Experimental investigations of water droplet transient phase changes in flue gas flow in the range of temperatures characteristic of condensing economizer technologies

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ABSTRACT

The heating and phase changes of water droplets in an air flow pre-heated to 140 °C and humidified up to water vapor volumetric fraction X_v of 0.3 were investigated experimentally in the context of heat recovery from flue gases with condensing economizers. The experiments were carried out in an original experimental set-up, where atmospheric air of a certain temperature and humidity passed over a water droplet suspended on a thermocouple ball. It was demonstrated that the initial temperature of the droplet and the humidity of the gas flow are the defining factors in transitional phase changes. However, the initial droplet temperature had no effect on the equilibrium evaporation regime. The experiments performed confirmed that the humidification of the atmospheric air flow causes changes in magnitude of the heating and the phase change process of water droplets suspended in the air flow. These changes translate into an increased temperature of equilibrium evaporation of favorable conditions for the condensation regime, and a change in the dynamics of the droplet's geometrical parameters in the initial stage of phase changes. In an additionally humidified air flow, the droplet volume increased by three percent, and the evaporation temperature of the droplet increased by 17 °C. Practical recommendations for water injection were produced to ensure optimal heat recovery from wet exhaust gases in a condensing economizer.

Keywords: water droplet, humid gas flow, complex transfer processes, condensation, evaporation, experimental investigation.

Nomenclature

G is mass flow rate, kg/s; *M* is molecular mass, kg/kmol; *p* is pressure, Pa; *R* is radius of a droplet, m; Re is Reynolds number; $R_{\mu,g}$ is gas constant J/(kg K); $R_{\mu,v}$ is vapor gas constant J/(kg K); *t* is temperature, °C; *V* is volume flow rate, m³/s; X_v is vapor volume fraction; Y_v is vapor mass fraction; ρ is density, kg/m³; τ is time, s; μ is dynamics viscosity, Pa s; *w* is velocity, m/s; φ is relative humidity, %. Subscripts: *a* is atmospheric; *dr* is dry; *dp* is dew point; *e* is equilibrium evaporation; *ek is* equivalent; *eks* is experimental; *g* is gas; *l* is liquid; *lm* is average; *s* is saturation; *w* is wand; *wb* is wet bubble; *v* is vapor; *vg* is vapor-gas mixture; *TK* is thermocouple; 0 is initial state.

1. Introduction

The incineration of fossil fuels is an irrational way of producing energy, firstly, because such production causes negative effects on the environment and, secondly, because they could be widely used for other technological purposes. Hence, a swift transition to more environmentally friendly energy production technologies based on renewable sources is crucial [1, 2]. Where the natural conditions are favorable, solar, wind and hydro energy can be employed. The development of technologies exploiting the massive energy potential of biomass also looks very promising. Well-developed agricultural and forest areas give favorable conditions for the development of energy generation technologies based on biofuel gasification and

incineration [3]. Solid biofuel (usually wood chips or pellets) is traditionally incinerated in boilers to generate heat and power; it is also used in domestic boilers. Liquid biofuels (usually a mix of liquid fuels or water emulsion) are increasingly used in engines and the energy sector.

Biofuel chips are usually stored in open air facilities and accumulate moisture, which could reach up to 50 percent, hence a wet flue gas is generated during the incineration process. Wet flue gas contains a large energy potential for water vapor phase changes (most commonly, it is wasted during the usual technological processes) because the volumetric fraction of water vapor in the flue gas mixture can be $X_v=0.4$ and more [4]. Water vapor forms in the flue gas when biofuel moisture evaporates and hydrogen or hydrocarbons incinerate. After the biofuel boiler, the flue gas is directed to the condensing economizer where it is cooled down before discharge into the atmosphere and where the phase change heat is recovered from water vapor. The most popular arrangements are contact-type or shell and tube-type condensing heat exchangers where the flue gas is cooled down to ≈ 40 °C and dried to $X_v \approx 0.07$. A heat pump in the condensing heat exchanger could increase the level of cool down and drying of the exhaust gas even further.

The condensing heat exchanger technology often employs water injection [5]. In a contact-type condensing shell and tube heat exchanger, water vapor is condensed from the flue gas directly onto the injected water droplets. The important thing is that the water must be of lower temperature than the dew point temperature (the incipience of surface evaporation of rapidly heated droplets must be prevented). The collected injected water and condensate are used to heat water (often in a duct-type heat exchanger) which results in a possible rapid contamination of the intermediate heat exchanger. This could be prevented by cleaning the flue gas from ash before the flue gas enters the contact-type condensing shell and tube heat exchanger (wet treatment technology recommended). In a shell and tube type economizer, water vapor is condensed when the flue gas flows through the tubes. Water is sprayed above the tubes to induce thermo-hydrodynamic transfer processes. In this case, the flue gas must also be cleaned from ash before it enters the condensing economizer. It would also be beneficial to cool the flue gas down to a temperature close to the dew point, so that the condensing process in the economizer could start faster (a compact economizer is preferred because of expensive non-ferrous metal tubes).

