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Averaged Heat Fluxes Densities During Condensation and Evaporation of a Water Droplet

Kristina BIKNIENĖ*, Linas PAUKŠTAITIS**
**Kaunas University of Technology, Studentų 56, Kaunas, LT-51424, Lithuania, E-mail: kristina.bikniene@ktu.edu*
***Kaunas University of Technology, Studentų 56, Kaunas, LT-51424, Lithuania, E-mail: linas.paukstaitis@ktu.lt*
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Nomenclature

B_T – Spalding heat transfer parameter; G – mass flow rate, kg/s; g_v – vapour mass flux, kg/s; k_c – effective conductivity parameter; m_v – vapour mass flux density, kg/(m^{2}s); L – latent heat of evaporation, J/kg; Nu – Nusselt number; Pe – Peclet number; Pr – Prandtl number; R – radius of a droplet, m; Re – Reynolds number; q – heat flux density, W/m^2; t – temperature, ^{o}C; T – temperature, K; X_v – vapour volume fraction; λ – thermal conductivity, W/(m K); ρ – density, kg/m^3; τ – time, s.

Subscripts: c – convective; C – centre of a droplet; d – gas; dp – dew point; e – equilibrium evaporation; f – phase change; h – additional humidity; i – time index; l – liquid; R – surface of a droplet; s – saturation; v – vapour; vg – vapor-gas mixture; 0 – initial.

1. Introduction

The process of heat and mass transfer, by using a water droplet as a reference system, is a widely used in various practical applications. Traditionally, such operations are used in fire protection systems [1], agricultural irrigation systems [2], gas cooling processes [3, 4], air conditioning and microclimate systems of buildings [5, 6], surface treatment and protection of technological processes [7-9]. In modern technologies water dispersion processes also takes place in various parts of technological process, such as sessile of droplets and their evaporation from solid surfaces for cooling [10, 11], controlling parameters of superheated steam [12], cleaning flue gases [13, 14], recovering waste heat from exhaust gas [15], reduction of pollutants in fuel combustion [16], controlling parameters of high-temperature combustion products [17], increasing the effectiveness of turbo-compressors operation [18].

Nowadays, a lot of attention is paid to environmental issues, so various directives [19] encourage the development of renewable energy sources. So recently, modern solid biofuel technologies are widely used for thermal energy and electricity production. This type of fuel has a high moisture content, typically 30-60% of its mass (depends on storage conditions). Therefore, burning of the solid biofuel a humid exhaust flue gas is generated, in which a large energy amount is accumulated in form of water vapour enthalpy. To recover this energy from the humid exhaust flue gas, condensing economizer technology is used in solid biofuel combustion systems [20]. In order to intensify the heat recovery process in condensing economizer a water injection system is applied: dispersed water droplets cool and wet the exhaust gas flow. In contact type condensing economizer, the condensation of water vapour from the exhaust gas flow takes place directly on dispersed water droplets. In recuperative type condensing economizer, the recovered heat and mass process takes place between the condensing water vapour and the pipe walls of the heat exchanger – in this case, water is sprayed to improve the hydrodynamic mode of the condensation film in the tubes. For this technology, it is necessary to control the heating process of the droplet surface to the dew point temperature. Thus, proper selection and ensuring of boundary conditions is an important factor which determines the effectiveness of the device operation.

Understanding the heat transfer and phase transformations processes of the water droplets, many theoretical and experimental investigations have been done [21,22]. Finding more and more innovative solutions of water dispersed application, numerical modelling method becomes important investigation instrument. Mathematical models used in calculations of numerical simulations are usually valid under certain conditions. Therefore, the development of new technologies and the modelling of their processes require experimental studies under the same boundary conditions to ensure the correctness of the numerical modelling results and the effectiveness of new technologies. It has the effect that in recent years, an increasing number of experimental studies have been carried out on mass and heat transfer processes of the water droplet under specific boundary conditions corresponding to the operating modes of a particular technology, for example, the operating conditions of the containment spraying system of nuclear reactors [23], the water injection system of the compressor of a gas turbine [24], the water injection system of the condensing economizer [25-26].

The experimental studies of heat and mass transfer process of the water droplet have mostly focused on the investigating the droplet equilibrium evaporation regime. The experiments performed [25-34] demonstrated that when the entire mass of the droplet heats almost equally, the flux of the heat transfers and the phase transformations between the surrounding gas and the droplet stabilizes and becomes constant – it is reached the equilibrium evaporation state of the heating droplet. In this regime, whole amount of the transferred heat to the droplet's surface is used to vaporize water. The thermal state of the equilibrium evaporation regime is defined by the specific temperature t_e which is higher than the temperature of the dew point t_{dp} but is lower than the temperature of the saturation state t_s. The experimentally obtained temperatures of a water droplet in equilibrium evaporation regime are given in Fig. 1. It is clearly seen that the temperature of equilibrium evaporation state depends on the temperature of the surrounding gas flow in all cases. From the results' curve of the equilibrium evaporation temperature some experiments [25-27, 32] are sticking out. These experimental investigations of the heat and mass process in the water droplet were performed with the humid air flow. In experiments [25, 26] the influence of the additional humidity in the air flow was researched. The obtained results showed that the amount of humidity defines temperature of the equilibrium evaporation state in the air flow. It confirmed that gas humidity also determines the equilibrium evaporation thermal state.

