem

The intensity of phase transformations at the droplet surface determines water vapour flux [12]:

$$m_v^+ = \frac{D_{vg}\mu_v}{T_{vg,R}R_\mu R}\left[p_{v,R} - p_{v,\infty} + \frac{\mu_v}{\mu_g}\left(p\ln\frac{p - p_{v,\infty}}{p - p_{v,R}} + p_{v,\infty} - p_{v,R}\right)\right]. \tag{1}$$

The influence of Knudsen layer for large-scale droplets evaporation is negligibly small, and steam and gas mixture temperature near the droplet in expression (2) is comparable to the droplet surface temperature: $T_{vg,R} \equiv T_R$. The droplet surface temperature determines the regime of phase transformations – when it is below the dew point temperature the water vapour of humid air condenses on the droplet surface. When heated droplet surface temperature reaches dew point temperature the regime of phase transformation changes and droplet starts to evaporate. Air humidity is defined by volumetric part of water vapour $\bar{p}_v = p_{v,\infty}/p$. The driving force of diffusive evaporation is defined by the water vapour pressure difference near the droplet and in humid air. The effect of Stefan hydrodynamic flow on the intensity of evaporation is evaluated by logarithm in expression (1). 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-stationarity enables to describe the heat flow balance by the condition:

$$\vec{q}_k^+ + \vec{q}_k^- + \vec{q}_f^+ \equiv 0; \frac{\lambda_{vg}}{R}\left(T_g - T_R\right)\cdot\ln\frac{1+B_T}{B_T} - \lambda\frac{\partial T(r,\tau)}{\partial r}\bigg|_{r\equiv R^-} = m_v^+ L . \tag{2}$$

Logarithmic function of Spalding heat transfer number in the expression (2) takes into account effect of Stefan hydrodynamic flow on the intensity of convective heating of evaporating droplet. Water circulation in the droplet has not been considered. It is assumed that there is no phase slippage in humid air flow carrying water droplets. The incident spectral radiation onto droplet is partially reflected and partially absorbed in the semitransparent droplet. The direction of vapour flux is determined by the logarithmic function in expression (1), and it is considered being positive in the case of evaporative regime. The temperature gradient for combined conductive-radiative heat transfer process in the droplet is described by expression [10]:

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

Flux density of radiation in spherical semitransparent droplet is calculated according to methodology [10] and the complex refractive index of water is used in accordance with [13, 14] recommendations. The Spalding heat transfer number takes into account the radiation absorption by droplet and temperature gradient in it [15]. The expression (2) is solved numerically. The time step is chosen freely. Instant droplet surface temperature is determined by the iterative method of fastest descent. Imbalance of heat fluxes on the droplet surface is achieved to less than one hundredth of a percent. After calculating the vapour flux on droplet surface in accordance with expression (1) the volume change of spherical droplet in time step $\Delta\tau$ is determined by:

$$\frac{\partial(\rho V)}{\partial\tau} = -4\pi R^2 m_v^+ . \tag{4}$$

To determine the droplet surface temperature its volume is assumed constant during time step $\Delta\tau$ while conducting iterative calculations. This ensures the stability of the numerical iterative scheme. The droplet volume is revised for every next time step.

3   Results and discussion

The analysis has been conducted for water droplets of various initial temperatures in the humid air (of $\bar{p}_v \equiv 0.2 \div 0.95$) of 700 K and 0.1 MPa. Conductive heating has been modelled assuming that droplets in air are stagnant.