The emission of fine particles from power plants could cause many environmental issues. Water and vapor phase change processes are widely employed to make fuel incineration technology more efficient, to clean the flue gas of solid particles and to lessen the concentration of toxins [6-12]. It was experimentally demonstrated [6] that there is a decrease in the emissions when using a cold condensing scrubbing method, where an inward Stefan flow would be created through water vapor condensing on cold droplets to speed up the solid particle capture from a saturated flue gas. A double-tower cascade wet flue gas desulfurization system based on water vapor condensation is effective. It was numerically and experimentally confirmed [7] that in the supersaturated water vapor environment created, fine particles could merge into larger condensation droplets, and then they can be effectively removed in the secondary tower. A phase transition agglomeration technology was developed based on condensational growth and enhanced removal of particles and droplets under supersaturated conditions [8]. Advanced water-lean solvents are being introduced to capture CO₂ after combustion, but the implementation of these new CO₂ capture technologies depends on the successful control of amine emissions. The water wash helps in reducing both gaseous and aerosol-born amine emissions, and the operating parameters of water wash systems were found to have an effect on mist formation, droplet growth and emission levels [9]. However, it is necessary to draw attention to the fact that small droplets provide nucleation sites for aerosols, and therefore the overall amine emission concentration in the flue gas can even increase [10].

Therefore, modern fuel combustion technology requires that water injection to the flue gas is organized purposefully and optimally. In order to do that, one should know the regularities of phase changes of water droplets. In the cases of the water injection into flue gas flow, the boundary conditions for the heat and mass transfer processes of droplets vary widely. Therefore, it is important for engineering practice to know well the regularity of droplet phase changes in the possible condensation, transient evaporation and equilibrium evaporation regimes (explosive evaporation is unlikely here).

The process of heat and mass transfer of droplets (mostly water and liquid fuels) has been investigated theoretically and experimentally for over a century, and the main results are well summarized in the monographs [13-15]. However, due to the wide use of dispersed fluid [16], the focus on this problem is

not diminishing. The first investigations focused on the evaporation of pure liquid droplets in an atmospheric air flow [13]. Later, the spectrum of the investigations broadened and the evaporation of droplets of liquids and their mixtures was investigated in a wider range of boundary conditions of heat and mass transfer processes. The investigations performed also concentrated on the evaluation of the Stefan flow influence on convective heat and mass transfer [14]. The modern investigation today concentrates on the transient processes of heat and mass transfer in droplets. Exceptional attention is also directed to the influence of spectral radiation on droplets evaporating in high-temperature flows [15]. The experiments performed over recent years on water droplet heat and mass transfer processes have been focused on the technological applicability of the results obtained [17–21]. The influence of mist droplets on heat transfer and the thermal performance of the heat sink was analyzed [17]. Slug formation and droplet accumulation in the flow channels was investigated in detail [18]. Air-side heat transfer enhancement through a frozen water droplet vortex generator using patterned surface wettability was demonstrated [19]. NO_x emission reduction possibilities were investigated by injecting water into the gas turbine compressor [20]. New-generation heat carriers based on water droplets for firefighting and flame cleaning from various impurities were investigated in [21].



Fig. 1. The experimentally obtained results of the temperature of water droplets in equilibrium evaporation:
(1) Ranz-Marshal [22], (2) Langstroth-Diehl-Winholde [23], (3) Nishiwaki [23], (4) Kobaiyasi [23], (5) Fedosejava-Polishcuk [23], (6) Apashev-Malov [23], (7) Downing [24], (8) Ivanov-Smirnova [25], (9) Yuen-Chen [26], (10) Strizhak et all. [27], (11) Volkov-Strizhak [28], (12) Ramanauskas et all. [29].