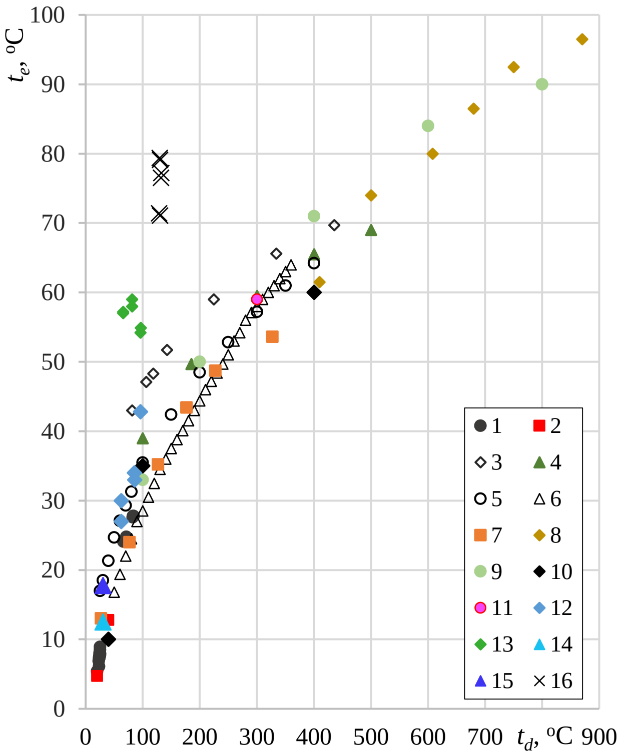


Fig. 1 The experimental results of the water droplet temperature in the equilibrium evaporation regime: 1 – Ranz-Marshal [27], 2 – Langstroth-Diehl-Win-Holder [28], 3 – Nishiwaki [28], 4 – Kobaiyasi [28], 5 – Fedosejava-Polishcuk [28], 6 – Apashev-Malov [27], 7 – Downing [29], 8 – Ivanov-Smirnova [30], 9 – Yuen-Chen [31], 10 – Strizhak et all. [33], 11 – Volkov-Strizhak [34], 12 – Ramanauskas et all. (low humidity) [25], 13 – Ramanauskas et all. (additional humidity) [25], 14 – Fujita et all. (low humidity) [32], 15 – Fujita et all. (high humidity) [32], 16 – Miliauskas et all. (additional humidity) [26]

In recent years heat and mass transfer processes of droplet were intensively experimental investigated by P.A. Strizhak and R.S. Volkov with colleagues. In their experimental and numerically studies [33-37], the heating and evaporation processes of water droplet suspended on the rod are investigated in a hot air flow (at temperatures up to 800-1000°C). To estimate the temperatures inside the water droplet they are using Planar Laser-Induced Fluorescence (PLIF) measuring method. In this series of the experiments the main attention is on temperature fields and internal process of heating water droplet, the application possibilities of the PLIF measuring method in the droplet research. The obtained results showed that distribution of temperature inside water droplets are inhomogeneous during the whole heating process. Summarizing the research results, a new model for heating and evaporation of a suspended droplet is suggested, in which influence of the temperature gradient and recirculation inside the droplet and the effect of a supporting rod are estimated.

The literature review and the examples of water spray applications shows that the investigated object is the same but very different processes take place during injection of a water droplet. Heating or cooling, condensation or evaporation of a droplet can occur at different stages during technological processes. It all depends on the initial temperature of a droplet and its surrounding. Therefore, it is important to understand and evaluate the impact of boundary conditions on heat transfer and phase transformation processes of the droplet processes, because the effectiveness of droplet spray system application in various thermal technologies depends on it.

The purpose of this experimentally investigation is to study the influence of boundary conditions on the intensity of phase transformations and heat transfer processes in the water droplet and to define the dynamics of the averaged heat fluxes densities during the phase change cycle of the water droplet.

2. Experimental method and processing of the results

The schematic of the experimental set-up was presented, and its operation described in detail in the study [26]. The single water droplet is suspended on the thermocouple ball using a mechanical pipette. With a system of two sliding glass tubes, the droplet is placed in the experimental section. In this two tubes system, the water droplet is heated up to its preferred initial temperature. Then the protective tube is withdrawn, and the supplied flow of atmospheric air is directly passed over the experimental droplet. To reach the desired temperature of the supplied atmospheric air flow, consecutively connected heaters are used. The additional humidity is ensured with the vapour generator in which generated vapour flux is defined by weighing it. The temperature of the droplet is measured every second with the thermocouple on which the droplet is suspended and a high-speed camera is used to record the size of the droplet. The temperature of the surrounding pre-heated and additional humidity air flow is determined by the stabilized temperature of the thermocouple on which the droplet is suspended after whole water vaporized. During the experiment, the thermodynamic parameters of ambient air (temperature, barometric pressure, relative humidity) is measured with a TESTO 445 device. All measured and recorded parameter is stored in the computer.

