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Experimental Research of Wetting and Drop Evaporation Processes on a Heated Substrate as a Method for Research Skills Development for Heat and Power Engineering Students

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Abstract

The article considers a method used for student research competency development during the course "Process energy sources for industrial facilities" in Tomsk Polytechnic University. The experiment is based on shadow and Schlieren optical methods for observing the water drop evaporation on the solid surface. Using the images obtained by plane-parallel light during the evaporation process and Drop Shape analyses software, students are to determine the drop's geometric parameters. After the experiment and results processing, they are required to determine the evaporation stages, study effects of surface roughness and temperature factors on characteristics of drop spreading (contact angle and diameter).

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Keywords: Experimental research; drop evaporation; temperature; shadow image; Schlieren method; contact angle.

1. Introduction

Development of technologies and changing environment draw attention to engineering education development and imply new aspects of training. Due to global competition, constant technological development and upgrade are the factors of a country's economic growth. With the growing interest of Russian economy to innovative development, the innovative engineering education became the subject of discussion a quite long time ago, along with issue of changing requirements of employers to graduates. Therefore, training of students should certainly

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include such aspects as: level of researches conducted by the departments, condition and upgrade of laboratory equipment, quality of educational programs, etc. (Pokholkov, et al., 2012).

Therefore, Tomsk Polytechnic University is making efforts to provide students with theoretical and practical knowledge along with research skills development. Two undergraduate students and one postgraduate student of TPU Department of Heat and Theoretical and Industrial Heat Systems Engineering within framework of the course "Process energy sources for industrial facilities" have experimentally studied the stages of drop evaporation on a solid heated substrate under guidance of the supervisor. Prior to experiment, the students reviewed the available researches and publications on the subject.

1.1. Review of theory and publications

Over the last twenty years wetting and drop evaporation processes have attracted the attention of researchers worldwide (Sobac & Brutin, 2012; Stapelbroek, et al., 2014; Erbil, 2012; Hu & Larson, 2006; Ristenpart, et al., 2007; Deegan, 2000; Bartashevich, et al., 2010; Barash, et al., 2009; Vinogradova & Belyaev, 2013, and others).

A sessile drop is a drop, placed on a solid substrate, where the wetted area is limited by a contact line (Erbil, 2012). Contact angles of sessile drops on substrates characterize the surface free energy for solid surfaces. If a contact angle formed between a water drop and solid surface is less than 90°, the surface has a hydrophilic property. But if a contact angle is more than 90°, the surface has a hydrophobic property (for example, water drop on the Teflon surface, or on a lotus leaf in nature). Super hydrophobicity is observed at contact angles more than 150° (Dorrer & Rühe, 2009; Zimmermann, et al., 2008).

Another parameter, characterizing wetting and drop evaporation processes, is contact diameter (d) or contact radius (r). A spherical cap of a drop is determined by four main parameters: contact radius, apex height, sphere radius and contact angle (Fig. 1) that can be presented as following equations (Matyukhin & Frolenkov, 2013):

$$r_b = R_s \sin\theta \tag{1}$$

and $$R_s = \left(\frac{3V_{sph}}{\pi\beta}\right)^{\frac{1}{3}}, \tag{2}$$

where $\beta = (1-\cos\theta)^2(2+\cos\theta) = 2-3\cos\theta+\cos^3\theta$.

Height of the spherical cap:

$$h = R_s(1-\cos\theta), \tag{3}$$

$$h = r_b \tan\left(\frac{\theta}{2}\right). \tag{4}$$

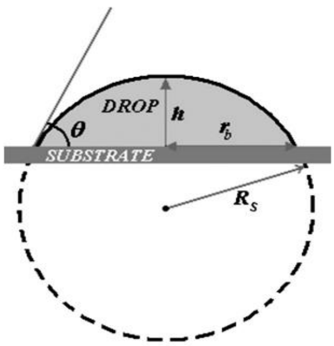


Fig. 1. A sessile drop on the substrate.

A spherical cap can be described by only two of these four parameters. This article considers contact angle and contact radius dynamics during distilled water drops evaporation on a heated substrate.

