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15th International Conference Applied Thermal Engineering

Heat Transfer Fluid Mechanics and Thermodynamics

Applied Thermal Engineering

VIRTUAL CONFERENCE

26-28 July 2021

PROCEEDINGS

15th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics

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AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF AIRFLOW HEATING AND HUMIDIFICATION ON A WATER DROPLET'S THERMAL STATE AND PHASE CHANGES

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ABSTRACT

This experimental investigation highlights the influence of the temperature and humidity of gas flow on water droplet phase changes for the effectiveness of technologies designed to recover heat from exhaust wet flue gas. The experiments were carried out in an original experimental rig where a water droplet hanged on a thermocouple in the atmospheric pressure airflow of 21ºC, which was then heated to the temperature of 112–114ºC and humidified to different levels. The airflow was humidified by vapor from a water evaporator. The vapor flow was defined by weighting the vapor generator. In the experimental rig, the humidity of the flowing air was defined by the volume and mass fractions of water vapor calculated based on the flows of heated atmospheric air and additionally supplied water vapor. Thermal images of the heating droplet were taken every second measuring the temperature of the water covering the thermocouple ball. A variation diagram of the droplet equivalent diameter was compiled by image recognition code analysing the photos of synchronous filming (25 frames per second). The droplet equivalent diameter was defined as the diameter of a sphere whose volume equals to the volume of the droplet covering the ball. The results of the experiment demonstrated the substantial influence of additional air humidification on the intensity of transfer processes in droplets in transitional as well as equilibrium evaporation regimes. Furthermore, additional humidification also significantly influences the variation of the droplet's thermal state. The temperature of equilibrium evaporation is also affected by air humidification, but the initial temperature of water is influential only in the transitional phase change regime. The results confirmed that transitional regimes could be defined qualitatively using dimensionless parameters expressed through the ratio of the dew point temperature with the droplet equilibrium evaporation temperature and the initial droplet water t_0 temperature.

INTRODUCTION

The technological applicability of liquid droplets is rather wide [1]. Transfer processes in two-phase flows of water droplets and gas define the effectiveness of such technologies as air conditioning, water-cooling in towers, wet cleaning of gases, waste heat recovery, and surface protection against intensive thermal effect [2–5]. Heat and mass transfer processes in water droplets play a significant role also in numerous atmospheric phenomena and are also used to clean polluted technological wastes generated in energy and industrial sectors. The combustion of various fuels generates thermal energy. In economic and environmental terms, fossil fuels should be used very moderately. The development of technologies based on renewable sources is a priority in our modern world [6].

NOMENCLATURE

G	[kg/s]	Mass air/gas flow rate
M	[kg/kmol]	Molecular mass
p_B	[Pa]	Barometrical pressure
R	[m]	Equivalent radius of a droplet
R_M	[J/(kmol K]	Universal gas constant
t	[°C]	Temperature
V	[m^3/s]	Volumetric air/gas flow rate
X	[-]	Volume fraction
Y	[-]	Mass fraction

Special characters

ρ	[kg/m^3]	Density
τ	[s]	Time

Subscripts

a	Air
co	Condensation
dp	Dew point
dr	Dry
e	Equilibrium evaporation
f	Phase transformation
g	Gas
l	Liquid
s	Saturated
v	Vapor

Technologies using biofuel combustion for energy generation are considered as an alternative to the combustion of fossil fuels. Flue gas of high humidity levels form during the combustion of hydrogen and evaporation of biofuel humidity (the water vapor mass fraction Y_v in a flue gas could reach 0.4 and more [7]). Flue gas must be cleaned, and waste heat must be recovered in a condensing economizer by cooling and drying the flue gas before its exhaust to the atmosphere. Water spray is frequently used in biofuel combustion technology (often the water vapor condensate is used as the sprayed water). In order to increase the efficiency of heat recovery, the exhaust flue gas should be cooled down and additionally humidified with sprayed water, so that it could enter the condensing economizer with a temperature close to the dew point temperature. For this purpose, the exhaust flue gas (with a temperature from 150ºC to 180ºC) must be cooled down to 90–100ºC. During the cool down, a significant amount of additional humidity is added to the flue gas. Water spray is also important in the condensing economizer, where flue gas is cooled down to about 40ºC and dried to $X_v \approx 0.07$.