The experimental investigation to determine the intensity change of phase transformations and heat transfer processes in the heating water droplet were performed. The change of the experimental droplet mass is defined by the vapour flux in the phase transformations processes on the droplet's surface:

$$\frac{d}{d\tau}\left(\frac{4}{3}\pi\rho_l(\tau)R_l^3(\tau)\right)=-g_v(\tau). \quad (1)$$

The vapour flux describes the rate of the phase transformations. Relatively, vapour flux in the condensation regime is considered negative, while in the evaporation regime the generated vapour flux is considered positive. The phase transformations vapour flux can be defined by the variation of the droplet geometric parameters:

$$g_v(\tau)=4\pi R_l^2(\tau)m_v(\tau). \quad (2)$$

From experimental data the average vapour flux can be calculated by the expression:

$$g_{v,i}=-\frac{4}{3}\pi\frac{\left[\left(\rho_{l,i+1}R_{l,i+1}^3\right)-\left(\rho_{l,i}R_{l,i}^3\right)\right]}{\Delta\tau_i}, \quad (3)$$

where $\Delta\tau_i$ is time changing step during which the average moment values of the droplet temperature and diameter are fixed.

In the performed experiments, the highest temperature of the pre-heated air flow was 132.7°C, so the effect of radiative heating of the droplet is not evaluated. In this case the energy balance on the suspended water droplet surface is defined as follow:

$$q_{c,d}(\tau)+q_{c,l}(\tau)-q_f(\tau)=0. \quad (4)$$

The convection heat flux provided from the surrounding gas is defined according to Nusselt number of the phase transformations:

$$q_{c,d}(\tau)=\lambda_{vg}(\tau)\frac{Nu_f(\tau)}{2R_l(\tau)}\left(T_d-T_R(\tau)\right), \quad (5)$$

$$Nu_f(\tau)=\left(2+0{,}57Re_l^{1/2}(\tau)Pr_l^{1/3}(\tau)\right)\cdot \cdot\left(1+B_T(\tau)\right)^{-0{,}7}, \quad (6)$$

where B_T is Spalding heat transfer parameter which in this study is assumed as the ratio of the phase transformations heat flux and external heat transfer flux, when the phase transformations do not occur.

The convective heat flux inside the droplet is described by the modified form of Furje law. In the case, when the water droplet is in the non-radiating gas flow, the internal heat transfer flux density is calculated according to the following equations:

$$q_{c,l}(\tau)=-\lambda_l(\tau)k_{c,l}(\tau)\frac{\left(T_R(\tau)-T_C(\tau)\right)}{R_l(\tau)}, \quad (7)$$

$$k_{c,l}(\tau)=1{,}86+tanh\left(2{,}245log_{10}\frac{Pe_l(\tau)}{30}\right). \quad (8)$$

The water droplet phase transformations energy is proportional to vapour flux density on its surface:

$$q_f(\tau)=m_v(\tau)L_l(\tau). \quad (9)$$

From Eqs. 4, 5, 7 it is seen, that the heat flux densities on the droplet surface depends on its surface temperature. This temperature is determined by the interaction of energy flows on its surface. In this case of performed experiment, the temperature of the water droplet surface can be computed by the following expression:

$$T_R(\tau)=\frac{a\cdot T_d+b\cdot T_c(\tau)-m_v(\tau)L_l(\tau)}{a+b}, \quad (10)$$

where: $a=\lambda_{vg}(\tau)\frac{Nu_f(\tau)}{2R_l(\tau)}$, $b=k_{c,l}(\tau)\frac{\lambda_l(\tau)}{R_l(\tau)}$.

The calculation results of the droplet surface temperature are given in Fig. 2 It is seen that in the beginning of the experiments, the initial temperature of the droplet has a significant influence. In the equilibrium evaporation regime, when the dynamic of the droplet temperature becomes horizontal, thermal state of the water droplet depends only on the temperature of the pre-heated air flow and the amount of the additional humidity. The first and second groups of temperatures curves (Fig. 3, curves 1-3) indicate the experiments when the air flow in the experimental section has humidity only from the ambient air (X_v =0.01) and it is preheated up to different temperatures (t_d ~81°C and ~132.5°C. The third group of temperatures curves (Fig. 3, curves 4-7) shows the cases when the air flow was additionally humidified with different amount of moisture (X_v =0.0133-0.238) and pre-heated up to the same temperature (t_d ~131°C). From these calculated results it is seen that increasing the temperature of the surrounding gas flow and increasing the amount of the moisture this flow, the droplet temperature of the equilibrium evaporation state is also increasing.

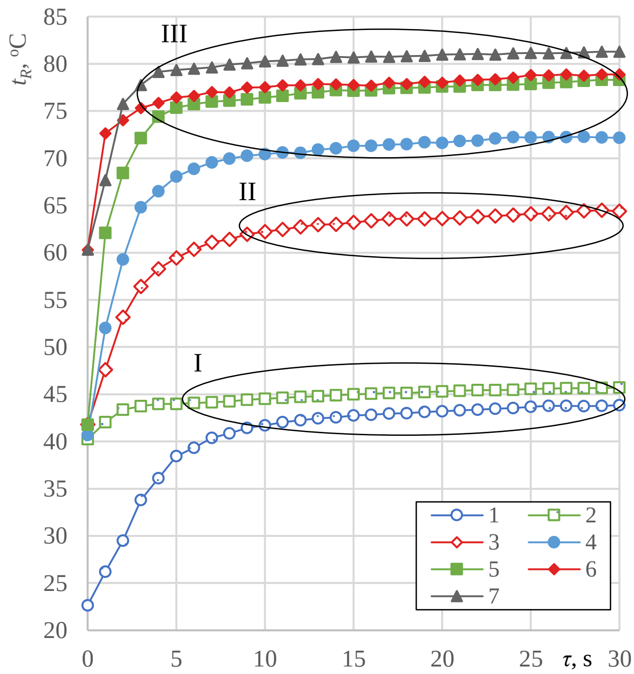


Fig. 2 Dynamics of the temperature on the water droplet's surface. The water droplet is suspended: *I* – in the dry air flow pre-heated up to ~81°C; *II* – in the dry air flow pre-heated up to ~132,5°C; *III* – in the additionally humidity air flow pre-heated up to ~131°C; experimental boundary conditions are presented in Table 1