In the case of combined heating by conduction and radiation the external black body radiative source with air temperature has been assumed. Droplet evaporation process is significantly influenced by the degree of moisture in the air (Fig. 1). Curves describing the change of heat and mass transfer parameters presented in the dimensionless form of Fourier number scale are general for all conductively heated droplets. The initial water temperature and air parameters must be defined.
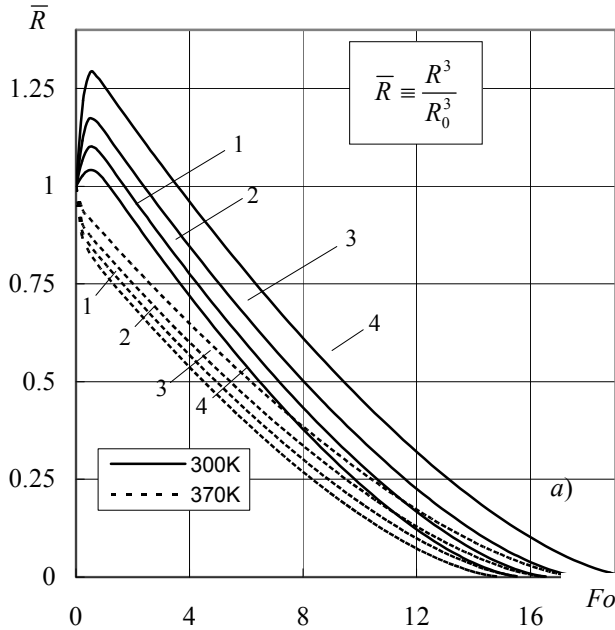

Figure 1:   Evaporation of conductively heated water droplets in humid air. $\Delta \bar{p}_{v,\infty}$: (1) 0.2, (2) 0.4, (3) 0.6, (4) 0.8.

The droplet volume dynamics $R^3(Fo)/R_0^3 \equiv \bar{R}(Fo)$ strongly depends on air humidity and sprayed water temperature. Volume of the low initial temperature droplets increases during the primary stage of phase transformations due to vapour condensation on their surfaces and expansion of warming water. The droplet volume is increasing for certain duration due to expansion of warming water during the initial stage of the droplet evaporation regime. The evaporating droplet volume 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 volume reach equality and are visible on the volume dynamics curve $\bar{R}(Fo)$ as an extremum point (Fig. 1). The droplet volume of high initial water temperature does not have volume expansion stage and its volume starts to decrease immediately. Rapid volume decrease is caused by

intensive evaporation process and shrinkage of cooling water. Water droplets quite quickly reach equilibrium evaporation regime. Equilibrium evaporation is defined as a phase transformation regime during which heat delivered to the droplet by the surroundings is solely consumed for droplet evaporation, i.e. $q_f^+\left(Fo \equiv Fo_e\right) \equiv q_\Sigma^+$. The beginning of equilibrium evaporation for conductively heated droplets is also indicated as convergence of curves $q_f^+\left(Fo\right)$ and $q_k^+\left(Fo\right)$.
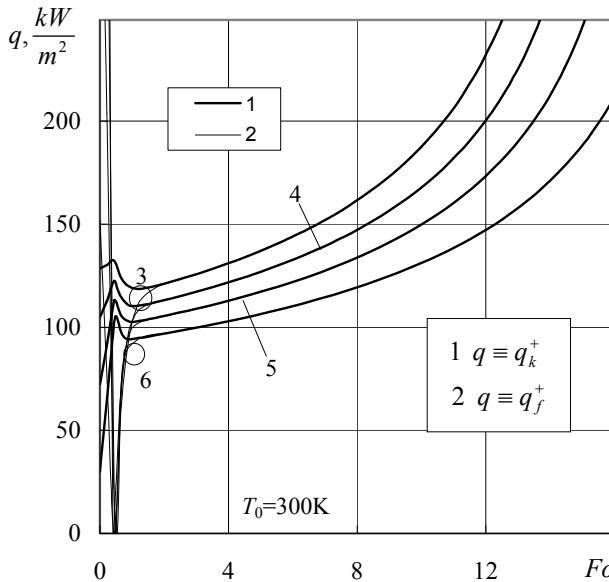

Figure 2:   Heat fluxes on the droplet surface for conductively heated cold droplets. $\Delta \overline{p}_{v,\infty}$: (3) 0.2, (4) 0.4, (5) 0.6, (6) 0.8; $R_0 = 0.0001$m.

