Experimental investigation of the gravity influence on the condensation behaviour on Al- and PTFE-samples

Experimentelle Untersuchung des Einflusses von Gravitation auf das Kondensationsverhalten an Al- und PTFE-Oberflächen

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Oberflächenkondensation, Tröpfchenbildung, Einfluss von Gravitation, Aluminium, PTFE

Abstract

The condensation heat transfer takes place in numerous industrial processes. The presented work was motivated by the possibility to increase the energy efficiency of industrial processes through the condensation of water vapour from flue gases (FG). It is especially relevant for such industries, like baking, textile, pulp and paper, drying, etc., where the FG at the end of the process is rich in water vapour (up to 90%vol). This FG is generally composed of non-condensable gas (mostly dry air) and condensable gas (mostly water vapour). Its thermal energy (sensible and latent) can be recovered, thus increasing the overall process efficiency.

The heat transfer efficiency plays an important role in the condensation process and is strongly influenced by the condensation type. The dropwise condensation exhibits the increased heat transfer coefficient by up to one order of magnitude, comparing to the filmwise condensation. Therefore, the research interest lies in the investigation of methods, prioritizing the dropwise condensation on solid surfaces. One of the decisive mechanisms for the increased heat transfer coefficient and condensation rate is the cyclical sequence of droplet formation, growth and drainage. Among others, these are initiated by the surface properties and gravitational force.

In order to investigate the influence of gravity on the surface condensation behaviour, the experimental investigation was done for a variable tilt angle of 0, 30, 60 and 75° relative to the horizontal, using two different sample materials (Aluminium and PTFE-Teflon® discs 60 x 3 mm). The reaction chamber was filled with ambient air and kept at 50°C. Simultaneously, the sample was cooled with air and the water vapour was gradually injected inside the chamber. The condensation on the sample was recorded by the HD camera with 180 mm macro lens. The pressure and temperature profiles along the reactor were continuously recorded.

The condensation process ran two times faster for the inclination angle of 75° compared to 0° in case of the Al-sample. Since the tilt angle induces the natural convection inside the re-

action chamber, the vertical temperature gradient decreased with increasing the inclination angle from 0 to 75° (by 40% for the Al-sample; by 20% for the PTFE-sample). Experimental data indicate that gravity reduces the critical droplet size for drainage (from around 4 to 2 mm for both samples) and facilitates coalescence effects. This results in an accelerated cycle of nucleation, droplet growth and drainage.

Introduction & Motivation

In order to meet the objectives of the Paris Agreement on Climate Change, Germany approved the “German Government’s Climate Action Programme 2020”. According to it, the 20% increase in energy efficiency is of key significance. The industrial sectors are encouraged to exploit their energy efficiency potential, with the enhanced use of waste heat being one of the measures.

The good potential for the increase in energy efficiency lies in the condensation heat transfer which takes place in numerous process and power generation industries. The presented work was motivated by the possibility to increase the energy efficiency of industrial processes through the condensation of water vapour from flue gases (FG). It is especially relevant for such industries like baking, textile, pulp and paper, drying, etc., where the FG at the end of the process can contain up to 90%vol of water vapour (Fedorova et al. 2019). This FG is generally composed of non-condensable gas (mostly dry air) and condensable gas (mostly water vapour). Its thermal energy (sensible and latent) can be recovered, thus increasing the overall process efficiency by around 10%, as reported by Terhan and Comakli, 2016.

The heat transfer efficiency plays an important role in the condensation process and is strongly influenced by the condensation type. The dropwise condensation exhibits the increased heat transfer coefficient by up to one order of magnitude, comparing to the filmwise condensation (Carey 2008). Therefore, the research interest lies in the investigation of methods, prioritizing the dropwise condensation on solid surfaces.

Various surface modification techniques result in the dropwise condensation. Polymer coating, ion implantation, chemical etching are few of them. The coating of surfaces with polymers leads to the decreased surface energy and promotes the dropwise condensation, as reported in the work of Ma et al. 2008 for the copper samples with fluorocarbon organic coating. The implantation of aluminium surfaces with nitrogen ions helped to sustain the stable dropwise condensation for 8 months, as per Rausch et al. 2008. The chemical etching of copper samples, performed by Bisetto et al. 2014, enabled to maintain the dropwise condensation for 5 days.