Depending on the contact angle and contact radius variation, several stages of evaporation are specified. Picknett and Bexon (1977) divided the process into three evaporation stages: 1 – constant contact angle while decreasing the contact area; 2 – constant contact area while decreasing the contact angle; 3 – mixed stage of evaporation (simultaneous increase of the contact angle and reducing the contact diameter or a simultaneous decrease of both parameters). They used water and Teflon as a liquid and a solid substrate. Evaporation stage of the constant contact area (radius) is called pinning.

1.2. Experiment objectives

The purpose of the research is to investigate the evaporation stages of distilled water drops evaporation on substrates at three temperature modes. The surface roughness is also taken into account as an influencing parameter. The following objectives were set for students:

- Develop the sequence of actions to obtain the maximum information at the least time period
- Select a number of experiments and conditions required and sufficient for solving the formulated scientific problem with the required accuracy
- Conduct a series of experiments
- Process the obtained results, analyze them in order to validate or disprove the hypothesis about possible system response to changing parameters during the experiments

2. Research method

First, the students were trained how to use the laboratory equipment. The experiments were done using the experimental setup, shown in Fig. 2. It consists of equipment for shadow and Schlieren methods implementation (Orlova, et al., 2014).

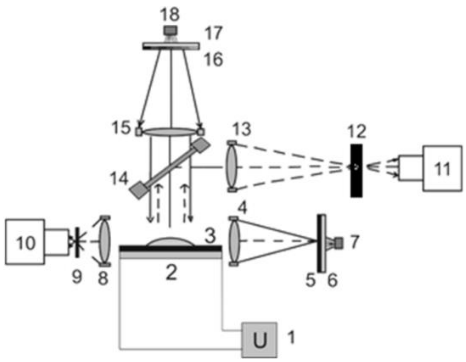


Fig. 2. Diagram of the experimental setup: 1 – power source, 2 – Peltier element, 3 – substrate, 4 – collimating lens, 5 – transparent shield with an opening, 6 – ground glass, 7 – light source, 8 – condensing lens, 9 – transparent shield with an opening, 10 – high-speed video camera, 11 – high-speed video camera, 12 – transparent shield with an opening, 13 – condensing lens, 14 – beam splitter, 15 – collimating lens, 16 – coding filter, 17 – ground glass, 18 – light source.

The high-speed camera Fastvideo-500M was used in each method. Recording was carried out with 10 frames per second and with a resolution of 1280 x 1024 pixels. Substrate heating was done using a Peltier element (a thermoelectric transducer type A-2TM 8.0-127/126-1.4 HR1).

In the shadow optical method light source 7, ground glass 6 and lens 4 were used to produce a beam of plane-parallel light illuminating the drop on the substrate. The condensing lens 8 and objective lens of camera 10 were used to project the image on the camera sensor. Transparent shield with an opening 9 was set to reduce the effect of external light sources on measurement.

In Schlieren method the incoherent light source 18, the ground glass 17 and the coding filter 16 were used to produce a light flux with a stepped intensity decrease in space. A light beam from source 18 passed through the collimating lens 15, which transformed it into a plane-parallel. Then it was reflected from the beam splitter 14, fell on the substrate and passed to the lens 13 and was projected on the high-speed video camera sensor 11.
Video recording of drop evaporation on the surface was carried out simultaneously in two coordinate directions. The equipment for Schlieren method was used to control the drop symmetry.

Measuring of the substrate temperature was done by means of eight-channel Agilent 34901A. Three thermocouples "chromel-copel" with measurement error ±0.1ºC were used as the temperature sensors. When the substrate temperature required value, the drop was placed on the substrate using a syringe dispenser. Then the drop was vaporized.

The substrates are the disks (54 mm in diameter and 4 mm thick) made of stainless steel of different microstructure. Two rough surfaces were obtained by bombarding a smooth surface with Al_2O_3 particles of 10 and 100 microns. The surface of the third substrate was not finished. Surfaces were studied on the profilometer “Micro Measure 3D station”, and the roughness parameter (arithmetic average roughness Ra) was obtained (Table 1).

3. Results and discussion

According to results of a preliminary experiment, the values of influencing factors were found (Table 1).