The droplet thermal state and phase changes are defined by the intensive interaction between the transfer processes in the flow of two-phase gas and dispersed water. The experiments performed confirmed that the equilibrium between the flows of heat transferred to the droplet and evaporative heat becomes constant, and the droplets enter the equilibrium evaporation state. In this state, the whole flow of the heat transferred to the droplet evaporates the water, when heated to the characteristic temperature t_e , which clearly depends on the gas temperature t_g but is lower than the temperature of the saturation state t_s [22–29]. The experimental temperatures of water droplets in equilibrium evaporation are summarized in Figure 1. Ranz W.E., Marshall W.R. [22] and G.O. Langstroth [23] experimentally measured the 5 °C t_e temperature while the water droplet was evaporating in an air flow of 20 °C. In the experiments conducted by N. Nisiwaki [23], when the droplet was evaporating in an air flow of 435 °C, the measured t_e was \sim 70 °C, and with the higher air temperature of 500 °C, the measured t_e was lower, i.e., \sim 68.5 °C. The experiments

[27] carried out in an original experimental set-up and employing modern advanced measuring methods confirmed the non-homogeneous heating of the water droplet's inner layers and defined the change in equilibrium evaporation by temperature t_e from 10 °C to 60 °C, when the air flow of 50 °C is heated to 400 °C. These results confirm the data from previous experiments [22–26].

Thus, the experimental temperatures t_e of the equilibrium evaporation of the water droplet are different in air flows of the same temperature, e.g., t_e varies from 28 °C to 46 °C in an air flow of 100 °C, and from 60 °C to 71 °C in an air flow of 400 °C (Fig. 1) (when t_g rises significantly, t_e is close to t_s and its sensitivity to the growing t_g weakens). This confirms the assumption that the temperature of the gas is not the only factor defining the equilibrium evaporation regime in water droplets. Experimental investigations of water droplet heat and mass transfer often ignore the factor of air humidity. Of all the cases presented in Figure 1 the air humidity had been defined only in experiments [22] and [29]. In [29], the measured temperature t_e of water droplets in equilibrium evaporation was 54–59 °C in an air flow of less than 100 °C and when additionally humidified with vapor was 10–30 °C higher than the temperature t_e in the data of previous measurements (Fig. 1). Hence, this confirms a possible significant influence of flue gas humidity on phase changes of injected water droplets.

The influence of radiation on droplet equilibrium evaporation was experimentally confirmed in [21, 25]. The thermal processes of water droplets heated by conduction, convection or radiation differs, and the temperature distribution in the droplets is also different [21]. In the case of the combined heating under small effect of convection (a large water droplet 2R>1 mm was suspended in an experimental chamber on a glass capillary in an air flow of 0.01 m/s velocity; the airflow was heated to 870 °C by radiation from a heated iron wall), when the wall temperature was 400 °C, the equilibrium evaporation started in the water droplet at $t_e \approx 60$ °C [24]. This temperature t_e is similar to the temperature of droplets evaporating in a radiation-free air flow. However, when the droplets evaporated in the radiative environment at 860 °C, the measured temperature t_e was nearly 95 °C [25] (this confirms a markedly increased influence of high temperature wall radiation on droplet evaporation). The surface layers of water droplets evaporating at high temperatures may heat up even to the temperature of the saturation state [21]; however, this does not mean that the water in the evaporating droplet will start boiling. However, intense laser heating can cause an explosive evaporation regime of the water droplets [30].

The phase changes of droplets is defined by vapor flow g_v , kg/s. The change in vapor flow (described by temporal function $g_v(\tau)$) defines the dynamic that happens within the surface area of droplets and which is relevant to the intensity of inter-phase heat and mass change. The surface area of water droplets in equilibrium evaporation decreases linearly (in literature, this is known as the D2 law [31]). In the case of combined heating, the equilibrium evaporation depends not only on the ambient radiation temperature, but also very clearly on the dispersity of the droplets [25]. The temperature of the water injected into the flue gas flow has an undeniable influence on phase change processes in the droplets. Experimental investigations of water droplet evaporation temperature lower than 100 °C confirmed that the droplets cool down to the equilibrium evaporation temperature t_e when the droplet initial temperature t_l is higher than t_e [29, 32]. Hence, this confirms the high intensity between the heat and mass transfer processes during phase change regimes in the droplet.

Thus, the equilibrium evaporation of dispersed water droplets has been widely investigated under different heat and mass transfer boundary conditions in droplets. However, the phase change processes of water droplets in transient phase change regimes (especially, in the condensation regime) are significantly relevant to fuel incineration technologies, and yet those processes have not been investigated thoroughly. The evaluation of the influence that the humid exhaust flue gas has on the heating of sprayed water droplets and on the process of water vapor condensation is very significant for condensing economizer technology. This paper presents experimental investigations of the impact of the humidity of the gas flow and the impact of the injected water temperature in the condensing economizer on the droplet's thermal state and transient phase changes.

2. The methodology of the experiments and result processing

It was assumed that the biofuel flue gas that reaches the condensing economizer had already been

cleaned from solid particles. Hence, during the experiments, the biofuel flue gas was modeled as an additionally humidified atmospheric air flow pre-heated to a specific temperature.