One of the decisive mechanisms for the increased heat transfer coefficient and condensation rate is the cyclical sequence of droplet formation, growth and drainage, which is achieved during the dropwise condensation. Among others, these are initiated by the surface properties and gravitational force.

This paper presents the intermediate results of the ongoing research on the droplet formation during the surface condensation. The first experiments aimed to investigate the influence of gravity on the surface condensation behaviour on the Al- and PTFE-samples. For this purpose, the following parameters were considered: the temperature and pressure profiles inside the reaction chamber, the experimental time of the condensation experiment, the critical droplet size for drainage and the droplet shape.

Materials & Methods

In order to investigate the influence of gravity on the surface condensation behaviour, the experimental investigation was done for a variable tilt angle of 0, 30, 60 and 75° relative to the horizontal. Two different sample materials were tested, namely, Aluminium and PTFE (Teflon®) discs of 60 x 3 mm in size. The Aluminium sample had the roughness of 4.8 µm and contact angle to water of 94°. The PTFE (Teflon®) sample had the roughness of 38.8 µm and contact angle to water of 114°. The surface roughness (S_a) was measured by the laser scanning confocal microscope. The contact angle to deionized water was measured using the drop shape analyser.

The experimental setup is schematically presented in the Figure 1. The inner reaction chamber of 3.4 litres in volume was filled with ambient air of 18°C and 50% relative humidity. The outer chamber was provided to create the space between the chambers for the heating water to circulate through. The temperature of the circulating heating water was kept at 50° C. After the temperature of the main volume inside the reaction chamber was stabilized at 49 ± 1°C, the sample was cooled from the bottom with the pressurized air at 5 bar flowing out of the 5 mm diameter nozzle. Simultaneously, the water vapour was gradually injected inside the reaction chamber. The experiment was terminated after the injection of 1 ml of water.

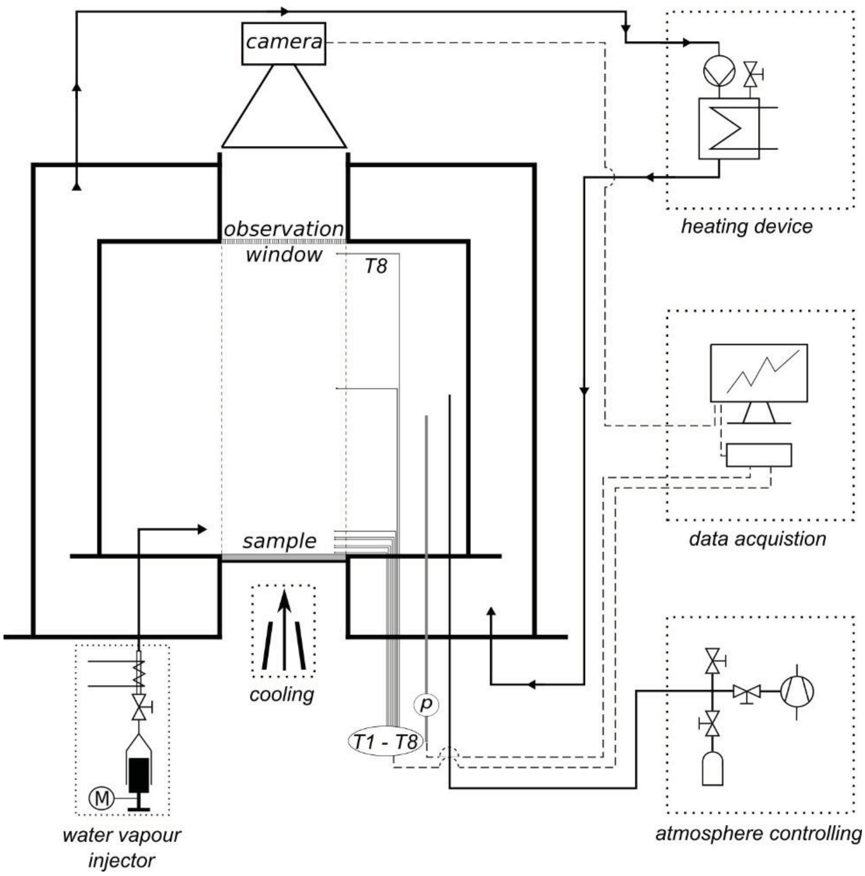

Fig. 1: Flow chart of the experimental setup. Solid lines represent the fluid flows, dashed lines represent the data flows

	Distance to the sample
T1	1 mm
T2	3 mm
T3	5 mm
T4	8 mm
T5	10 mm
T6	13 mm
T7	80 mm
T8	145 mm

Tab. 1: Position of thermocouples

The condensation on the sample was visually recorded from the top through the observation window, using the digital camera. The camera was combined with the 180 mm F2.8 macro lens with the fixed focal length of 180 mm to achieve the image scale of 1:1. In order to provide the immovability of the experimental setup, the photographing was performed remotely by the open source software digiCamControl (Version 2.1.0.0) with the frequency of 1 picture per 10 seconds.

