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ZBIGNIEW ZAPAŁOWICZ*

Effect of thermodynamic parameters of surrounding air on the dynamic wetting of surface by droplets

Technical University of Szczecin Department of Heat Engineering,
Al. Piastów 19, 70-310 Szczecin, Poland

Abstract

The paper presents the test stand, methodology, and results of experimental research on the phenomenon of surface wetting by a water droplet evaporating into air. The influence of environmental parameters on the size of wetting area has been expressed by means of the dimensionless parameter N that takes into account the intensity and direction of mass transfer between the droplet and the environment. It has also been confirmed experimentally that the parameter N, standing for the mass of moisture exchanged with the environment, can be used to describe the influence of the thermodynamic environmental parameters on the wetting process. It has been found that there is a relation between the parameter N and coefficient C appearing in theoretical models of the wetting phenomenon.

Keywords: Wetting phenomenon; Heat transfer; Droplet

Nomenclature

c	–	specific heat, J/(kg K)
C	–	parameter
d	–	diameter of the spherical droplet, m
D	–	diameter of wetting area, m
H	–	height, m
$\dot{m}$	–	mass flux, kg/(m^{2}s)
N	–	dimensionless mass flux of vapour, $N = \dot{m}_v/\dot{m}_{v0}$
p	–	partial pressure, N/m^2
R_z	–	roughness parameter
Re	–	Reynolds number
t	–	temperature, °C
T	–	absolute temperature, K

*E-mail address: zbigniew.zapalowicz@ps.pl

u – velocity, m/s
V – volume, m^3
We – Weber number
X – moisture content
Z – dimensionless temperature
β – spreading coefficient
φ – relative humidity
κ – coefficient, equation (4)
λ – coefficient of heat conduction, W/(m K)
π – disjoining pressure, pressure of the film of the substance absorbed on the solid body surface, N/m^2
ρ – density, kg/m^3
σ – surface tension, N/m

Subscripts

a – absorption
c – contact
l – liquid
max – maximal
n – saturation
p – air
w – surface
v – water vapour
z – wetting
0 – reference condition
∞ – in infinity

1 Introduction

Surface wetting by liquid droplets or liquid streams is often present in technological processes. In some practical applications, formation of a thin liquid film on the surface is required, e.g. material coating with a protective layers, production of photo films, distributing plant protection agents on leaf surfaces etc. [1, 2]. In turn, in some other applications, droplet structure must be provided, e.g. production of tin welds, where electronic elements are soldered to the chips with printed integrated circuits [3-5]. Wide range of applications which utilise wetting processes is, thus, the reason to carry out an intensive research on the phenomenon.

Thermodynamic parameters of the environment, such as pressure and temperature, can have a significant effect on the dynamics of droplet spreading. The surrounding gas is, in the most general case, a mixture of real gases. Interaction between gas molecules and the surface causes formation of a thin liquid film in the disjoining area between phases. Presence of this liquid film affects significantly the process of surface wetting by the droplet.

The present paper shows the analysis of the influence of environmental parameters on the process of evaporating a water droplet from a flat, horizontal metal surface. A three-phase-system: water droplet – surface of stainless steel – free air, was under scruting. Effect of thermodynamic parameters of air that surrounded the water droplet was determined by means of parameter N, proposed by Trela and Gajewski [6]. The aim of the present paper was to prove experimentally, whether parameter N could characterize the effect of environmental parameters on wetting the surface by liquid droplets and to prove presence of a relation between the above effect and the coefficient C. Coefficient C characterizes the surface energies present in interface areas among particular phases.