Table 1. The main influencing factors.

Drop volume	0.02 ml
Substrate material	Stainless steel
Roughness parameter of surface Ra	Sample No.1 (smooth steel) – Ra 1.5 µm; Sample No.2 (bombarded steel with 10 microns particles) – Ra 1.554 µm; Sample No.3 (bombarded steel with 100 microns particles) – Ra 4.59 µm;
Wetting liquid	Nondeaerated distilled water
Heating mode and appropriate surface temperature	I heating mode – t_s=54°C II heating mode – t_s=62°C III heating mode – t_s=70°C
Microstructure of surface	Sample No.1 - the substrate roughness is formed by longitudinally arranged grooves; Sample No.2 - the substrate roughness is formed by chaotically arranged asperities and cavities; Sample No.3 - the substrate roughness is formed by chaotically arranged asperities and cavities;

3.1. Time dependences of evaporation

Time dependences of contact diameter are given in Fig. 3. Three spreading stages of drop evaporation, depending on contact diameter variation, were indicated. The first stage is characterized by slight spreading of a drop on the substrate (an increase of contact radius for not more than 10%). It is a fast process and lasts 10% of total evaporation time. Pinning happens during the second stage (contact area is constant). It lasts for up to 60% of total evaporation time. And the third stage is characterized by drop depinning (decrease of contact radius), continuing for 30% of total evaporation time. These stages are marked in Figure 3.

During contact of a drop and a solid substrate (the first stage) “liquid-solid” interface is rapidly heated due to small volume of liquid. A change of liquid properties, in particular reduction of the surface tension at the "solid-liquid" interface, occurs. It should be noted that such a tendency is only suitable for pure liquids. Whereas a change of solute concentration for solutions in the superficial layer is possible along with a change of the surface tension.

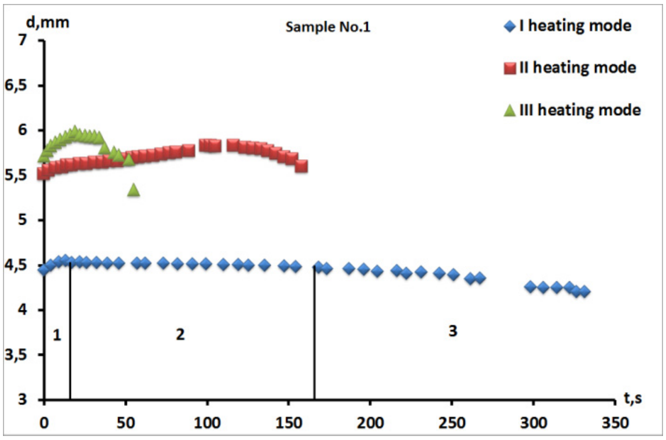
It can be assumed that the first stage corresponds to a viscous regime (Summ & Goryunov, 1976). A specific parameter of this regime in a flowing liquid to the three-phase contact boundary is the viscosity of liquid. The first stage duration is from 1 to 10% of the total evaporation time (at contact angle up to 10°).

The main factor influencing the spreading during the first stage is the surface microstructure and the method of drop placing onto a substrate (using a mechanical dispenser). It is known that parallel-arranged microgrooves, formed by grinding the surface substrate, promote spreading, but transverse grooves keep the liquid flow opposite (Summ & Goryunov, 1976).