The experimental results defined the influence of the initial water temperature and the heated and humidified air flow on heat and mass transfer processes in a large experimental water droplet suspended on a thermocouple ball. The experiments were carried out with an atmospheric air flow heated up to 130 °C and additionally humidified to the water volumetric fraction $X_{v,a}$ =0.3. Figure 2 shows the principal scheme of the experimental setup.



Fig. 2. The principal scheme of the experimental setup.

The systems of atmospheric air two-step heating (4 and 5) and a water vapor generator (6) as well as a flat vertical 5x5 cm experimental section fenced by glass walls (7) are the key elements of the experimental setup. An atmospheric air flow was supplied through channel L1 by an air pump (2) and controlled using a rotameter (3) and heated to a preferred temperature in consecutively connected heaters (4 and 5) of the heating system. The heated air flow, before it entered the experimental section, could be additionally humidified by vapor flux G_{ν} [kg/s] supplied through channel L2 from the vapor generator (6). The vapor flux was determined by weighing the vapor generator with a scale (8). The temperature of the air flow at the beginning, the middle and the upper part of the experimental section was measured with thermocouples T2, T3 and T5, respectively. Thermocouple T5 was installed above the droplet suspension area in the center of the experimental channel so that no additional turbulence could affect the air flow flowing past the experimental droplet. The approximate desirable temperature of pre-heated air flow was defined based on the results obtained from thermocouple T5. When the air flow in the experimental section became constant, the experimental droplet was suspended on the ball of thermocouple T4 in the air of the experimental apparatus using a mechanical pipette. The droplet was placed in the experimental section using the system of two sliding glass tubes (13). Thermocouple T4 was placed within the first glass tube and the experimental droplet was suspended on its ball. The second glass tube was installed in the experimental section and could move between the opposite walls of the section without compromising the tightness of the section. The first glass tube was inserted into the second tube together with the suspended experimental droplet; the presence of the droplet in the center of the rectangular section was then fixed (13). The

experimental droplet was pre-heated to a desired reference temperature $t_{l,0}$. The experiment started when the protective tube was withdrawn. The temperature of the experimental droplet was measured every second with thermocouple T4 and the droplet size was also recorded at 25 frames per second using a Phantom V711 camera (9) (the lighting source (10) provided additional lighting). During the experiment, a TESTO 445 instrument (1) measured atmospheric pressure, atmospheric air temperature and relative humidity. The temperature t_g [°C] of the pre-heated and humidified air flow was defined by thermocouple T4 after the water had evaporated. All thermocouples were connected to the Pico Logger TC-08 data logger (11). All collected data (measured parameters and recordings) were stored in the computer (12).

The accuracy of the experiment was determined by measuring devices and their descriptions provided and certified by the manufacturers. A Pico-Logger TC-08 has a temperature measurement accuracy of ± 0.38 °C. The TESTO 445 measures air temperature, relative humidity and pressure with accuracies of ± 0.3 °C, $\pm 2\%$ RH and ± 0.01 hPa respectively. In the evaporator, the evaporated water mass was measured with an accuracy of ± 0.5 g. The initial equivalent diameter of the droplet was defined with an average confidence of ± 0.04 mm. The measured equivalent diameter of the thermocouple ball was $2R_{TK}=0.92\pm 0.02$ mm.

The thermogram of the heating process of the experimental droplet was produced based on the temperature measurements obtained every second. The dynamics of the thermocouple ball and the diameter $2R_{ek}$ [mm] of the sphere equivalent to the total volume of the suspended water was defined based on the results obtained through the analysis of the stills. Figure 3 presents typical images of the stills. The initial diameter $2R_{ek,0}$ was defined based on the first still (Fig. 3a). The second still represents the condensation regime of phase changes and defines the instantaneous growth of the experimental droplet in the condensation regime (Fig. 3b). The third still (Fig. 3c) represents the evaporation regime and defines the decreasing diameter $2R_{ek}$ when the droplet evaporates. The fourth still (Fig. 3d) defines the diameter of the sphere equivalent to the volume of the thermocouple ball ($2R_{e,TK}\approx 0.92$ mm) and shows that the water has already evaporated.



Fig. 3. Representative photos of the experimental droplet: a) the first photo; b) photo representing the condensation regime; c) photo representing the evaporation regime; d) photo representing the thermocouple ball after the water had evaporated. Boundary conditions defined in the table below (experiment 11). Experiment time τ , s: (a) 0, (b) 2, (c) 20, (d) 100.