The temperature profile along the reactor was measured by eight T-type thermocouples (T1 – T8), at the distance to the sample presented in the Table 1. The excess pressure inside the reactor relative to the ambient conditions was continuously recorded in time using the pressure transmitter with the measurement range from 0.9 to 10 mbar. The measured data was collected by the developed Data Acquisition System (DAQ), using the LabVIEW 2017 software.

Results and Discussion

The present experimental work on the ongoing research examined the indirect condensation process on the two different sample materials (Aluminium and PTFE-Teflon®) inside the closed system. The impact of gravity could be changed by varying the tilt angle of the experimental setup (0, 30, 60 and 75°) relative to the horizontal. Each condensation test lasted between 24 and 57 minutes, with the time strongly depending on the tilt angle of the experimental setup.

The temperature profiles along the reaction chamber were qualitatively similar for all the tests, with T7 to be the highest temperature representing the temperature of the main volume and T1 to be the lowest, since T1 is the closest to the cooled sample.

Figure 2 shows the representative example for the Al-sample at the 75° tilt angle. In the first 8-10 minutes of the experiment the temperatures T1 - T8 displayed the changeable values, since the sample was cooled during this time. Once the temperature above the sample T1 got stabilized, the water vapour was gradually injected inside the chamber. Approximately after the 10th minute the recording of each thermocouple showed quite stable character. The further irregular oscillations can be attributed to the release of the latent heat during the condensation process.

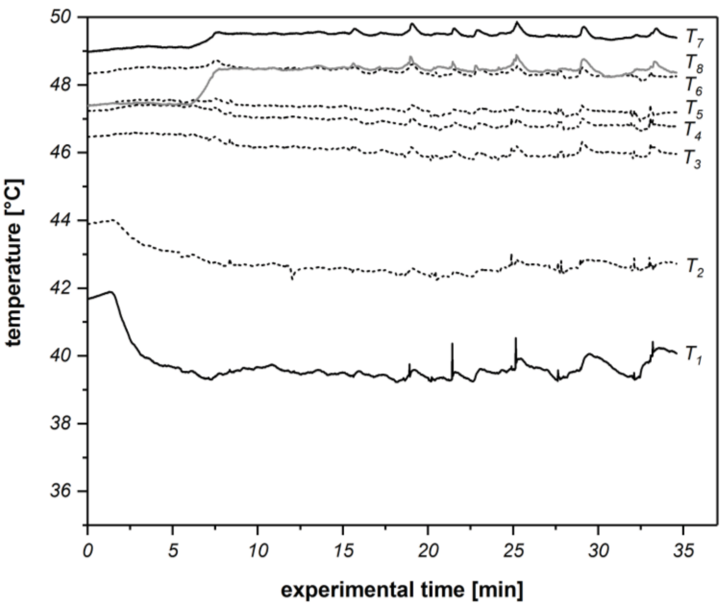

Fig. 2: Time dependence of the temperature profile for the Al-sample at the 75° tilt angle

The average temperatures with respect to the tilt angle can be found in Figure 3 for the Al-sample and in Figure 4 for the PTFE-sample. The temperature values of each thermocouple were averaged over the time from the first injection of the water vapour to the end of the experiment, when 1 ml of water was introduced. Since the tilting of the setup induces the natural convection inside the reaction chamber, the vertical temperature gradient decreased with increasing the inclination angle from 0 to 75°: by around 40% for the Al-sample, and by 20% for the PTFE-sample.