3. Experimental results and discussion

During the experiments, the regularities definition of heat fluxes densities of phase transformations and heat transfer processes in the water droplet suspended in the air

Table 1

Boundary conditions of the experiments

No	$t_{l,0}$	$2R_{l,0}$	t_d	G_h	X_v
-	ºC	mm	ºC	g/s	-
1	22.60	1.775	80.65	-	0.01
2	40.33	1.789	81.20	-	0.01
3	41.80	1.766	132.13	-	0.01
4	40.68	2.129	130.15	0.288	0.133
5	41.79	2.073	132.11	0.594	0.238
6	60.31	2.331	132.5	0.594	0.238
7	60.33	2.051	129.5	0.879	0.317

flow was investigated. The experiments are conducted with relatively large diameter water droplets. In all cases the supplied flow of the atmospheric air to the experimental set-up was 10 m^3/h (atmospheric pressure 0.999 bar, temperature 20.9-22.45ºC, relative humidity about 38%) and in the experimental section the air flow regimes were transitional (Re_d=3174÷4161). The hydrodynamics regimes of the droplet overflow were determined by the modified Reynolds number Re_l which values at the initial moment of experiments differ from 105 to 188. The main boundary conditions of performed experiments are provided in Table 1.

Fig. 3 shows distribution of calculated averaged heat fluxes densities on the surface of the experimental droplet in the pre-heated and additional humidified air flow (experiment 6). This dynamic of energy flows is in good agreement with the typical results of numerical calculations of heat and mass transfer of the water droplet [38-40].

As one can see from Fig. 3, at the beginning of the droplet phase change cycle the averaged phase transformations heat flux density q_f has negative value. It shows that condensation process of vapour from the surrounding air

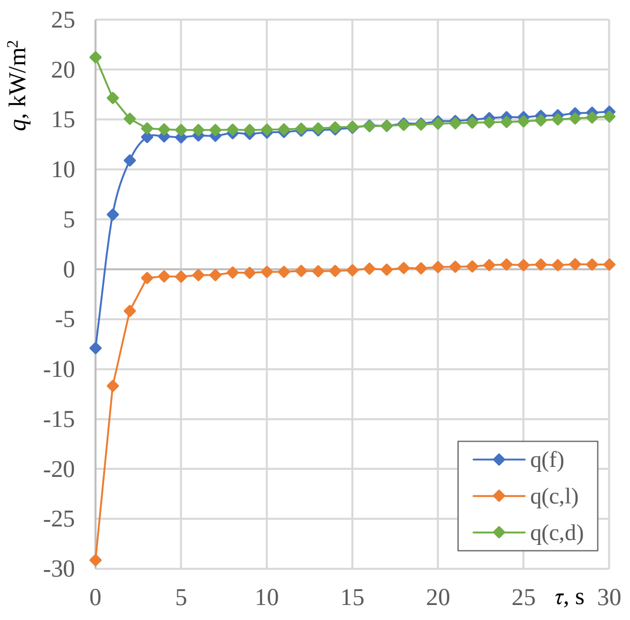


Fig. 3 Balance of energy flows on the experimental droplet's surface in the pre-heated and additional humidified air flow. Experimental boundary conditions are presented in Table 1 (experiment 6)

flow takes place on the water droplet's surface. This is due to the initial temperature of the water droplet $t_{l,0}$ is lower than the dew point temperature of the air flow t_{dp} in which the water droplet was suspended (t_{dp}≈62.9 ºC in experimental 6). At the same time the averaged external convection heat transfer flux density $q_{c,d}$ is positive and together its value is maximum at this initial moment. This happens because the temperature gradient between the surrounding air flow and the water droplet's surface is the highest at the beginning of this case. At the initial moment $\tau \approx 0$ s, the value of the averaged heat transfer flux inside the water droplet $q_{c,l}$ is negative. This means that heat flows from the hotter surface toward the cooler centre and heats the mass of the droplet. Thus, during the condensation mode, all the released heat from phase transformations process and the heat obtained by convection from the surrounding gas are used for heating the water droplet.

From about time moment $\tau \approx 1$ s (Fig. 3), the averaged heat flux density of phase transformations becomes positive – the temperature of the droplet's surface has reached the temperature of the dew point (this time moment is defined $\tau \approx \tau_{co}$ when q_f=0) and the evaporation process on the water droplet begins. But at the same time the averaged heat transfer flux density inside droplet is negative. This indicates that the heat provided by gas convection is used not only for the evaporation process, but also for heating the whole droplet. Therefore, the energy balance defines transit evaporation regime.