The droplet stills were analyzed according to recommendations set out in [33] using the specifically developed software in the MatLAB environment. The applied methodology for the analysis is described in detail in [29]. Figure 4 presents an example of the analysis of one of the stills at the initial stage of phase changes. The instantaneous diameter $2R_l$ of the sphere equivalent to the volume of the water suspended on the thermocouple ball was calculated based on the defined instantaneous diameter $2R_{ek}$:

$$2R_l = 2(R_{ek} - R_{e,TK}).$$
 (1)



Fig. 4. An example of the change in the instantaneous diameter $2R_{ek}$ defined based on the stills in the initial stage of phase changes. Boundary conditions defined in the table below (experiment 11).



Fig. 5. The variation of instantaneous diameter $2R_l$ calculated from equation (1) at the initial stage of phase changes (a) and the dynamics of diameter $2R_{l,m}$ (b). Boundary conditions defined in the table below (experiment 11).

Then the graph (Fig. 4) of the equivalent diameter $2R_{ek}$ was transformed into the graph (Fig. 5a) of the diameter $2R_l$ of a sphere equivalent to the water volume. The dynamics of the diameter of the sphere equivalent to the water volume was linked to the change for every second (similar to the measurement of temperature every second). For this to happen, an average diameter was calculated, which summed up the results of a course of 25 stills (starting with the second one), and its variation was drawn graphically, which maintained the initial value $2R_{l,0}$ (τ =0), and the calculated instantaneous diameters $2R_{lm}$ were provided consecutively every second starting from τ =0.5 s (Fig. 5b).

The supplied atmospheric air flow rate $V_a[m^3/h]$ was measured by a KROHNE H250 rotameter. Based on the atmospheric air flow temperature behind the rotameter and the selected air density, the mass flow rate G_a [kg/s] of the air supplied to the experimental section and the vapor mass flow rate $G_{\nu,a}$ [kg/s] component inside it were calculated as follows:

$$G_{a} = \rho_{a} V_{a}; \quad X_{v,a} = \frac{p_{v,a}}{p_{b}} = \frac{\phi_{a}}{100^{0}/o} \frac{p_{s}(t_{a})}{p_{b}};$$

$$Y_{v,a} = X_{v,a} \frac{M_{v}}{X_{v,a}M_{v} + (1 - X_{v,a})M_{a,dr}}; \quad G_{v,a} = G_{a} Y_{v,a}..$$
(2)

The humidity of the air flowing through the experimental section was defined by the water vapor mass $Y_{v,g}$ and volume $X_{v,g}$ fraction in the air-gas mixture:

$$Y_{\nu,g} = \frac{G_{\nu,a} + G_{\nu}}{G_a + G_{\nu,}}; \quad X_{\nu,g} = Y_{\nu,g} \frac{R_{\mu,g}}{R_{\mu,\nu}};$$

$$R_{\mu,g} = Y_{\nu,g} R_{\mu,\nu} + (1 - Y_{\nu,g}) R_{\mu,dr,a}..$$
(3)

The air flow regime in the experimental section was defined by the Reynolds number:

$$Re_{g} = \frac{\rho_{g} w_{g} l_{k}}{\mu_{g}}; \ w_{g} = \frac{G_{g}}{\rho_{g} l_{k}^{2}}; l_{k} = 0.05m.$$
(4)

3. Experimental results

During the experiments, the influence of the pre-heated and additionally humidified atmospheric flow on the thermal state of the droplet suspended in this air flow was investigated. Also the effect of the initial water temperature on transitional transfer processes was evaluated.

Boundary conditions characteristic of the technology of heat recovery from biofuel exhaust gases in condensing economizers were considered in relation to pre-heated and additionally humidified atmospheric air. Eleven experiments were conducted during which the experimental section was supplied with an air flow V_a =10.43 m³/h when p_b =999 hPa and $\varphi_a \approx 39$ %. Other experimental boundary conditions are provided in Table 1 below.