2 Effect of thermodynamic parameters of the environment on the wetting phenomenon

When the surface of a solid body contacts with the gas environment, being pure vapour or a mixture of gases, then as a result of mutual attraction between molecules of the solid phase and molecules of the gas phase, concentration of gas phase molecules rises in the surface layer [7, 8]. In the case of gases mixture, concentration of various kinds of gas molecules depends on their chemical affinity to the solid body surface. Concentration can be different for particular components of the mixture. Thus, there is a density difference of molecules in the gas phase between the surface layer and the neighbouring gas environment caused by the effect of intermolecular forces, or by formation of chemical bonding. The phenomenon is called adsorption (surface sorption). In the most general case, adsorption is a phenomenon where one solid body or liquid retains molecules, atoms or ions of another substance, that is solid body, liquid, or gas, in the interface area.

Adsorption of molecules of a substance on the surface of a solid body can thus change the solid body – gas (vapour) surface tension. Difference between solid body – gas (vapour) surface tensions defined under conditions without adsorption and with adsorption of molecules is expressed by disjoining pressure π_w [6-8]:

$$\pi_w = \sigma_{wv} - \sigma_{wv,a} \,. \tag{1}$$

In this formula, $\sigma_{wv,a}$ denotes the surface tension in presence of adsorbed substance.

It is thus important to know the conditions at which the contact of droplets with the surface occurs. It is clear that the droplets spreading dynamics depends on the situation whether or not the surface has already been wetted by the liquid [9-15]. Previous presence of droplets or liquid streams on the surface cause that vapour molecules of this liquid could additionally remain on the surface and the

process of their removal is significantly longer than the droplet evaporation time. The above fact changes the parameters of a thin microfilm that is present on the surface. The wetting process of the droplet looks different when the surface contacts only with the gas phase for a 'longer' time.

Thus, the phenomena occurring in the contact area of three phases decide on the wetting process. Relations between the parameters of the three involved phases might cause evaporation of liquid, or vapour condensation in the region of interface between phases. Presence of the absorbed liquid film in the vicinity of the contact line between the three phases enhances the spreading of the droplet on the solid surface. Absence of the microfilm causes that the droplet spreads with more difficulties on the surface.

The paper presents the analysis of the three phase system: stainless steel surface-water droplet-air. Such situation occurs in many practical applications. Ambient air, with definite physical properties, surrounds both the metal surface and the water droplet. In the case when the air parameters change within a wide range then the lack of reproducibility of surface wettability occur and the so called transient area [16] around the spreading droplet appears. The present research was carried under conditions where the surface had not been previously wetted by a liquid. Thus, only the conditions in the system surface-gas environment before droplet impingement could affect the droplet spreading.

With regard to the above arguments, Gajewski and Trela [6] introduced into analysis of droplet spreading a dimensionless parameter N in order to respect the intensity and direction of mass flux of water steam between the droplet and the air. It is defined by the formula:

$$N = \frac{\dot{m}_v}{\dot{m}_{v0}} = 1 - \frac{p_{v\infty}}{p_{vwn}} . \tag{2}$$

This parameter stands for the dimensionless mass flux of vapour exchanged with the ambient air.

For the considered system, $p_{v\infty}$ in formula (2) denotes partial pressure of water vapour at sufficient from the water surface (in infinity), and p_{vwn} is the partial pressure of water vapour in the saturated air at the air-water interface.

As already mentioned, the mass flux of water vapour depends (due to the Ficks diffusion law) on its concentration in the vicinity of droplet, so it is related to the vapour partial pressure distribution. This is shown schematically in Fig. 1 (chart due to Mollier [17]).

In the case $p_{v\infty} < p_{vwn}$, water evaporates into the surrounding air. In ideally dry air, partial pressure of vapour in the large distance from the water surface $p_{v\infty}$ equals zero, and then the liquid evaporation is highest and the parameter N equals 1. If the air is unsaturated with water vapour, value of pressure $p_{v\infty}$ is calculated on the basis of indications of the dry thermometer and relative