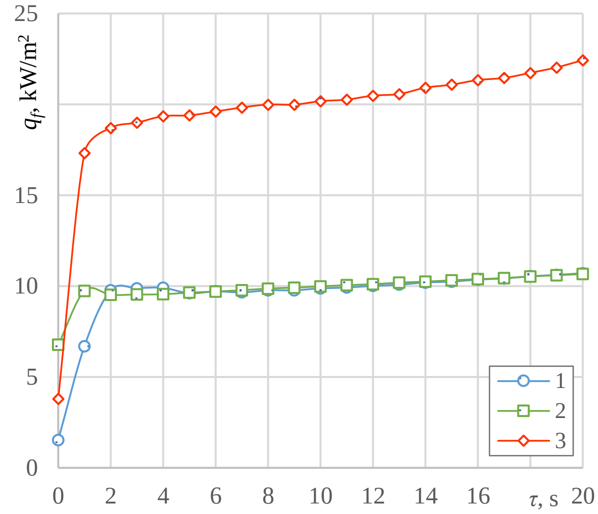
At about time moment $\tau \approx 8$ s (Fig. 3), the averaged heat flux density of internal heat transfer is almost zero and the value of the averaged phase transformations heat flux density increases to the value of the averaged external heat transfer heat flux density. It is because the water droplet heats up to the temperature t_e (t_e≈77.2ºC in experimental 6) which characterized the thermal state of the equilibrium evaporation (this time moment is defined $\tau \approx \tau_e$).

Theoretically, in all cases of droplet heating (conduction, convection or complex heating by radiation and convection) in the equilibrium evaporation regime the temperature t_e is almost constant and can decrease very slightly due to possible cooling of the water droplet mass during the equilibrium evaporation regime [38]. So usually, the slight change of the temperature t_e is insignificant and equilibrium between the transferred heat flows to the droplet and evaporation heat flow remains constant at the equilibrium evaporation regime. Only at the end of the droplet phase change cycle the heat fluxes of the water droplet suddenly intensify because sharply decreasing droplet's surface area becomes the dominant factor currently. However, from the analysed case it is seen that the temperature of water droplet increases quite significantly throughout the whole phase change cycle of the heating droplet (Fig. 2, 6 curve; the same trend is also observed in all performed experiments) and at about time moment $\tau \approx 20$ s (Fig. 3) the averaged heat transfer flux inside the droplet becomes positive and continues to grow significantly. At the same time the phase transformations heat flux density becomes higher than the external heat transfer heat flux density. It shows that not only the heat obtained by convection from the surrounding gas is used to vaporize water but also additional heat from inside the droplet. This disagreement with theoretical calculations can be caused by the amount of heat flowing through wires of the thermocouple on which the water droplet is suspended. Especially this effect is noticeable in cases where the initial diameter of the droplet is the smallest (experiments 1-3). Considering all that has been said, the assumption can be done that the heat of thermocouple wires effects the dynamics of heat fluxes density in the droplet, but its influences is visible only in the equilibrium evaporation regime when this amount of the additional heat flows from the centre to the surface of the experimental water droplet and significant contributes to the vaporization process of water.

Fig. 4 depicts the variation of averaged phase transformations heat flux density in the experimental droplet changing the boundary conditions. As expected, results of the performed experiments show that temperature of the gas flow surrounding the suspended water droplet has a pronounced influence on intensity of phase transformation process. This is well illustrated by the experiment data in dry atmospheric air flow (Fig. 4, a, 2 and 3 curves): at equilibrium evaporation regime, in higher temperature of air flow (experiment 3) the phase transformations heat flux density has higher values when the other boundary conditions are the same. Obviously, it is determined by the larger temperature gradient between the water droplet and its surrounding ambient in the case of the hotter air flow. However, at the beginning of experiments the value of phase transformations energy is not bigger in the case of the hotter air flow (Fig. 4, a; curve 3). That is because of the initial temperature of the suspended droplet which defines what temperature difference between the droplet and its surrounded gas flow is caused. Also, this parameter determines what process of the phase transformations (condensation or evaporation) will begin first on the surface of the water droplet.

In all experiments with the dry pre-heated air flow (Fig.4 a), the initial temperature of the droplet was higher than the dew point temperature of the surrounding gas flow. Because of that, when the water drop gets in the air flow, the evaporation process of droplet surface immediately begins. In all cases when the experimental droplet was suspended in pre-heated and additionally humidified air flow (Fig. 4, b), the initial temperature of the droplet was lower than the dew point temperature of the air flow and firstly the condensation of the vapour from the surrounding air flow takes place on the suspended droplet surface. From the results given in Fig. 4, it is seen that in condensation regime the lower initial temperature of the droplet influences more intensity flux density of the phase transformations. However, when the droplet phase change cycle starts immediately with the evaporation process (transit evaporation regime), the higher initial temperature of the droplet defines intensity process of the phase transformations. This is an important condition in engineering practice, depending on the purpose of the device the initial parameters of the sprayed water could be properly selected.