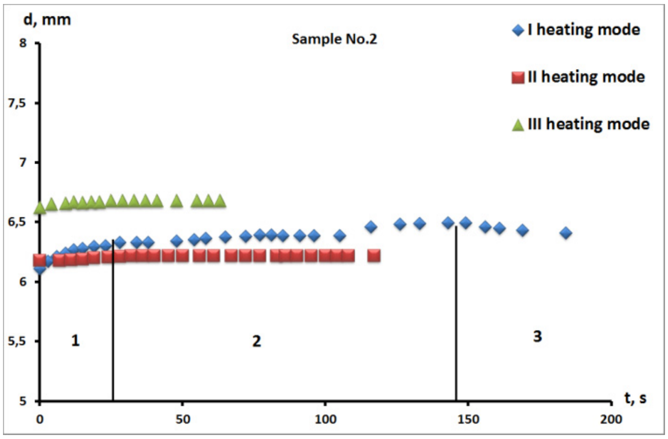
According to results of the drop evaporation diagrams (Samples No. 2 and 3), it was found that the surface roughness influences spreading: a smaller contact diameter is observed on the substrate with a higher roughness parameter under equal conditions of experiment. Three-phase contact line is held pinned on the microroughnesses obtained by bombardment with Al_2O_3 particles. Similar results were obtained in (Shanahan & Bourges, 1994) at conducting experiments with water drops on Teflon, polyethylene, and in (Wayner, 1973) at placing water drops on a copper surface. On a smooth substrate (Sample No. 1) drops have spread less in comparison with Samples No. 2 and 3. It happened only for I and II heating modes. There was no general dependency of spreading in case with III heating mode. This can be the reason for interfacial interaction at a sufficiently high temperature of surface heating. It is important to note that, in spite of drop pinning on the surface microroughnesses of Sample No.3 during the initial period, and then more obvious spreading in comparison with Sample No.2 wasn't observed. However, the contact diameter was smaller than the one on the substrate with a smaller roughness parameter even after the spreading stage.

The second stage was characterized by constant contact line at decreasing the apex height and contact angle of the drop. So the process was accompanied by contact line pinning and an increase of drop shape "flattening". It is known that drops evaporation along the perimeter (at the edges) is significantly higher than in the center. It leads to large liquid losses from the edges. As it has been noted, the contact line is fixed in this stage; therefore, the losses from the edges must be supplied to keep the line. Physically it is possible if liquid flows from the center to the edges.

(a)



(b)



(c)

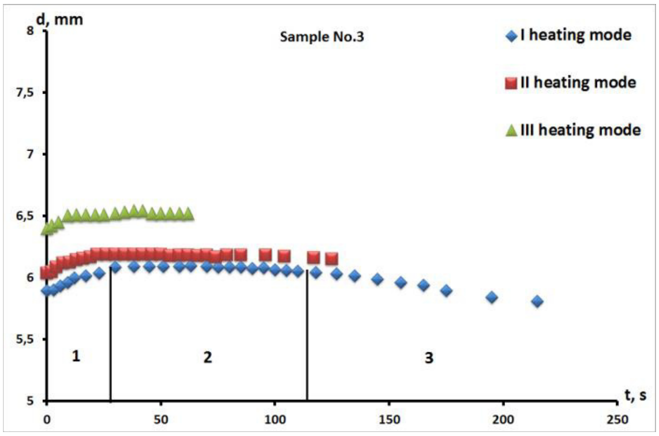
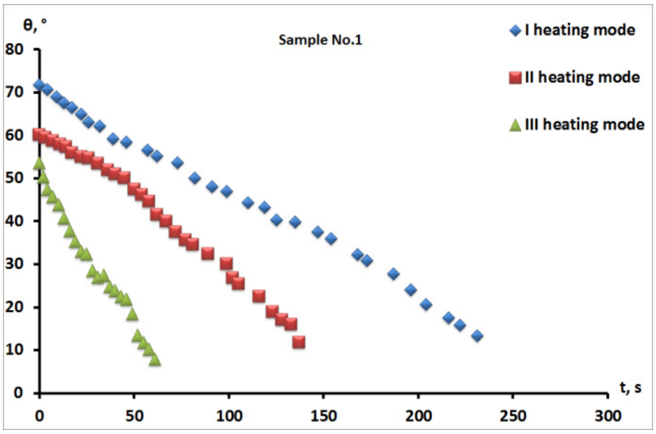


Fig. 3. Time dependence of contact diameter during drop evaporation for three heating modes:
(a) Sample No.1; (b) Sample No. 2; (c) Sample No. 3.

The contact angle decreases at the third stage (as in the previous two). The contact line begins to "reduce", the radius decreases, there is a drop "flattening". It can be assumed that the surface tension force, which is directed towards the drop center, reduced in the third stage in comparison with the second one due to drop temperature increase. The drop area tends to decrease to the minimum. Time dependences of contact angle are given in Fig.4.