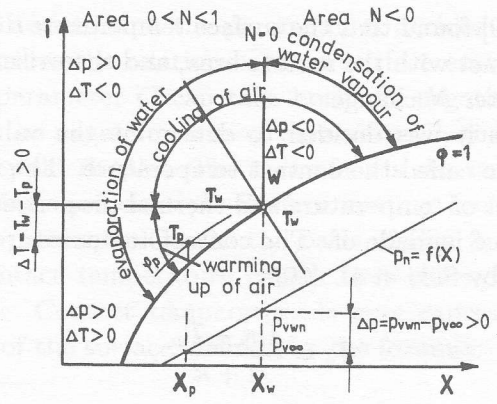

Figure 1. Chart i-X illustrating the interaction between liquid film and humid air.

humidity of unsaturated air φ. In this case, parameter N is in the range $0 < N < 1$.

A particular case occurs when $p_{v\infty} = p_{vwn}$, then the parameter $N = 0$. It means that there is a lack of evaporation or vapour condensation on the water-air interface.

In the case when the relation $p_{v\infty} > p_{vwn}$ holds, there is a condensation process of vapour on the droplet surface and $N < 0$.

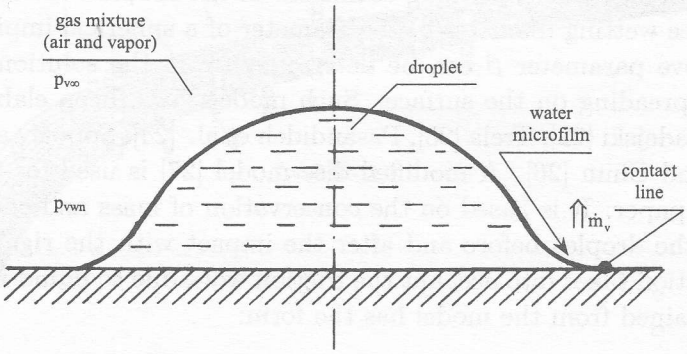

Figure 2. Conceptual view on contact line of three phases (air-liquid-solid).

The value of the partial pressure depends on the temperature of the thin microfilm that forms on the surface at the contact line between three phases (Fig. 2). Due to difficulties in determination of temperature of the thin water film, it can be assumed that temperature of the film is identical with the surface temperature. It should, however, be mentioned that the surface temperature also changes due to the effect of its contact with the dropping liquid droplet. Makino

and Michiyoshi [18,19] found that the surface temperature diminished in the first phase of droplet contact with the surface area, and then risen. Due to that effect the values of parameter N change.

For these reasons it was decided to determine the value of pressure for a reference temperature called the contact temperature. The contact temperature accounts for the effect of temperature and thermal properties, as well as the kind of material the surface is made of. The contact temperature is described by the equation elaborated by Seki et al. [20]:

$$T_c = \frac{T_l \kappa + T_w}{1 + \kappa} , \tag{3}$$

where

$$\kappa = \left(\frac{\lambda_1 c_1 \rho_1}{\lambda_w c_w \rho_w} \right)^{1/2} . \tag{4}$$

Contact temperature is thus the liquid temperature that arises 'nearly immediately' after the droplet contacts with the surface.

Surface wetting by the liquid droplet is characterized by a dimensionless parameter that can be defined through the formula [21]:

$$\beta = \frac{D_{zmax}}{d_0} . \tag{5}$$

Parameter β, called the spreading coefficient of the droplet, is defined as a ratio of the surface wetting diameter to the diameter of a spherical impinging droplet.

The above parameter β can be determined from the solution of the model of droplet spreading on the surface. Such models have been elaborated among others by Madejski [22], Trela [23], Pasandideh et al. [24], Sobolev and Guilemany [25], Kim and Chun [26]. A modified disc model [27] is used for the analysis in the present paper. It is based on the conservation of mass and energy equations applied to the droplet before and after the impact with the rigid surface. The energy equation takes into account the friction work due to liquid viscosity. Final relation obtained from the model has the form:

$$\left[3(1 + C) + \frac{4\mathrm{We}}{\sqrt{\mathrm{Re}}} \right] \beta^3 - (12 + \mathrm{We})\beta + 8 = 0 , \tag{6}$$