No	ta	Ga	G_{v}	tg	Reg	Re _l	$Y_{v,g}$	$X_{\nu,g}$	t_{dp}	<i>t</i> 1,0	$2R_{ek,0}$	$2R_{lm,0}$
	°C	g/s	g/s	°C					°C	°C	mm	mm
1	20.9	3.42	0	80.6	3272.5	134	0.006	0.01	6.4	24.3	1.854	1.775
2	20.9	3.42	0	81.2	3268	133.1	0.006	0.01	6.4	40.2	1.865	1.787
3	21	3.43	0	81.1	3267.6	111.7	0.006	0.01	6.5	46.4	1.567	1.453
4	21.3	3.41	0	132.1	2950	126	0.006	0.01	6.8	41.8	1.845	1.765
5	21.4	3.41	0	132.7	2946	121	0.006	0.01	6.8	60.2	1.754	1.665
6	22.1	3.4	0.2881	130.2	3373.1	164.5	0.084	0.128	50.8	40.7	2.178	2.122
7	22	3.4	0.2881	128.5	3385.2	167.7	0.084	0.128	50.8	60.1	2.193	2.138
8	21.9	3.4	0.5939	132.1	3809.2	178.5	0.154	0.226	62.8	41.8	2.148	2.09
9	22.1	3.4	0.5939	132.6	3803.4	200.1	0.154	0.226	62.8	60.3	2.383	2.336
10	22.4	3.4	0.8791	130.1	4239	217.4	0.211	0.3	69.1	41.3	2.41	2.364
11	22.2	3.4	0.8791	129.5	4246.5	192.8	0.211	0.3	69.1	60.3	2.112	2.052

Table 1. Experimental boundary conditions and main parameters

In the first five experiments, the water droplet suspended on the thermocouple ball (the experimental droplet) was suspended in an atmospheric air flow with different temperatures (in experiments 1–3, the air was pre-heated to \approx 81°C and in experiments 4 and 5 to \approx 132°C). In the remaining six experiments, the atmospheric air flow was pre-heated to 128.5–132.6 °C and additionally humidified to different levels with vapor G_v [g/s] from the evaporator (0.2881 g/s in experiments 6 and 7, 0.5939 g/s in

experiments 8 and 9, 0.8791 g/s in experiments 10 and 11).

In all experiments, the air flow regime in the experimental section was transitional (the calculated Reynolds Reg number varied from 2946 to 4246). The flow regime around the droplet was defined by a modified Reynolds number Re_l= $2R_{ek}\rho_g w_g/\mu_{vg}$, which varied from 111 to 217. The water suspended on the thermocouple ball was pre-heated in the air of the protective tube to different temperatures, from 22.6 to 60.3 °C. The temperature was recorded at the moment the droplet was withdrawn from the tube (the beginning of the experiment and $\tau=0$). Heating thermograms of the experimental droplet are presented in Figure 6. The thermograms show three periods of changing thermal state of the experimental droplet. The first period is defined by pre-heated (Fig. 7a) and humidified (Fig. 7b) air flow and is also the period when transitional processes of the droplet's heat and mass transfer take place. Also, the influence of the initial water temperature is very clear (Fig. 6). The thermal state of the droplet does not become steady during the first period and, therefore, the second period cannot be identified as the regime of droplet equilibrium evaporation. The initial temperature of water had no influence on the second period of the changing thermal state of the experimental droplet, and a consistent increase in the temperature of the experimental droplet was recorded in all cases (Fig. 6). A steep increase in the temperature of the experimental droplet is characteristic of the third period (Fig. 6). In this heating period, separate areas of the thermocouple ball start coming into direct contact with the flowing air until all of the water evaporates. The third period is important, because, based on the heated thermocouple after the water had evaporated, the local temperature t_g of the air flow around the experimental droplet can be defined.



Fig. 6. A summary of experimental thermograms of the equivalent droplet: (a) the droplet suspended in preheated air flow; (b) the droplet suspended in pre-heated and humidified atmospheric air flow. Numbers of the points correspond to the experiment numbers in the table.

In order to define the influence of the pre-heated and additionally humidified atmospheric air flow on the transitional processes of heat and mass transfer in the experimental droplet, a reference time frame of 10 seconds of the first period was chosen (Fig. 7). Then the measured temperature $t_{l,1}$ °C of the experimental droplet at the end of the first period is: (1) 41.7, (2) 44.6, (3) 46.1, (4) 62.1, (5) 64.9, (6) 70.1, (7) 71.4, (8) 75.9, (9)77.4, (10) 79.2, (10) 80.2. When the atmospheric air flow, of which the humidity according to the volumetric fraction of water vapor was $X_{v,a}\approx 0.01$, was heated to ≈ 132 °C, the temperature $t_{l,1}$ of the experimental droplet was higher by 20 °C (compared to the case of the air preheated to ≈ 81 °C). When the atmospheric air flow was heated to ≈ 130 °C and additionally humidified to $X_{v,a}=0.128$, $X_{v,a}=0.226$ and $X_{v,a}=0.3$, the temperature $t_{l,1}$ increased by about 7 °C, 13 °C and 17 °C, respectively, (compared to the case of the atmospheric air pre-heated to ≈ 132 °C). Thus, this is a clear consequence of additional humidification. The temperature $t_{l,1}$ measured in the air flow that was pre-heated to the temperature similar to the temperature t_g and uniformly humidified was practically the same within the limits of the measurement error, irrespective of the initial water temperature (Fig. 7b).