(a)



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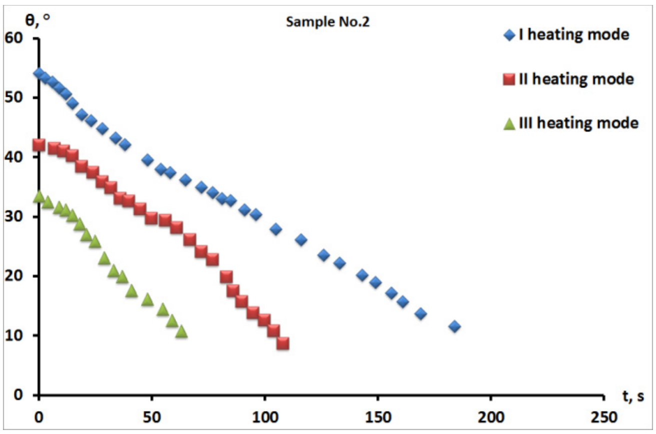

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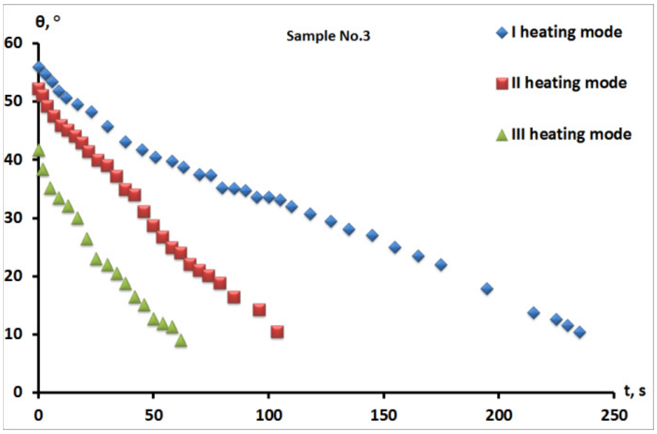

Fig. 4. Time dependence of contact angle during drop evaporation for three heating modes: (a) Sample No.1; (b) Sample No.2; (c) Sample No. 3.

It was found that during all indicated stages contact angle varied linearly. However, the higher temperature the more intensively and faster the contact angle decreased. According to the analysis results, the contact angle initially is higher on a rougher surface (sample No.3) in comparison with the smooth substrate (sample No. 1).

4. Conclusion

The following findings were obtained by the students after the experimental results processing and analysis. The spreading stages of distilled water drop evaporation on substrates at three temperature modes were investigated and the surface roughness was also taken into account as an influencing parameter. According to results of the diagrams analysis, three spreading stages were specified: 1 – initial spreading; 2 – pinning; 3 – reduction. During all indicated stages the contact angle varied linearly. However, the higher temperature the more intensively and faster the contact angle decreased.

In addition, the research on water drop evaporation on a solid heated substrate allowed students acquire the skills to work with the optical equipment, high-speed video cameras, Peltier element and measuring instruments. As a result of experimental data processing, they learnt how to use the DSA software (Drop Shape Analyses) by KRUSS Company, along with Origin Pro software, applied for graphic curves plotting.

According to evaluation given by the supervisor, students have completed all of the set objectives. They needed some assistance during solving minor problems, such as information search for laboratory equipment settings, workplace organization and results analysis. The pedagogic value of such work for the supervisor lies in setting and formulation of the objectives for a research group, and allocating the assignments among the participants.

In our understanding, an opportunity to carry out an experiment is important for research skills development for engineering students, and can even stimulate their research interest more than traditional lectures (Xiao Chen, 2008). Involvement of undergraduate students along with postgraduate students in experiment organization and performance helps them to indulge in scientific work and see how the results are obtained and processed (Redish & Smith, 2008). They also learn how to use the equipment specific for their area of expertise. Upon experiment completion, students also had an opportunity to present the results at a university conference in the English language.

No doubt that a high quality of research is important for a scientific field development. Moreover, when students are provided with such opportunity, it helps them understand if they are willing to pursue a researcher career and probably learn how to enhance the process.

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