The temperature of the conductively heated droplets does not change during the equilibrium evaporation regime (Fig. 3). The equilibrium evaporation temperature is reached by intensive droplet heating for low initial temperature droplets (Fig. 3a) and intensive cooling for high initial temperature droplets (Fig. 3b). The distinct non-isothermality is observed during the initial stage of phase transformations. The droplet non-isothermality diminishes when approaching the regime of equilibrium evaporation. The near equilibrium temperature is first reached by the subsurface layers in the droplet and later by the central layers of the droplet.

During the unsteady phase transformations not only the droplet temperature changes rapidly, but also the heat fluxes at the droplet surface change significantly (Fig. 4). This is caused by the initial water droplet temperature and their way of heating.
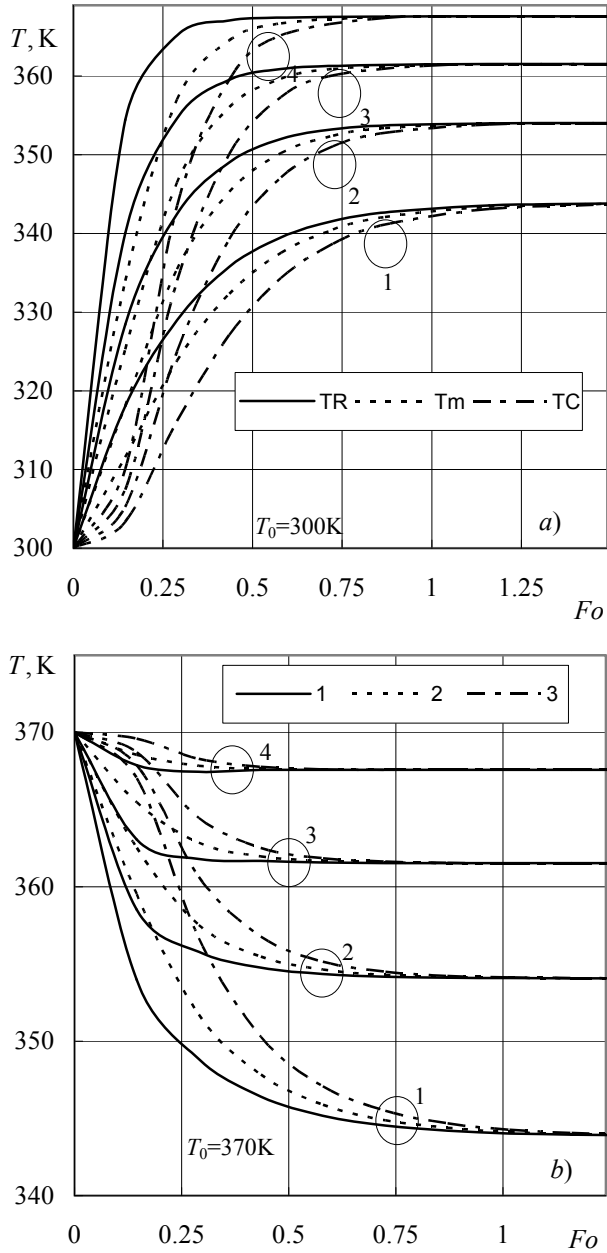
Figure 3:   The influence of initial water temperature to the droplet temperature dynamics for conductively heated droplets during the initial stage of phase transformations. $\Delta \bar{p}_{v,\infty}$: (1) 0.2, (2) 0.4, (3) 0.6, (4) 0.8.
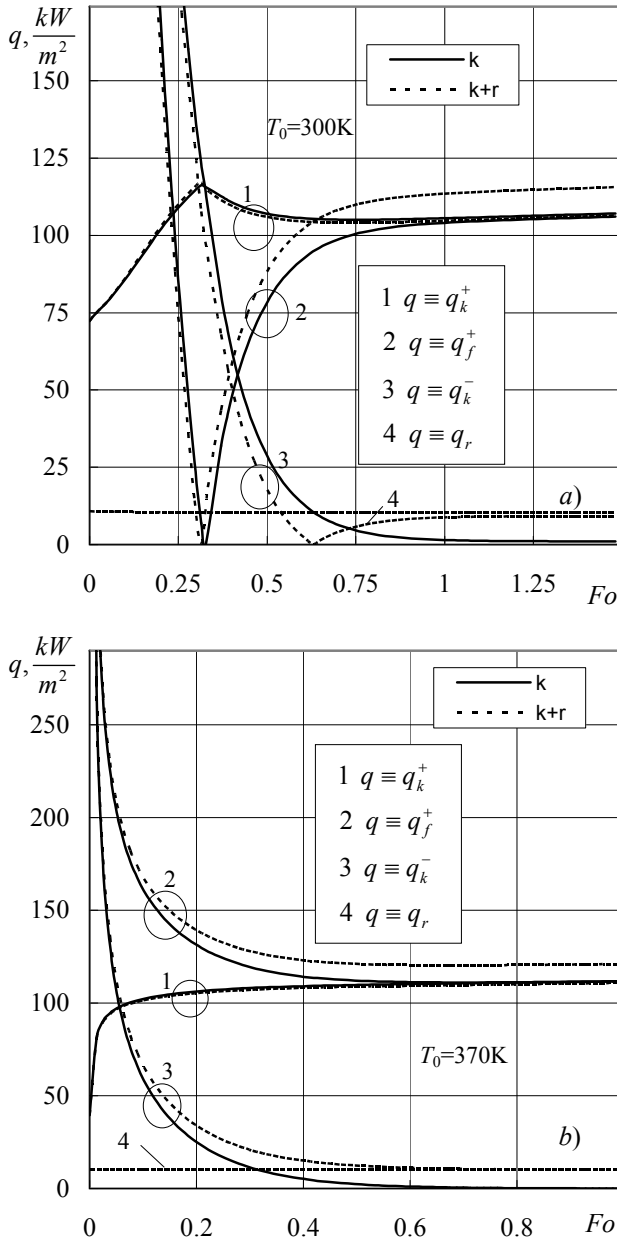
Figure 4:   Heat fluxes at the droplet surface for low and high temperature droplets during unsteady phase transformation regime for the conductive heating case (k) and the combined heating case ($k+r$). $\Delta \overline{p}_{v,\infty}$: (1) 0.2, (2) 0.4, (3) 0.6, (4) 0.8.