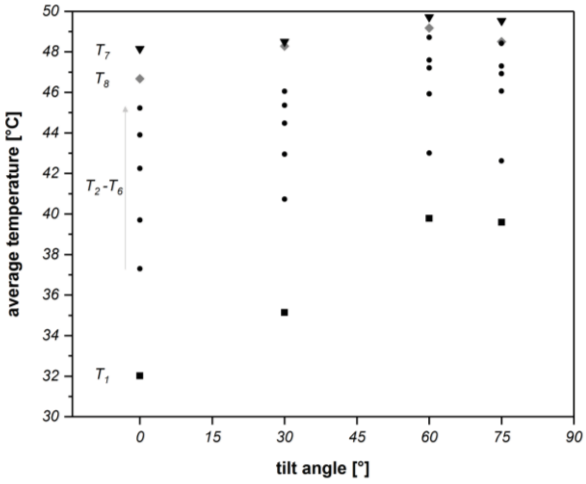

Fig. 3: Average temperatures T1-T8 depending on the tilt angle for the Al-sample

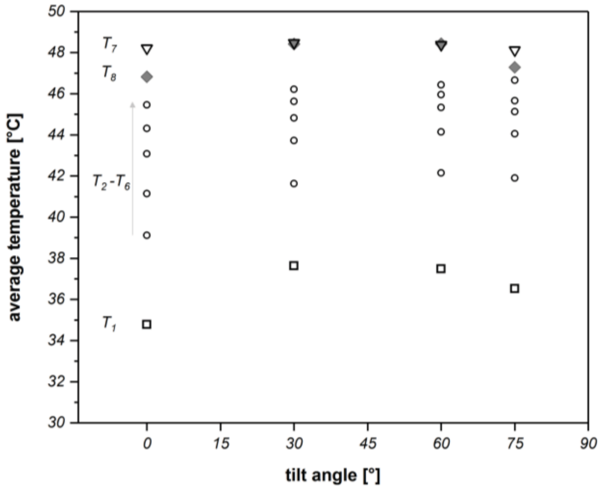

Fig. 4: Average temperatures T1-T8 depending on the tilt angle for the PTFE-sample

As expected, the tilting of the setup, and therefore the gravitational influence, helped to reduce the experimental time. In case of the Al-sample the condensation process ran two times faster (30 instead of 57 minutes) for the inclination angle of 75° compared to 0°. In case of the PTFE-sample the experimental time was 20% shortened from 39 to 30 minutes for the tilt angle of 75° and 0°, respectively. This is related to the low thermal conductivity of the PTFE material, namely 0.2 W/(m·K), which resulted in the poorer cooling of the sample.

The experimental data, shown in Table 2, indicate that gravity reduces the critical droplet size for drainage: from 4.1 to 2.9 mm for the Al-sample and from 4.1 to 2.1 mm for the PTFE-sample. This leads to the accelerated regeneration of the surface, and therefore, to the accelerated cycle of nucleation, droplet growth and drainage.

Tab. 2: The critical droplet size for drainage d_{crit} with the standard deviation σ in case of the Al-sample and PTFE-samples at different tilt angles

Sample material	Al-sample			PTFE-sample		
Tilt angle	30°	60°	75°	30°	60°	75°
$d_{crit} \pm \sigma$ [mm]	4.1 ±0.5	2.3 ±0.4	2.9 ±0.5	4.1 ±0.9	3.1 ±0.4	2.1 ±0.3

Figure 5 presents the example of the visual observations of the condensation process on the samples' surfaces approximately in the middle of the process (0.438 ml of water injected). The influence of gravity on the droplet shape can be observed from the images at different angles of inclination. In the horizontal position of the setup (0°), most of the Al-sample surface didn't have the round droplet shape. The PTFE-sample was mainly covered with round droplets at all of the investigated tilt angles, which is attributed to the wetting behaviour of the material. As mentioned above, the PTFE material is hydrophobic and has the higher contact angle to water. The round droplet contour was formed at tilt angles, higher than 60° for both samples.