The discrepancy of $t_{l,1}$ 3–5 °C obtained for the droplets with different initial water temperatures in the case of pre-heated atmospheric air (Fig. 7b) was most probably caused by the higher sensitivity of the thermal state of water equilibrium evaporation to the boundary conditions of the droplet's heat and mass transfer, when the droplet evaporates in a low humidity air flow. Hence, the experiments confirmed that the initial temperature of water has no influence on the equilibrium evaporation regime; however, the initial water temperature and additional humidification of the air flow are the defining factors of the transitional phase change regime.



Fig. 7. Experimental thermograms of the equivalent droplet at the initial stage of phase changes: (a) the droplet suspended in pre-heated air flow; (b) the droplet suspended in pre-heated and humidified atmospheric air flow. Numbers of the points correspond to the experiment numbers in the table.

The influence of the tube withdrawal on the heating dynamics of the experimental droplet can be seen at the beginning of the thermograms (at ≈ 2 s): there are fluctuations in the curve representing the measured t_l temperature (Fig. 7). An especially interesting case is recorded in the thermogram of the third experiment where the experimental droplet heats up at the beginning (for about 2 seconds) and then later cools down (in the first period of the thermal state change) (Figure 7a, curve 3). The conditions for this occasion formed during the process of droplet pre-heating to a desired reference temperature in the tube. The level of air humidity in the tube could have exceeded the level of air flow humidity in the experimental section because of water evaporation, and then the equilibrium evaporation temperature of the water in the air of the tube could have been higher. In such a case, conditions could have formed that allowed the droplet to heat up to a temperature higher than the temperature of equilibrium evaporation of water in the air flow. At the moment of tube withdrawal, the droplet was heating up for two seconds under the influence of the air within the tube, until it appeared in the air flow of lower humidity and started to cool down (its temperature was approaching the equilibrium evaporation temperature defined by the air flow humidity). Later, under the influence of additional heat supply by thermocouple wires, the experimental droplet started heating up again in the second period (Fig. 6a, curve 3).

The equilibrium evaporation temperature of water is approaching the temperature t_{wb} of the wetbulb thermometer, which is defined by the air temperature and relative humidity [34]. The temperature $t_{wb,eks}$ of the wet-bulb thermometer congruous with the boundary conditions of the experimental droplet heat and mass transfer is defined according to the algorithm:

$$t_{g,eks}, X_{v,g,eks}, p_b \to p_{v,s} = p_s(t_{g,eks}); p_{v,g} = X_{v,g,eks}p_b \to \phi_{g,eks} = \frac{p_{v,g}}{p_{v,s}} 100^{\,0}/_{0};$$

$$\phi_{g,eks}, t_{g,eks} \to t_{wb,eks} \ [34].$$
(5)

The following temperatures $t_{wb,eks}$, °C of the wet-bulb thermometer of the experimental droplet were defined: (1) 30.02, (2) 30.14, (3) 30.12, (4) 38.69, (5) 38.75, (6) 56.86, (7) 56.75, (8) 66.23, (9) 66.25, (10) 71.12, (11) 71.8. These temperatures $t_{wb,eks}$ congruous with the boundary conditions of the experimental droplet heat and mass transfer are treated as approximate (during the experiments, the measured pressure of atmospheric air was $p_b=999$ hPa, while in the database [34] the indicated atmospheric pressure is $p_b=1013.25$ hPa). The defined temperatures $t_{wb,eks}$ are extremely important to the validation of the numerical model (the calculated thermal state of equilibrium evaporation of the water droplet should correlate well with the temperature $t_{wb,eks}$ when the boundary heat and mass transfer conditions are congruous). It is impossible to define the end of the transitional evaporation regime of the experimental droplet according to the temperature $t_{wb,eks}$. This happens because the experimental droplet is complex and includes the solid material (in this case it was the thermocouple ball of 0.92 mm equivalent diameter, to which heat was additionally supplied through the thermocouple wires). In the second period of the thermal state change, the measured temperature $t_{l,2}$ showed a clear deviation (exceeding 10 °C) from the temperature $t_{wb,eks}$ of the wetbulb thermometer, and thus proved the significant influence of additional heat supply by the thermocouple wire on the heat and mass transfer processes of the experimental droplet. The influence grew even more in the second period when water evaporated from the thermocouple ball.