As one can see from Fig. 4, when the air flow surrounding the suspended droplet is additionally humidified with the vapour flow from the water evaporator (Fig. 4, b), the averaged heat flux density of phase transformations at the same gas flow temperature is smaller than in the cases of dry air flow (Fig. 4, a, 3 curve). For example, in equilibrium evaporation regime this energy flow decreases by 1.35÷1.45 times depending on the amount of the additional humidity when the initial droplet temperature is the same ($t_{l,0}$≈41,5 °C; Fig.4; curves 3, 4, 5). It is because the temperature of the equilibrium evaporation state has higher values



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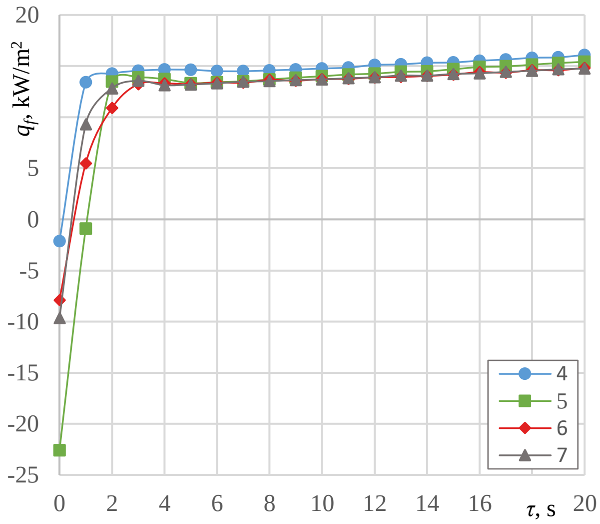


b

Fig. 4 The change of the averaged phase transformations heat flux density of the experimental water droplet: a – in the pre-heated dry air flow; b – in the pre-heated and additionally humidified air flow; experimental boundary conditions are presented in Table 1

in the humid air flow than in the cases of the dry air flow (Fig. 2). As a result, from the surrounding humidified air flow it is obtained less heat which in the equilibrium evaporation regime is used only for phase transformations process. So, the increased amount of additional humidity in the surrounding gas influences the lower averaged phase transformations heat flux density. This means that in the equilibrium evaporation regime the temperature of the air flow and moisture amount in this flow together determine the intensity of the phase transformations heat flux.

In the beginning of experiments, the highest module value of the phase transformations energy is in the additionally humidified air flow (Fig. 4, b; curve 6, at τ = 0 s, $|q_f|$=22.6 kW/m^2). In this case, the moisture content is not the highest that was used in the performed experiments, but the initial temperature of the droplet was lower than in the case with the highest amount of moisture (Fig. 4, b; 7 curve). So, these analysed results show that in the condensation regime the whole investigated parameters influence the intensity of the phase transformations energy. In the transit evaporation regime, the size of the initial diameter of the droplet effects is noticeable: the smaller initial diameter of a droplet the more intense evaporation heat flux in the equilibrium evaporation regime because the mass of smaller droplet heats up faster to temperature t_e.

The variation of the averaged external heat transfer flux density in various boundary conditions is presented in Fig. 5. In the performed experiments the external heat transfer is defined by convection of the surrounding gas flow (as was mentioned earlier, the influence of radiation is not estimated). As can also be seen in both images shown in Fig. 6, the droplet heating cycle despite the boundary conditions in all cases. Depending on the current regime of the droplet phase this heat energy flow has positive values throughout the change cycle, the obtained heat from air flow is used for heating of the droplet mass and/or vaporizing the water.

From Fig. 5, it is seen that in all cases of performed experiments the dynamic of the averaged external heat transfer flux density is the same: at the beginning of the

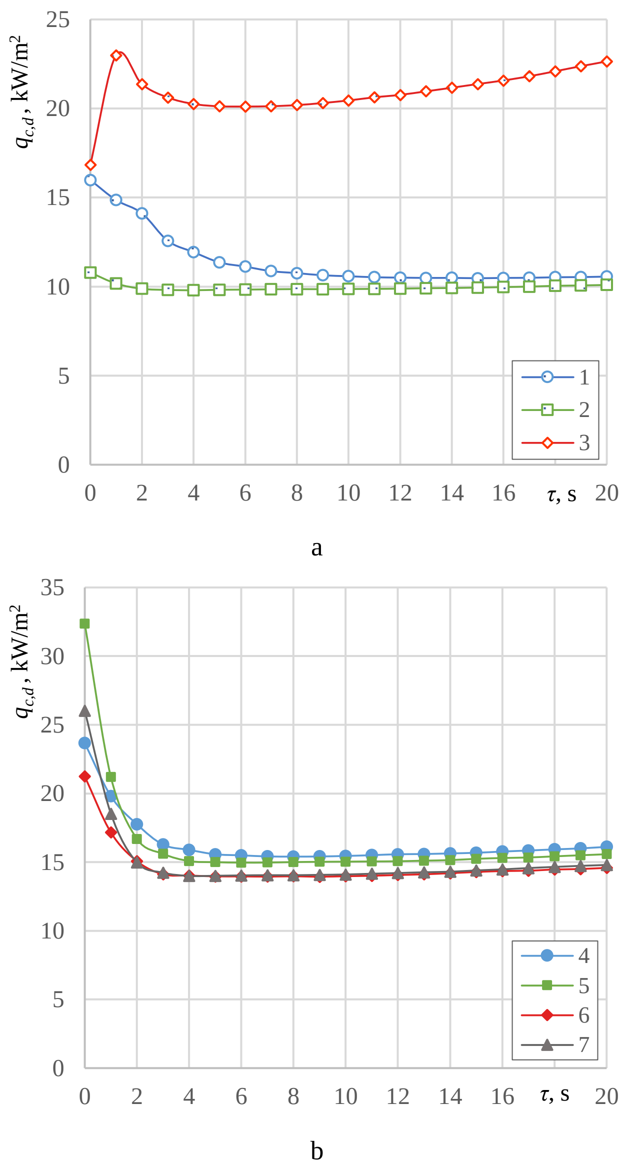


Fig. 5 The change of the averaged external heat transfer flux density of the experimental water droplet: a – in the pre-heated dry air flow; b – in the pre-heated and additionally humidified air flow; experimental boundary conditions are presented in Table 1