Multiple factors affect the intensity of heat and mass transfer processes in water droplets sprayed to flue gas flow [1, 8]. An individual effect depends on the flue gas flow and parameters of the sprayed water. In this respect, the flue gas flow temperature and droplet dispersity are considered as key parameters [8]. It is very important to ensure optimal conditions for water droplet phase changes. This calls for considerable knowledge of the regularities in water droplet heat transfer and phase changes for different cases of the water sprayed to wet gas flow. The influence of the relative humidity of atmospheric airflow on the heat exchange, vaporization and thermal state of water droplets was experimentally investigated in [9]. The influence of increased relative humidity caused by heating of atmospheric air flow to a temperature lower than 100ºC and additional humidification was experimentally investigated in [10, 11]. These experimental investigations [9–11] of droplet heat and mass transfer can be considered as corresponding to the boundary conditions of the transfer processes happening in the water sprayed to a condensing economizer. The present investigation evaluates the effect of humidified atmospheric airflow, which was heated to a temperature higher than 100ºC, on water droplet phase changes in the context of flue gas effective cooling before a condensing economizer.

METHODOLOGY

The experiments were carried out in an original experimental rig, whose basic setup was presented in detail in [10]. The main constructive components of the rig were an atmospheric air heater, a water vapor generator, and a 5x5 cm vertical experimental section fenced by glass walls. A water droplet was formed on the thermocouple ball with a mechanically regulated pipette, which meters water volume. A droplet was placed in the centre of the experimental section using a special system constructed of two tubes and ensuring the tightness of the channel. Measurements of the droplet temperature were taken every second, and a Phantom V711 camera was filming at the same time 25 frames per second. The parameters of the atmospheric air (temperature, relative humidity and barometric pressure) were measured by a TESTO 445 device. This investigation applied a two-step principle to form the air flow in the channel. The first step was to heat the atmospheric air flow to 60–80ºC and to humidify it to the desired level with vapor flow Gv [kg/s] from the water evaporator. The second step was to heat up the humidified airflow to a reference temperature defined in the experimental conditions. The flow rate of the supplied atmospheric air was measured by a KROHNE H250 rotameter, which had been calibrated in a certified laboratory. Thermocouples measured the air flow temperature after the rotameter, before and after the heaters, and at the inlet and outlet of the experimental section. The temperature of the heated air t_g [^{o}C] flowing around the droplet was identified measuring the temperature of the thermocouple ball after the surrounding water droplet had vaporized. All used thermocouples were connected to a Pico Logger TC-08 data logger.

The accuracy of the experiments was determined by comparing the measurement readings to the descriptions of the used measuring devices provided and certified by their manufacturers. The Pico Data Logger TC-08 has a temperature measurement accuracy of ± 0.38ºC. The TESTO 445 measures air temperature, relative humidity and pressure at the accuracies of ± 0.3ºC, ± 2 % rH and ± 0.01 hPa, respectively. In the evaporator, the evaporated water mass was measured with the accuracy of ± 0.5 g. The initial equivalent diameter of the droplet was defined with the average accuracy of ± 0.04 mm.

The air flow rate G_a [kg/s] and the component of water vapor flow $G_{v,a}$ [kg/s] in it was defined by the equation:

$$G_a = V_a \rho_a; \;\; G_{v,a} = G_a Y_{v,a} \tag{1}$$

Water vapor mass fraction $Y_{v,a}$ in atmospheric air was calculated based on the parameters measured in the air:

$$Y_{v,a} = X_{v,a} \frac{M_v}{X_{v,a} M_v + (1 - X_{v,a}) M_{a,dr}} \; ;$$
$$X_{v,a} = \frac{p_{v,a}}{p_b} = \frac{\phi}{100\%} \frac{p_s(t_a)}{p_b}. \tag{2}$$

In order to humidify atmospheric air additionally water vapor flow G_v [kg/s] was supplied. The water vapor flow was measured by weighting the vapor generator at the beginning and end of each experiment. The humidity (water vapor mass and volume fractions) of the air flowing through the experimental channel was calculated taking into account the components of dry air and water vapor flow:

$$Y_{v,g} = \frac{G_{v,a} + G_v}{G_a + G_v};$$
$$X_{v,g} = Y_{v,g} \frac{R_M}{M_v} \frac{1}{Y_{v,g} \frac{R_M}{M_v} + (1 - Y_{v,g}) \frac{R_M}{M_{a,dr}}} \; . \tag{3}$$

All measured parameters and filming data were automatically saved in a computer. Thermograms of the heated droplet were created based on the results obtained measuring the droplet's mass average temperature every second. The droplet size was defined by the initial $2R_0$ [mm]-equivalent diameter that was considered to be the diameter of a sphere whose volume equals to the volume of the droplet covering the thermocouple ball. The variation in the droplet equivalent diameter was defined by the results obtained after a thorough analysis of 25 stills (filming every second), excluding the equivalent diameter of the thermocouple ball. Figure 1 presents an example of the stills. The analysis of the stills was performed according to the recommendations [12], with optical view processing code developed in MATLAB. The applied analysis method is described in detail in [11].