In experiments 1–5 and 7, the initial temperature of the droplet $t_{l,0}$ was higher than the dew point temperature of the air flow t_{dp} in which the droplet was suspended ($t_{dp}\approx 6.5$ °C in experiments 1–5 and $t_{dp}\approx 50.8$ °C in experiment 7). As a result, once the protective tube was withdrawn, the process of transitional water surface evaporation started immediately in these experiments, and the heat supplied to the droplet at the same time heated and vaporized the water. In other experiments, the initial temperature of the droplet $t_{l,0}$ was lower than the dew point temperature t_{dp} of the humidified air flow. These experiments began with the condensation phase change regime, during which the droplet was heated not only by the heat from heat transfer processes, but also additionally by the phase change heat released during the process of vapor condensation. The change from the condensation regime to the transitional evaporation regime was recorded at the moment when the surface of the experimental droplet was heated to the dew point temperature.

Transitional phase change regimes defined the dynamics of the experimental droplet's diameter $2R_{ek}$ in the first period of thermal state change (Fig. 8). The dynamic was specific in the heated atmospheric air flow (Fig. 8a) and in the additionally humidified air flow (Fig. 8b). This is very clear from the dynamics of the diameter $2R_{lm}$ of the sphere equivalent to the volume of the water suspended on the thermocouple ball (Fig. 9). In experiment 10, the diameter of the droplet increased by one percent in the humidified air flow in the initial stage of phase changes (Fig. 9b, curve 10). This was due to the expansion of the heated water and the condensate collected on the droplet's surface. When the water evaporation process compensated for the expansion of the heated water, the droplet's volume started decreasing (Fig. 10).

The volume of the water suspended on the thermocouple ball increased by up to three percent during the heating in humidified air (mainly under the influence of the condensation process) (Fig. 10a). Only in experiment 7 vapor did not condense when the droplet was heated up in humidified air (the initial temperature of the droplet was higher than the dew point temperature). In the air flow that was not additionally humidified, the water volume of the experimental droplet increased slightly because of the expansion of the heated water only in experiment 1 (Fig. 10b, curve 1). In this experiment, the initial temperature of the water was the lowest, and the droplet heated up to the highest temperature (up to about 20°C) in the atmospheric air flow in the transitional evaporation regime (Fig. 7a, curve 1). In other cases of the droplet heating up in a non-humidified air flow, the evaporation process compensated for the expansion of the heated water, and thus the volume of the water suspended on the thermocouple ball was decreasing from the beginning of the experiment (Fig. 10b, curves 2–5).

The experimental results of the investigation of the heating and phase changes of the water droplet suspended in pre-heated and humidified air flow demonstrated that the humidity of the gas flow is the defining factor in the droplet's heat and mass transfer processes.



Fig. 8. The change in the experimental droplet's dimensionless diameter in the transitional phase change regime: (a) the droplet suspended in pre-heated atmospheric air flow; (b) the droplet suspended in pre-heated and humidified atmospheric air flow. Numbers of the points correspond to the experiment numbers in the table.



Fig. 9. The change in the experimental droplet's diameter $2R_{lm}$ (a) and dimensionless diameter $R_{lm/R_{lm,0}}$ (b) in the transitional phase change regime. Numbers of the points correspond to the experiment numbers in the table.



Fig. 10. The increase in the volume of the water suspended on the thermocouple ball in the condensation regime when the heated water expands and the droplet is increased due to condensate (a) and the change in the evaporation regime when the water heats up (b) in the initial stage of phase changes. Numbers of the points correspond to the experiment numbers in the table.

4. Conclusions

The following conclusions were drawn after the experimental investigation of phase changes of water droplets in wet flue gas flows:

- 1. It was experimentally demonstrated that the temperature of the sprayed water and the humidity of flue gas flow are the factors defining the transitional phase changes of the droplets in the flue gas flow. However, the initial water temperature has no influence on the equilibrium evaporation process of droplets.
- 2. The experiments confirmed that the additional humidification of atmospheric air flows results in changes in magnitude of the heating of the water droplet suspended in the flow and also in phase change regimes. The changes include an increase in the temperature of equilibrium evaporation, the conditions necessary for the condensation regime, and a change in the dynamics of geometrical parameters (diameter, surface area and volume) of the droplets at the stage of phase changes.
- 3. During the experiments it was confirmed that, under the influence of additionally humidified atmospheric air, the temperature of the evaporating water droplet increased by 17 °C and the droplet's volume increased by three percent in the condensation regime.
- 4. In humid flue gas flows, the change in the thermal state of water droplets and the variation of phase change regimes are closely connected. When planning water injection to biofuel exhaust gas flows, the technological goal must be clearly defined and optimal conditions at which phase changes in water droplets occur must be ensured according to their initial temperature and dispersity.

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Declaration of interest

Conflicts of interest: none

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