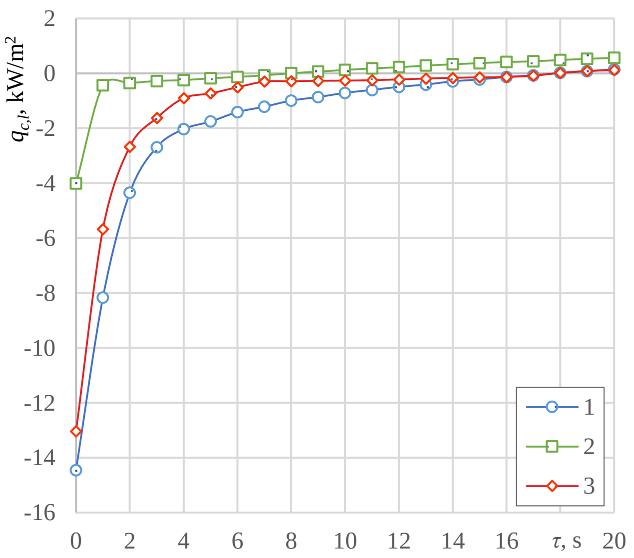
water droplet phase transformations cycle the curve of the external droplet phase transformations cycle the curve of the external heat energy decreases while the droplet heats up to the thermal state of equilibrium evaporation and then stabilizes. That is because of the temperature difference between the heated droplet surface and its surrounding gas flow.

As in the case of phase transformations heat flux, at the equilibrium evaporation regime the intensity of the external heat transfer flux is defined by the temperature of surrounding air flow and the amount of the additional humidity in it. The more moisture is in the surrounding gas flow, the temperature of equilibrium evaporation regime becomes higher (Fig. 2). As a result, the external energy flux decreases and less heat by convection of gas flow is provided to the droplet. So, at this regime the most intense averaged external heat transfer flux density is in case of hot and no additional humidity air flow (Fig. 5, a; curve 3).

When the surrounding air flow is additionally humidified, the highest value of the averaged external heat transfer flux densities was calculated at the initial moment of the droplet phase change cycle (Fig. 5, b; 5 curve, at $\tau = 0$ s, $q_{c,d} = 32.36$ kW/m^2). It is the same time moment, when the highest value of the averaged phase transformations heat flux density was identified (Fig. 4, b; curve 5). During this experiment, the amount of humidity in the surrounding gas was not the highest ($X_v = 0.238$) but the initial temperature of the droplet was lower than in the case of the experiment with the highest amount of moisture in gas flow (Fig. 5, b; curve 7, $X_v = 0.317$). At the beginning of the phase change cycle the initial temperatures of the water droplets were the same in the experiments 4 and 5 (Fig. 5, b; curves 4 and 5), but in case of the experiment 4 the gas humidity was lower. Thus, at initial time moment the averaged external heat transfer flux density is smaller in case of the experimental 4 than in the case of experiment 5. But as the droplet phase change cycle continues, the external heat transfer flux density is more intensive in the case of the experiment 4. It shows that the additional humidity influences the heat transfer flux from surrounding gas flow in the droplet phase change cycle: during the condensation regime external heat transfer flux is intensified but decreases in the equilibrium evaporation regime.

In Fig. 5, a, it is seen that the dynamic of the third experiment curve is different from the others at the initial time moment. This discrepancy could have been influenced by the tube withdrawal in which the droplet was pre-heated to the preferred initial temperature and by which the droplet was placed in the experimental section. As the water droplet was heating up in the tube, because of water evaporation the humidity of air in the tube could have become higher than the humidity of the air flow in the experimental section. At the withdrawal moment, the experimental droplet is surrounded by gas with additional moisture from the tube. Because of this at the initial time, the conditions are formed where the averaged external heat transfer flux density has the smaller value than the following time moment during this experiment (Fig. 5, a; curve 3).

The experimental results of the averaged internal heat transfer flux density are given in Fig. 6. This energy flow describes the heating or cooling processes of the water droplet mass during the phase transformations cycle. From given results in Fig. 6, it is seen that in all cases, at the beginning of the experiment the averaged heat transfer flux density inside the water droplet has negative value. It shows