Figure 1 An example of a droplet photo

RESULTS

The atmospheric airflow at the inlet to the experimental section had a temperature t_a≈21ºC and the relative humidity φ_a≈47 %, when p_b=1005 hPa. Five experiments were carried out, and during each of them, the volumetric airflow rate was V_a≈16.27 m^3/h. During the first experiment, the droplet was in the atmospheric airflow that was heated to ≈30ºC. The water droplet with the initial temperature of 17ºC evaporated fully, and the thermocouple ball heating time up to the atmospheric air temperature is about 555 seconds (Fig. 2a). During the second and third experiments, the atmospheric air temperature was ≈114ºC, but the initial temperature of the droplet was different, i.e. 20.2ºC and 22.7ºC, respectively (Fig. 3).

The water droplet fully evaporated, and the temperature of the thermocouple ball increased till the atmospheric air temperature in about 87 and 83 seconds during the second and third experiments, respectively (Fig. 3a). Although in the transitional evaporation regime, the droplet's heating differed during the second and third experiments (Fig. 3b), the equilibrium evaporation of the droplet started at the same temperature of t_e≈40.6ºC in both experiments. Both experiments were carried out at close boundary conditions, and therefore, within the temperature measurement accuracy the thermograms correlate rather well in the equilibrium evaporation regime (Fig. 4a) and confirm the reliability of the experimental methodology.

During the fourth and fifth experiments, the atmospheric airflow was humidified to different levels by supplying the vapor flow of G_v≈0.26 g/s and G_v≈0.89 g/s, respectively.

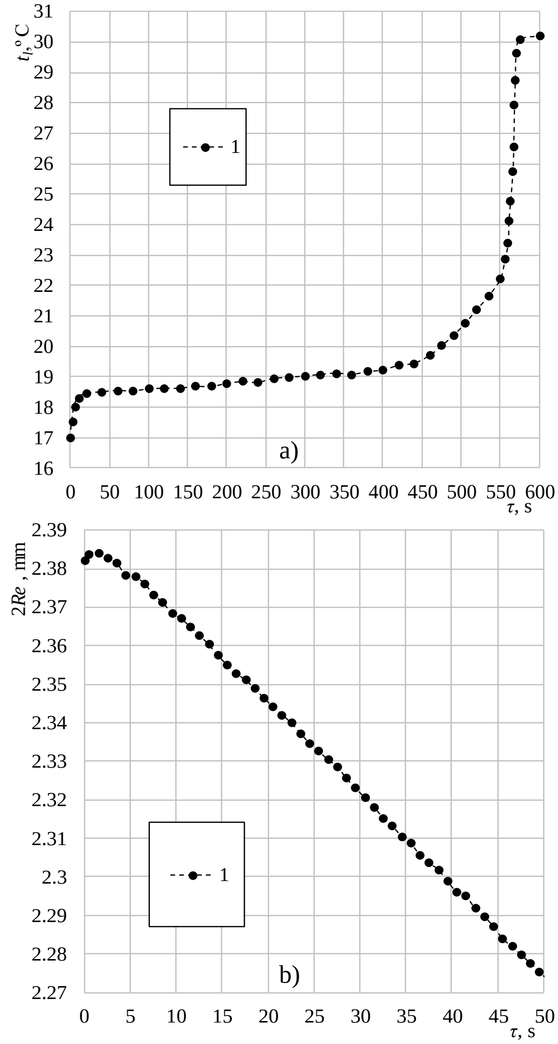

Figure 2 A thermogram showing a droplet heating up in the airflow (a) and the dynamics of the equivalent diameter (b), when t_g=30.1ºC and $X_{v,a}$=0.0116. Exp. No. 1.