where the parameter C is expressed by the following formula:

$$C = \frac{\sigma_{wl} - \sigma_{wv}}{\sigma_{lv}} . \tag{7}$$

Calculation results of the spreading coefficient, calculated on the basis of Eq. (6), and experimental results for toluene droplets are given in paper [28] and presented

in Fig. 3. It can be noticed that the parameter C decides on the size of wetting area, and thus describes the relation between surface energies (tensions) at the contact line. The parameter C can take both the negative as well as positive values. The higher the negative value of parameter C, the bigger is the area of the surface wetted by the droplet. The above fact is also confirmed by the higher value of the spreading coefficient β. Surface wetting area diminishes with the rise of the value of parameter C. On the basis of Fig. 3, it can also be stated that the rise of contact temperature causes that the wetting area of toluene droplets diminishes. Contact temperature is here expressed by dimensionless initial temperature of the surface, defined by the formula:

$$Z = \frac{T_c}{T_n} . \tag{8}$$

Thus, coefficient C describes properly the tendency of wetting surface due to the increase of surface temperature. It seems that the parameter C can be applied to describe the surface wetting by impinging droplets.

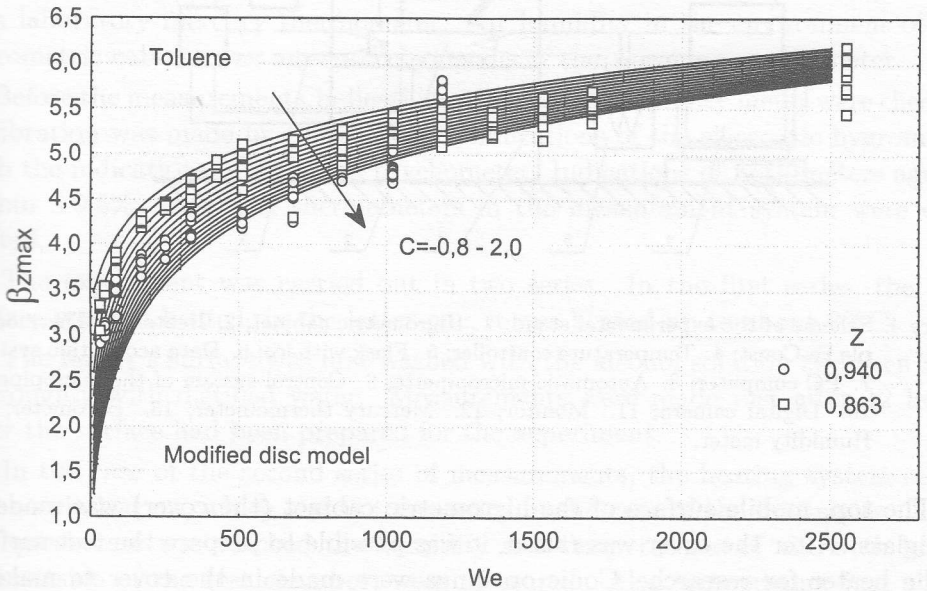

Figure 3. Comparison of the spreading coefficient, calculated from Eq. (6), with experimental results for water droplets.

3 Experimental stand and research methodology

Experimental research was carried out on the stand, the scheme of which is presented in Fig. 4. Electric heater was placed inside a higrometric cabinet. Water droplets were dropped onto the upper, horizontal surface of the heater. The heater surface served as the test surface. It was made of polished stainless steel type SW7M. The roughness parameter of test surface is equal to $R_z = 1.660 \cdot 10^{-6}$m. Heater's power was controlled by means of a power supply, which allowed to change the temperature of the test surface. Two thermocouples Fe-Const were placed just beneath the test surface of the heater. The task of the first thermocouple was to give a signal to the temperature controller. The latter thermocouple measured the temperature values just under the test surface. Its readings were stored in the computer memory.