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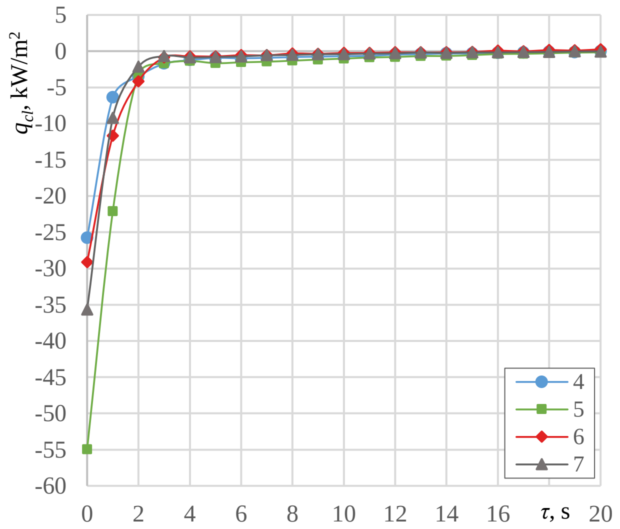

b

Fig. 6 The change of the averaged internal heat transfer heat flux density of the experimental water droplet: a – in the pre-heated dry air flow; b – in the pre-heated and additionally humidified air flow; experimental boundary conditions are presented in Table 1

that the droplet mass is heated first, because the initial temperature of the suspended droplet is lower than the temperature of the equilibrium evaporation thermal state in all test cases. When water evaporation process takes place on the droplet surface the initial relatively low droplet temperature leads to the higher temperature difference between the droplet and surrounded gas flow thus, the internal heat transfer of a droplet becomes more intensive. It is well seen in the cases of experiments with dry gas flow (Fig. 6, a). But in the additionally humidified air flow (Fig. 6, b), when condensation occurs first, the amount of moisture has a strong influence on the heat flux density inside the droplet. During the condensation regime, at the same time the droplet is heated by the heat obtained from the surrounding air flow and the heat released from phase change during the vapour condensation on the water droplet surface process. As already mentioned, additional humidity is the factor which determines the intensity of external heat transfer and phase transformations heat fluxes densities. So, as a result, at the beginning of experiments the averaged internal heat transfer flux density is more intensive in the humid air flow.

Also, it can be seen in Fig. 6 that when the equilibrium evaporation thermal state is reached, the value of the internal heat transfer flux density becomes almost zero in all cases despite the boundary conditions. Thus, the entire mass of the droplet heats almost equally.

4. Conclusions

An experimental investigation on the intensity of the heat fluxes of the phase transformations and heat transfer between the suspended water droplets and its surrounding air flow were conducted. The influence of boundary conditions and averaged heat fluxes densities were estimated in various cases. The results of the work confirmed the following:

1. Results of the performed experiments show that all boundary conditions influence the intensity of the heat transfer and phase transformations fluxes across the heated droplet surface in the air flow, but the effect varies in the distinct regimes of the droplet phase change cycle. At the beginning the averaged heat fluxes densities is determined by the temperature of the air flow and the initial temperature of the droplet and if the condensation process takes place on the droplet, the additional humidity has the significant influence; in the equilibrium evaporation regime the temperature of the gas flow and the amount of moisture in this flow defines heat fluxes intensity, the initial temperature of the water droplet has no influence on the energy fluxes in this regime.

2. During the experiments was confirmed that the pre-heated air flow makes the heat fluxes of the droplet more intensive during the water droplet phase transformations cycle.

3. It was experimentally demonstrated that the initial temperature of droplet determines at which process of the phase transitions (condensation or evaporation) the droplet phase change cycle will begin and influences its intensity.

4. The influence of the additional humidity of the surrounding gas flow is different in the separate regimes of the droplet phase transformations cycle: in the condensation regime the additional moisture increases the intensity of the heat fluxes densities, but in the equilibrium evaporation regime it is decreased.

5. The experiments demonstrated that in the equilibrium evaporation the boundary conditions have no influence for the averaged internal heat transfer flux density, it shows the influence of only internal factors.

6. The results show that at the beginning of the experiment the dynamic of heat fluxes densities decreases or increases while the droplet heats up to the thermal state of the equilibrium evaporation and then stabilizes. It means that the maximum amount of heat from the surrounding air flow is taken until the water droplet mass heats up to equilibrium evaporation thermal state.

7. The results of this investigation show that condensation process occurring on the droplet is very important for cleaning and heat recovery from flue gases. The higher condensation rate is, the more heat will be recovered from the flue gases thus, smaller heat exchangers and material savings can be achieved.

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K. Bikninė, L. Paukštaitis

AVERAGED HEAT FLUXES DENSITIES DURING CONDENSATION AND EVAPORATION OF A WATER DROPLET

S u m m a r y

This study is intended for experimental investigation of the influence of boundary conditions on the intensity of phase transformations and heat transfer processes in a suspended water droplet. The results of the dynamics of the averaged heat fluxes densities during the droplet phase change cycle are presented and analysed. The influence of the droplet initial temperature, the surrounding air flow temperature and the additional humidity in the air flow were defined in separate regimes of the droplet phase transformations cycle. The experiments performed demonstrated that the parameters of the air flow surrounding the suspended water droplet affect the intensity of heat fluxes in the droplet throughout whole its phase change cycle. It was experimentally claimed that the initial temperature of the water droplet has no influence on the droplet heat and mass transfer processes in the equilibrium evaporation regime. The obtained results showed that most intensity heat flux densities are at the beginning of the droplet phase change cycle when condensation process occurs on the droplet's surface in case with biggest amount of additional humidity in the surrounding air flow. This is very important in technologies of cleaning and heat recovery from flue gases.

Keywords: water droplet, phase transformations, heat flux density, experimental investigation.

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