In both experiments, the humidified air was heated to the same temperature, i.e. ≈111ºC, and flowed around the droplet that had different initial temperatures, namely 17.5ºC and 25.7ºC, respectively (Figure 4). The water droplet in the airflow humidified to different levels not only heated up differently in the transitional evaporation regimes (Figure 4a), but also evaporated in the equilibrium regime at clearly different) temperatures, i.e. ≈50ºC and ≈68.2ºC, respectively (Figure 4b). Therefore, the temperature of the water droplet during equilibrium evaporation in heated and additionally humidified airflow is higher compared to the case of droplet evaporation at atmospheric airflow conditions. In each experimental thermogram, it is easy to notice and distinguish between characteristic initial, middle, and final temperature variation periods (Figures 2–4), which can be explained and substantiated by the specificity of droplet heating and phase changes. In the initial period, which is represented by the transitional phase change regime, water in the droplet is intensively heated by internal heat convection diverting a significant amount of external heat convection (in the condensation regime it means all heat additionally generated in the condensation process, until the droplet surface heats up to the dew point temperature). The middle and final periods are indicating the regime of the equilibrium evaporation of the droplet. The equilibrium evaporation regime of surface water begins when the balance between the flow supplied to the droplet by external convection and the heat flux of phase changes settles. According to the Reynolds analogy, the energy balance between convective heat and mass transfer processes in a freely moving droplet remains during the whole equilibrium evaporation regime. In this case, the droplet hangs on the thermocouple ball, and therefore additional heating of the droplet occurs by conduction through the thermocouple wires. In the transitional region of phase changes and in the initial stage of equilibrium evaporation, heat transfer through the thermocouple wires had no significant influence because droplet is comparatively rather big, and therefore, in the middle part of the thermogram, the droplet temperature remains practically unchanged (Figure 2a, 3, 4).

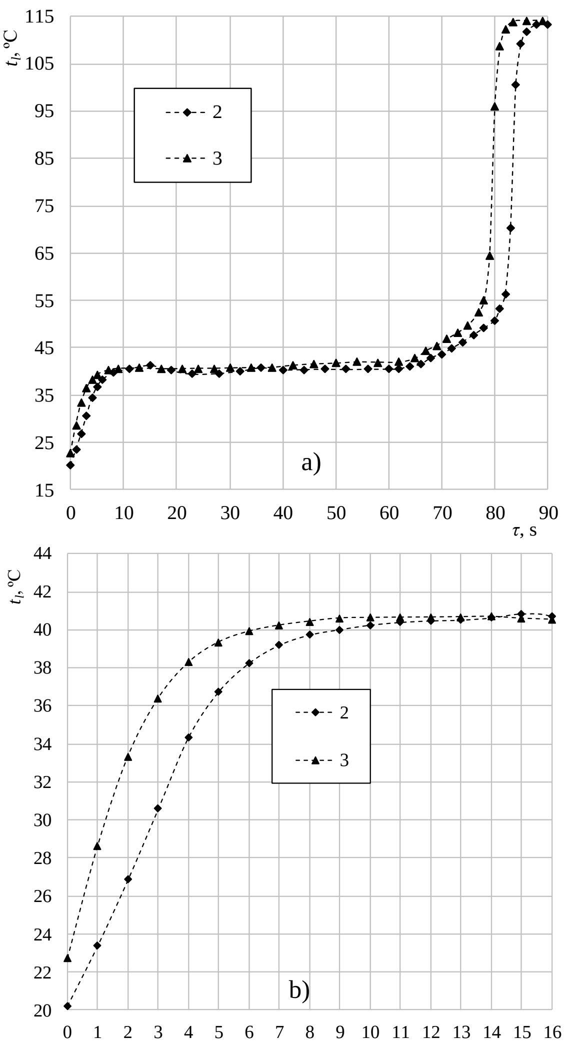

Figure 3 A thermogram showing a droplet heating up in the air flow (a) and the thermogram's initial stage (b), when t_g,°C: (2) 113.5, (3) 113.9 and $X_{v,a}$=0.0116. Exp. No. 2 and 3.