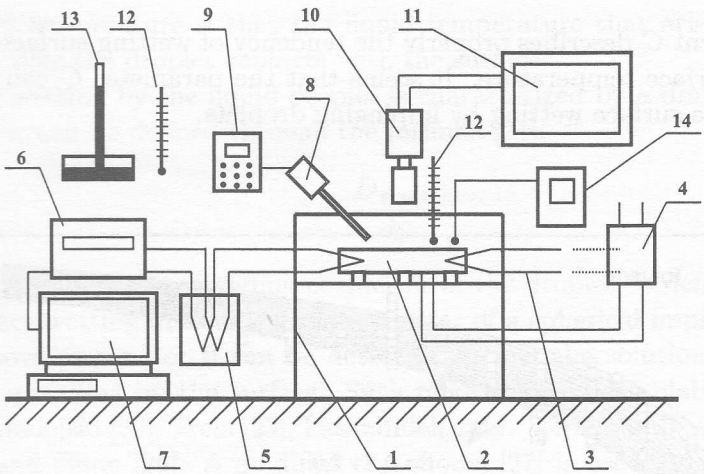

Figure 4. Scheme of the experimental stand: 1. Higrometric cabinet; 2. Heater; 3. Thermocouple Fe-Const; 4. Temperature controller; 5. Flask with ice; 6. Data acquisition system; 7. PC computer; 8. Automatic micropipette; 9. Control system of the micropipette; 10. Digital camera; 11. Monitor; 12. Mercury thermometer; 13. Barometer; 14. Humidity meter.

The top, mobile surface of the higrometric cabinet (the cover) was made of plexiglass. After the cover was raised, it was possible to prepare the test surface of the heater for research. Conic openings were made in the cover to make it possible to introduce the tips of automatic micropipette. The distance from tips to the test area of the heater was equal $H = 6.5 \cdot 10^{-3}$m.

Redistilled water droplets with the temperature of environment (20-30°C) were dropped separately by means of automatic micropipette driven by a con-

troller. On the basis of test measurements, it was noticed that water droplets with volume $V_0 = 12 \cdot 10^{-9}\text{m}^3$ separated from the micropipette due to their weight. The droplets with the above volume were the subject of the research. It was further assumed that droplet in the air, before its contact with the surface, was a sphere and its diameter was equal to $d_0 = 2.8405 \cdot 10^{-3}\text{m}$. Additionally, it was assumed that at the moment of its contact with the surface, its potential energy transforms ideally into the kinetic energy. Hence, the contact velocity, calculated from the conservation energy equation, equalled to $u_0 = 0.3571$ m/s. In the energy balance equation for the droplet, it was also assumed that the droplet initial velocity was equal to zero.

The droplet spreading process on the test surface was registered by means of a digital video camera, connected to a monitor. The optical axis of the camera was set up perpendicularly to the test surface of the heater. Droplets were registered through the plexiglass cover of the cabinet.

Temperature inside the higrometric cabinet was measured by means of a laboratory mercury thermometer and, additionally, by a resistance thermometer. Resistance sensor together with a lithium sensor created an integrated probe of a humidity meter.

In order to measure the pressure of environment, mercury barometer with vernier was applied, and the environment temperature was determined by means of a laboratory mercury thermometer. Air humidity in the environment of the higrometric cabinet was measured by means of the Assmann psychometer.

Before the measurements, indications of electronic humidity meter were checked. Calibration was made by comparison of indications of the electronic hygrometer with the indications of Assmann psychometer. Indications of both meters agreed within $\pm 0.5\%$. Also the thermometers in the measurement system were calibrated.

The experiment was carried out in two series. In the first series, the test surface was not heated, in the latter one, it was heated up to about 80°C.

The heater's surface was first washed with the alcohol solution and then very thoroughly with distilled water. Measurements were made just after 12 hours after the surface had been prepared for the experiment.