The influence of radiation to phase transformations for larger droplets is more significant (Fig. 5). Intensive heating of low initial temperature droplets up to dew point temperature is caused by intensive vapour condensation process (Fig. 4a). 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, and in the case of combined heating – by the total heat flux. The total heat flux on the internal side of the droplet surface during the regime of condensational phase transformation is $q_{\Sigma}^-(0 \div Fo_{co}) \equiv q_k^+ + q_r^+ + q_{f \equiv co}^+$, where term q_{co}^+ approaches zero. At the moment of phase transformation regime changeover the condition $q_k^- \equiv q_k^+$ is valid. Accelerating process of evaporation inhibits water warming in the droplet: $q_h(Fo_{co} \div Fo_e) \equiv q_k^+ + q_r^+ - q_f^+$. The phase transformation heat flux during the unsteady evaporation regime is $q_f(Fo_{co} \div Fo_e) \equiv q_{\Sigma}^+ - q_{\Sigma}^-$. The dynamics of heat fluxes during the unsteady evaporation regime determines the initial spayed water temperature and the ways droplet are heated (Fig. 4). The influence of heating manner is especially distinct for low temperature droplets (Fig. 4a). Conditions for absorbed radiation in the semitransparent droplet to participate in the water evaporation process establish only when droplet temperature field of negative gradient is formed. The conductive heat flux becomes zero at the moment of the vector direction
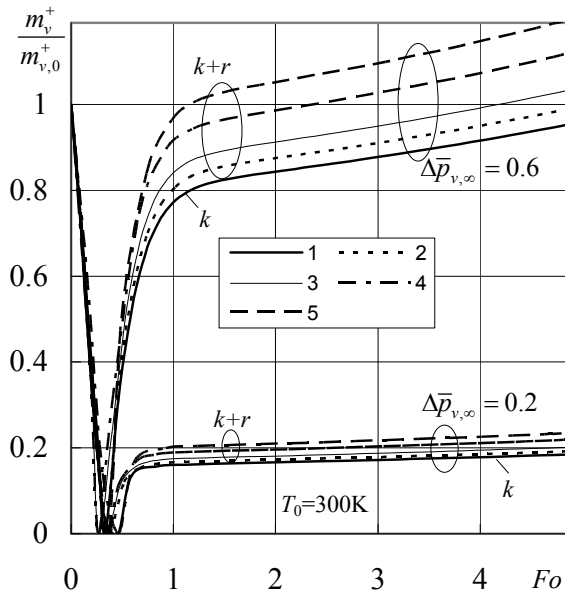