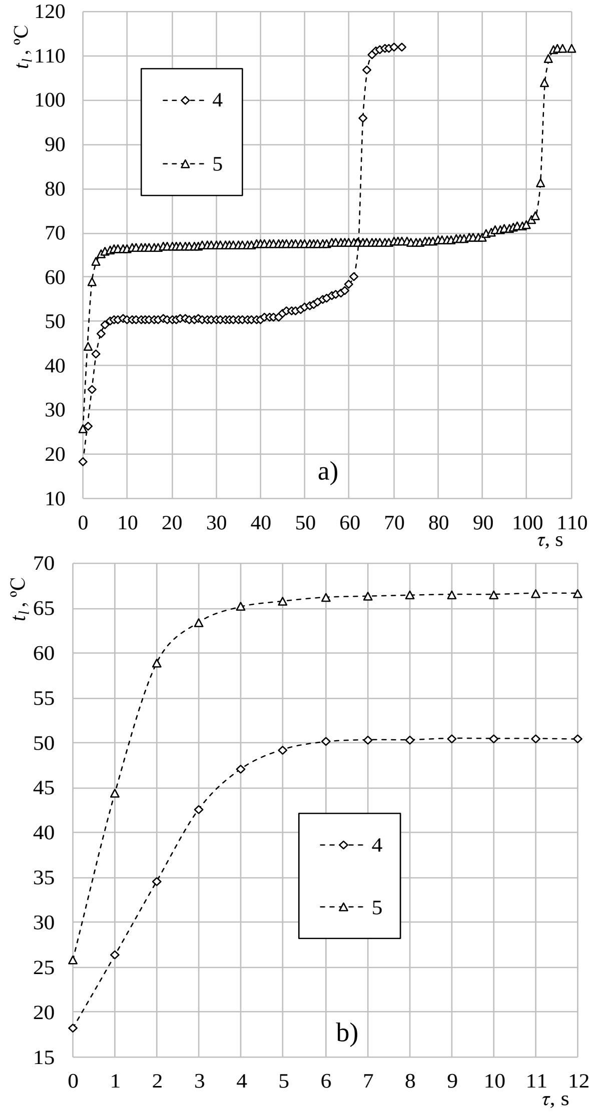

Figure 4 A thermogram showing a droplet heating up in the heated and humidified airflow (a) and the thermogram's initial stage (b), when t_g,°C: (4) 111.4, (5) 111.3; G_v, g/s: (4) 0.264, (5) 0.893; $X_{v,g}$: (4) 0.084, (5) 0.22. Exp. No. 4 and 5.

As equilibrium evaporation begins, the droplet starts to decrease rapidly (Figure 2b, 5, 6), and hence the influence of heat transfer through the thermocouple wires on the droplet energy balance starts to increase. This gives what is presented at the final stage of the thermogram: the increase in the droplet temperature is slight at first but starts to grow gradually after a while, and finally, after the water fully evaporates the thermocouple ball heats up to the flowing air temperature. Hence, the experimental results can be considered as rather accurately reflecting the influence of heated and additionally humidified airflow on the transitional regime in water droplets and the thermal state of equilibrium evaporation. Three stages can also be distinguished in the experimental diagrams of the droplet equivalent diameter. The first and second stages are clear in the case of heated airflow with higher humidity (Figure 7) when the initial water temperature in the droplet is lower than the dew point temperature.