In the case of the second series of measurements, the heating system ought to be switched on, which was not necessary in the case of the first series. After the quasi-state was reached the humidity and temperatures of air, both inside and outside of the test chamber, were measured. Also temperature just above the test surface of the heater was measured. Next, two water droplets were dropped successively, and the process of their spreading was registered by a video camera. Droplets were dropped to two different sites of the heating surface. After the two tests were made, the humidification system was switched on and

the relative humidity rose to the desired value. Two successive tests for water droplets spreading were made with the new value of air humidity. Thus, it was possible to register 4 cycles of droplet spreading within every measurement day.

Magnification of the picture was obtained during the computer elaboration of the video film, on the basis of a filmed object with known size (a coin). Droplet spreading area was measured in five different directions of the spread droplet. The mean value of droplet spreading diameter was analyzed. In turn, the diameter of impinging droplet was calculated from its volume. After dividing of both diameters the value of droplet spreading coefficient β was obtained.

Exact analysis of the video film allowed to determinethe moment in which the droplet spread maximally. Because of too low registering velocity, some of tests failed, as the phase of maximal droplet spreading was not registered.

4 Results of experimental research

On the basis of experimental measurements pertinent parameters for the phenomenon were calculated. For the above task, approximation equations describing the change of physical properties of water with temperature were elaborated on the basis of water tables. The following quantities were needed for the analysis: coefficient of thermal conductivity, specific heat, density and surface tension of water. Respective equations for them are given by:

$$\begin{aligned}
\lambda_{H_2O} &= 0.561 + 0.002 \cdot t_{H_2O} && [\mathrm{W/(mK)}] \\
c_{H_2O} &= 4.201 + 0.0009 \cdot t_{H_2O} && [\mathrm{kJ/(kgK)}] \\
\rho_{H_2O} &= 1003.2 - 0.25 \cdot t_{H_2O} && [\mathrm{kg/m^3}] \\
\sigma_{H_2O} &= 76.03 \cdot 10^{-3} - 0.000168 \cdot t_{H_2O} && [\mathrm{N/m}]
\end{aligned}$$

and they are valid for the temperatures range $20 \div 30^0$C.

It was much more difficult to determine the change of physical properties of stainless steel with temperature. For the above reason, the following tabular values were assumed for calculations: coefficient of thermal conductivity $\lambda_{steel} = 45.4$ W/(mK), specific heat $c_{steel} = 0.46$ kJ/(kg K) and density $\rho_{steel} = 7900$ kg/m^3.

The dynamics of droplet spreading was characterized by the Weber number defined by the equation:

$$\mathrm{We} = \frac{\rho_l d_0 u_0^2}{\sigma_{lv}} . \tag{9}$$

For the experimental conditions the Weber number equals about 5 ($\mathrm{We} \cong 4.97 \div 5.06$).

In order to determine the parameter N, the value of partial pressure of water vapour in the long distance from the surface was calculated from the relation:

$$p_{v\infty} = \varphi_p \cdot p_{vln} \ , \tag{10}$$

where p_{vln} was the partial pressure of water vapour determined for the temperature of dry thermometer. Next, the contact temperature and pressure P_{vwn} was determined. Parameter N was calculated from Eq. (2).

Results of calculations are presented in Figs. 5-8. Fig. 5 presents the change of coefficient β_{max} in function of contact temperature. It was noticed that the value of the above coefficient diminishes with the rise of contact temperature. With higher contact temperatures, water droplets wet smaller areas of the test surface. Toluene droplets investigated in paper [28] (Fig. 3) behaved similarly. Thus, contact temperature is a significant parameter in the process of water droplet spreading.