Figure 5: Influence of radiation on droplets phase transformations. R_0, m: (2) 0.00005, (3) 0.0001, (4) 0.0002, (5) 0.0003.

changeover for droplet temperature field gradient. Later it increases to $q_{k,e}^{-} \equiv q_r$ (Fig. 4a). The condensational phase transformation regime for the high initial water temperature droplets is impossible. The temperature field of negative gradient is formed immediately at the start of evaporation. The rapid cooling of the droplet is caused by very intensive evaporation process (Fig. 4b), which is associated with the participation of cooling droplet internal energy. The droplet cooling is slowing with approach to the equilibrium evaporation regime and the influence of the droplet internal energy reduces. For equilibrium evaporation regime the gradient of temperature field in the droplet ensures participation of the droplet absorbed radiation flux in the evaporation process.

4   Conclusions

The regime of unsteady phase transformations for water droplets in humid air is short and droplets rapidly reach the characteristic equilibrium evaporation temperature. Nonetheless, 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 and water initial temperature play an important role during this phase transformation regime.

The process of water vapour condensation, which is contained in air, 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 initial water droplet temperature does not influence heat transfer processes during the equilibrium evaporation regime.

The effect of radiation to temperature dynamics and phase transformations is more significant for droplets of bigger size than for smaller ones. The influence of radiation is very significant for conductive heat flux dynamics in the cold water droplets.

5   Nomenclature

a – thermal diffusivity, m^2/s; B_T – Spalding heat transfer number; c_p – specific heat, J/(kg K); D – mass diffusivity, m^2/s; Fo – Fourier number; k – conductive heating; $k+r$ combined heating; L – latent heat of evaporation, J/kg; m – vapour mass flux, kg/(s·m^2); n – number of terms in the infinite sum; p – pressure, Pa; q – heat flux, W/m^2; R – radius of a droplet, m; R_μ – universal gas constant, kg/(kmol K); r – radial coordinate, m; T – temperature, K; V – droplet volume, m^3; η – non-dimensional coordinate; λ – thermal conductivity, W/(m K); μ – molecular mass, kg/kmol; ρ – density, kg/m^3; τ – time, s;
Subscripts: C – droplet centre; co – condensation; e – equilibrium evaporation; f – phase transformation; g – gas; k – conductive; m – mass average; r – radiative; R – droplet surface; rt – dew point; v – vapour; vg – vapour-gas mixture; 0 – initial state; ∞ – far from a droplet; Σ – total.
Superscripts: $+$ – external side of the surface; $-$ – internal side of the surface.

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