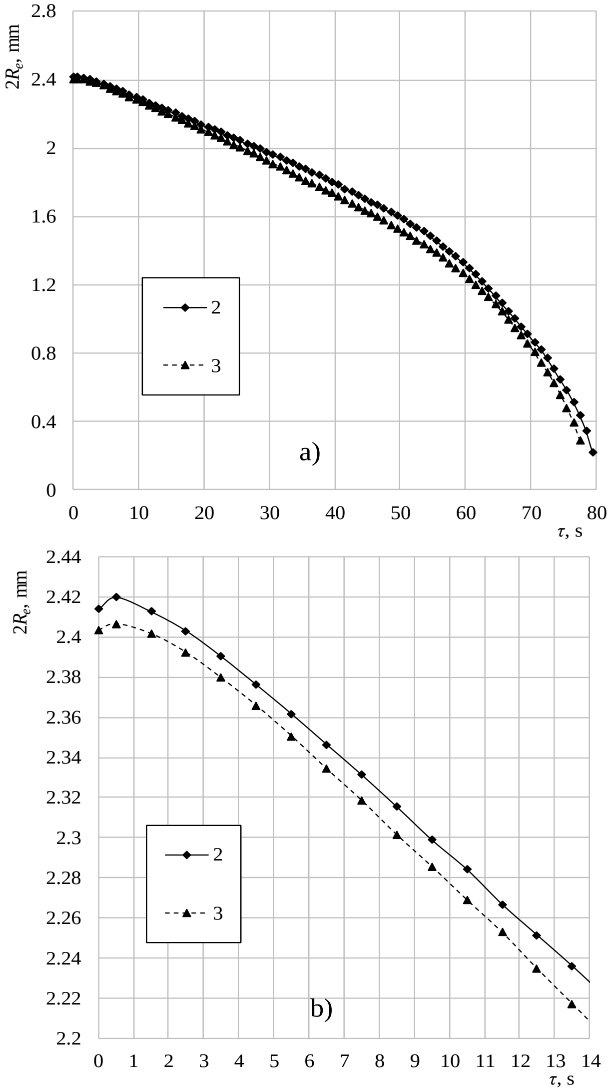

Figure 5 The dynamics of the equivalent diameter of a water droplet heating up in the airflow (a) and its initial stage (b), when t_g,°C: (2) 113.5, (3) 113.9; $X_{v,a}$=0.0116. Exp. No. 2 and 3.

In both stages, the equivalent diameter of the droplet varies in a non-linear manner. In the first stage, the equivalent diameter of the droplet increases due to the expansion of the heated water and the phase change regime on the droplet surface. At the beginning of this stage, the increase in the droplet size is determined by water vapor condensate formed on the droplet surface. However, the droplet heats fast to a temperature higher than the dew point, and therefore, at the end of the first stage, the expansion of the still heating water droplet is inhibited by water vaporization. The first stage ends when water expansion and vaporization are balanced. In the second stage, the heating of the droplet becomes weaker, and the influence of water expansion disappears at the end of the second stage. In the case of heated air with lower humidity (Figure 2b, 5) and when the condensation regime is absent (Figure 6b), the first two stages of the change in the droplet equivalent diameter are insignificant. In the third stage, the droplet equivalent diameter decreases rapidly.

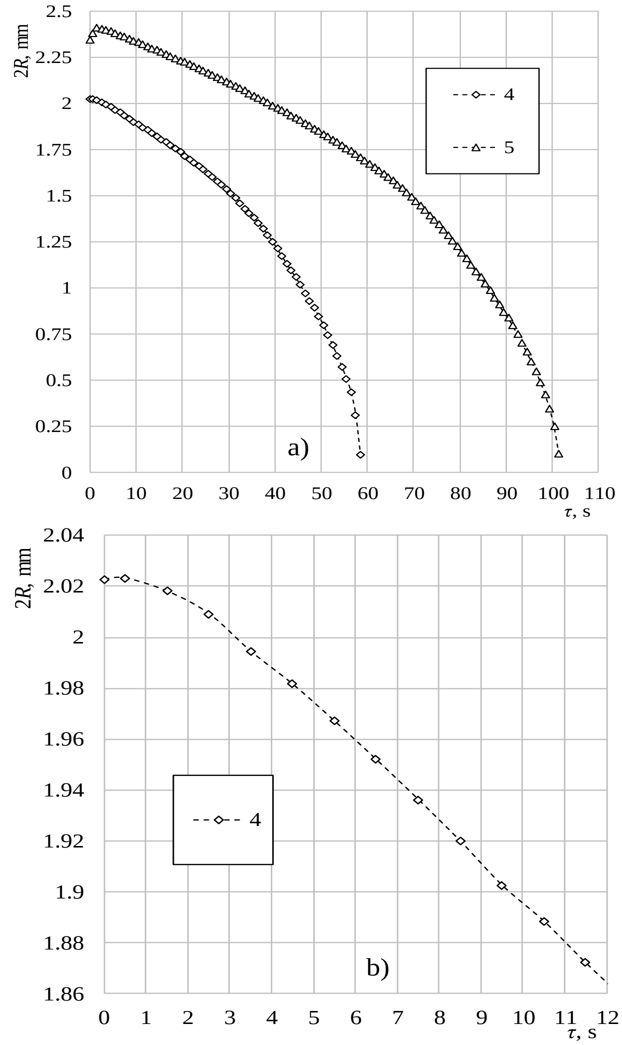

Figure 6 The dynamics of the equivalent diameter of a water droplet heating up in the heated and humidified air flow (a) and its initial stage (b), when t_g,°C: (4) 111.4, (5) 111.3; G_v, g/s: (4) 0.264, (5) 0.893. $X_{v,g}$: (4) 0.084, (5) 0.22. Exp. No. 4 and 5.