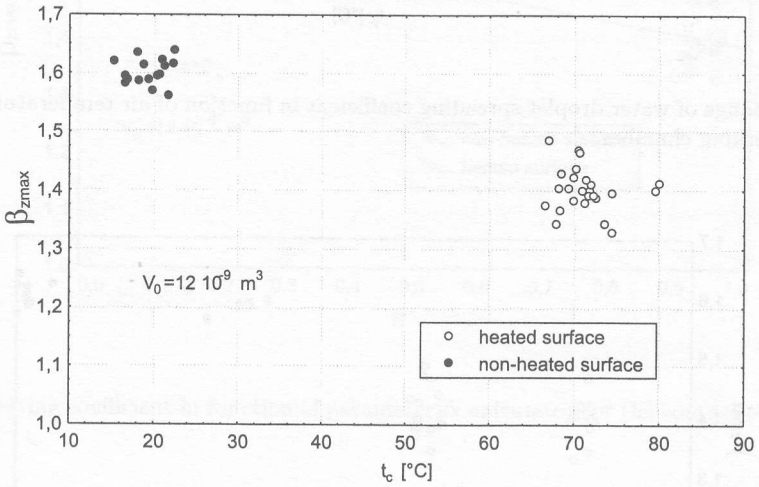

Figure 5. Change of water droplet spreading coefficient in the function of contact temperature.

Then, the effect of thermodynamic parameters in the surrounding air was investigated. To do so, two successive charts were drawn to illustrate the change of spreading coefficient β_{zmax} in the function of temperature and relative humidity inside the test chamber (Figs. 6 and 7). It results from the position of measurement points in Fig. 6 that the air temperature inside the chamber does not affect significantly the value of spreading coefficient β_{zmax}. Similarly, the analysis of Fig. 7 shows that also relative humidity of air in the test chamber does not influence meaningfully the value of wetting coefficient. Thus, both parameters can not be applied for the analysis of the effect surface wetting by droplet.

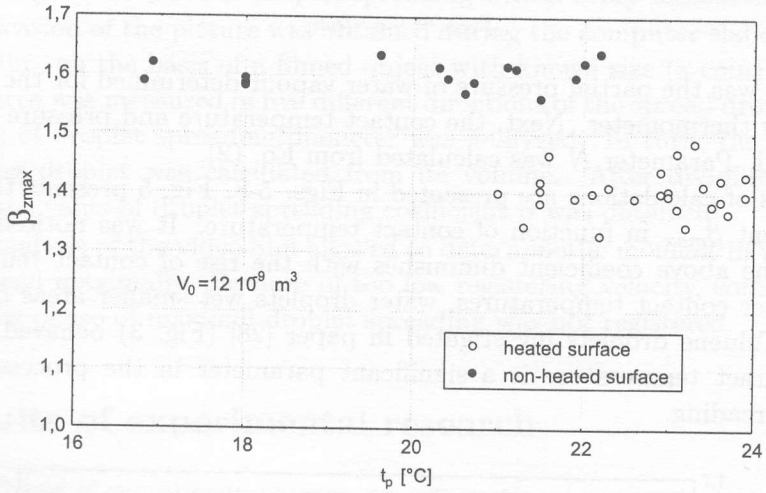

Figure 6. Change of water droplet spreading coefficient in function of air temperature inside the working chamber.

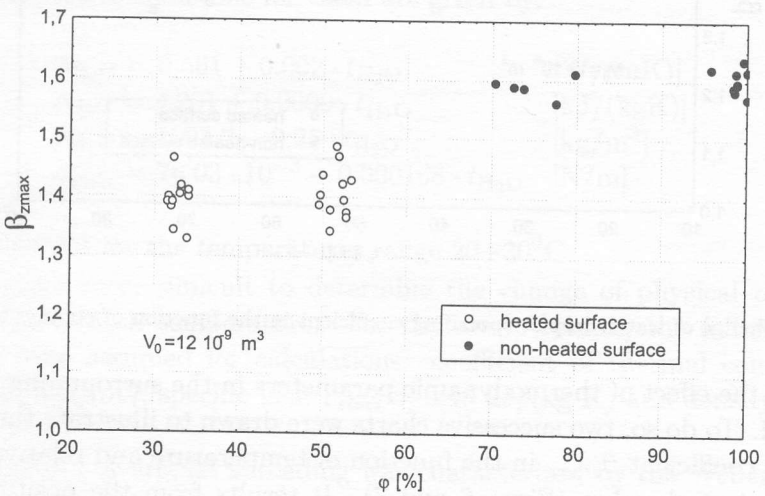

Figure 7. Change of water droplet spreading coefficient in function of relative air humidity inside the chamber.