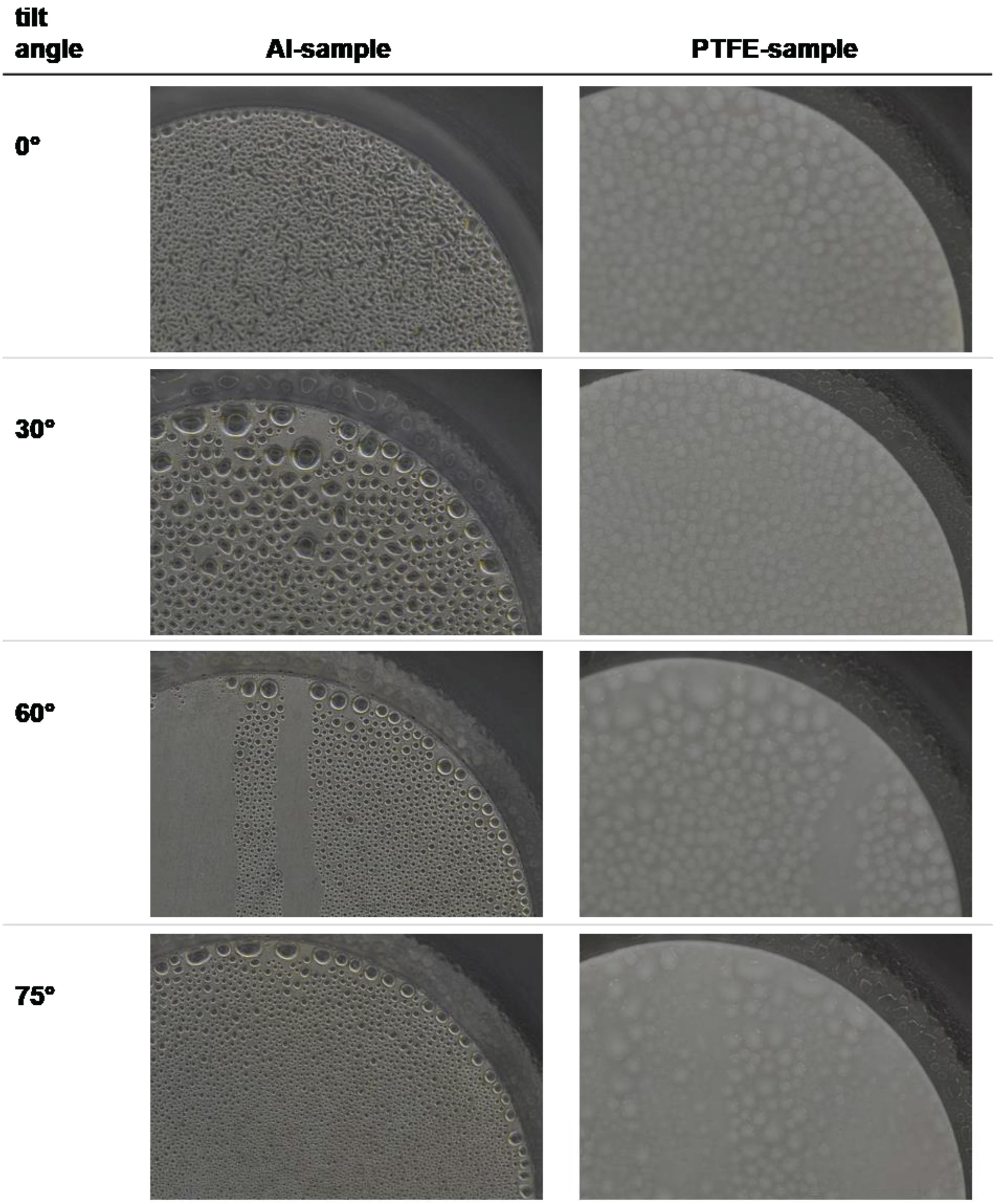

Fig. 5: Camera images of the condensation process on the Al- and PTFE-samples at different tilt angles after the injection of 0,438 ml water

Conclusions

The present experimental study of the condensation process on the Aluminium and PTFE (Teflon®) samples under the influence of gravity was performed within the scope of the ongoing research. The impact of gravity was changed by varying the tilt angle of the experimental setup (0, 30, 60 and 75°) relative to the horizontal. The indirect condensation process on the solid surfaces inside the closed type reactor was visually observed by a camera, the pressure and temperature profiles along the reactor were continuously recorded.

According to the obtained results, the condensation process ran two times faster for the inclination angle of 75° compared to 0° in case of the Al-sample. Since the tilt angle induces the natural convection inside the reaction chamber, the vertical temperature gradient decreased with increasing the inclination angle from 0 to 75° (by 40% for the Al-sample; by 20% for the PTFE-sample). The experimental data indicate, that gravity reduces the critical droplet size for drainage (from around 4 to 2 mm for both samples) and facilitates coalescence effects. This results in an accelerated cycle of nucleation, droplet growth and drainage. The further experimental work on the ongoing research is related to the surface modification techniques, such as coating, plasma treatment, chemical etching, etc., in order to investigate the influence of the sample properties on the condensation process.

Acknowledgements

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