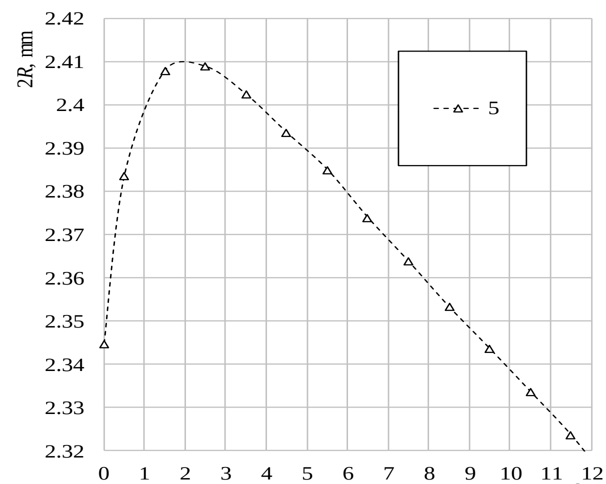

Figure 7 The initial stage of the equivalent diameter dynamics of a water droplet heating up in the heated and humidified air flow, when t_g=111.3ºC; G_v=0.893; $X_{v,a}$=0.22. Exp. No. 5.

The linear decrease in the surface area of a droplet during equilibrium evaporation is known as the d^2-Law [13]. Strictly speaking, the d^2-Law is valid only in the case of convective heat and mass transfer in the droplet. In order to describe water droplet phase change regimes in wet gas flow and predict the change in their thermal state, it is convenient to use dimensionless parameters: ratios between the dew point temperature and droplet equilibrium evaporation temperature with an initial water temperature [8]. The results obtained during the experimental investigation confirm the applicability of these ratios.

CONCLUSION

Heated atmospheric airflow influences the thermal state of equilibrium evaporation in droplets. When atmospheric air of ≈21ºC and ≈47 % of relative humidity ($X_{v,a}$=0.0116) was heated to the temperature of ≈30ºC, the water droplet evaporated in the equilibrium regime at ≈18.5ºC. When the airflow was heated to ≈114ºC, the equilibrium evaporation temperature increased by more than 22ºC and reached the temperature of 40.6ºC.

Heated and additionally humidified atmospheric airflow not only had a significant influence on the thermal state of the equilibrium evaporation of the droplet in the flow, but also allowed the condensation regime when the initial droplet temperature was lower than the dew point temperature of the atmospheric airflow. When the atmospheric air flow was heated to ≈111.5ºC and additionally humidified by water vapor ($X_{v,g}$: 0.084; 0.22) the droplet started evaporating in the equilibrium regime at ≈50ºC and ≈68ºC, respectively.

When the initial droplet temperature was lower than the dew point temperature, the transitional condensation phase change regime is followed by transitional evaporation regime; however, it did not affect the thermal state of equilibrium evaporation. The change in the droplet thermal state can be predicted qualitatively using the dimensionless parameter expressed as a ratio between the equilibrium evaporation t_e temperature and the initial water $t_{l,0}$ temperature ($t_e/t_{l,0}$) When $t_e/t_{l,0}$>1, the droplet will heat up to the thermal state of the t_e temperature, but when $t_e/t_{l,0}$<1, the droplet will cool down.

Heating and humidification of atmospheric airflow also affected the dynamics of the droplet equivalent diameter in the initial stage of phase changes. It can be predicted using the dimensionless parameter expressed as a ratio between the dew point t_{dp} temperature and the initial water $t_{l,0}$ temperature ($t_{dp}/t_{l,0}$). When $t_{dp}/t_{l,0}$>1, the water droplet under intense heating conditions will increase in the initial stage of phase changes because of water expansion and surface water vapor condensation. When $t_{dp}/t_{l,0}$<1, the droplet will start evaporating immediately, its size will increase slower and only because of the expansion of the heating water until the evaporation process will overcome the water expansion effect.

In order to select a right dispersing systems for heat recovery from exhausted wet flue gas (water sprayed in the flue gas flow to cool down and additionally moisten the flue gas before the condensing economizer or to effectively dry the flue gas inside the economizer), the influence of the earlier discussed parameters $t_{dp}/t_{l,0}$ and $t_e/t_{l,0}$ on water droplet phase change processes in flue gas should be considered.

FUNDING

This research was funded by Research Council of Lithuania (LMTLT), grant number S-MIP-20-30.

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