In turn, Fig. 8 presents the relation between droplet spreading parameter β_{zmax} and the coefficient N. It could be noticed from Fig. 8 that the value of spreading coefficient β_{zmax} diminishes with the increase of parameter N. As it was expected, the above fact means that evaporation of absorbed water film does not act in favour of water droplet spreading on the surface. Thus, parameter N, which accounts for the influence of heat and mass exchange between the droplet and the environment, can be applied in the analysis of the wetting process on the surface by droplet.

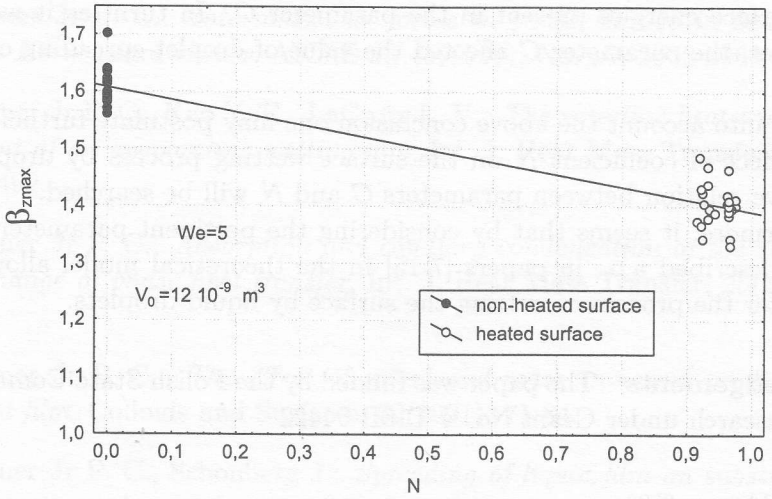

Figure 8. Wetting coefficient in function of parameter N calculated for the contact temperature.

Therefore, two quantities characterize the wetting process of surface by droplet: coefficient C and parameter N. Coefficient C is the ratio of respective surface energies at the contact line, the values of which depend on the properties of the thin microfilm forming on the surface. In turn, the properties of the above film are characterized by the coefficient N, the value of which depends on the intensity and direction of vapour mass flux. From the above discussion it is quite evident that the coefficient C depends on the parameter N. In the case of evaporation, value of the coefficient N is higher than zero. For $N = 1$, the microfilm evaporation is the most intense one. In turn, negative values of the parameter N show that the process of vapour condensation occurs on the microfilm surface, which causes the droplet spreading totally on the microfilm surface.

5 Conclusions

On the basis of results of experimental research, it can be stated that there is a qualitative relation between parameters C and N. Parameter C depends on the parameter N. Parameter N, introduced by Gajewski and Trela [6], and characterizes the intensity and direction of vapour mass flux, plays an important role in the analysis of wetting the surface by droplet. For water droplets that evaporate into the free air from the metal surface, it was noticed that spreading coefficient β_{zmax} diminished with the increase of parameter N. Evaporation of the microfilm in the vicinity of the contact line between three phases limits the water droplet spreading on the surface. Thus, the parameter N influences the ratio of surface energies present in the parameter C. In turn, as it was shown in the paper, the parameter C affected the value of droplet spreading coefficient β_{zmax}.

Taking into account the above conclusion one may postulate further research into the effect of coefficient N on the surface wetting process by droplet. The quantitative relation between parameters C and N will be searched.

Furthermore, it seems that by considering the pertinent parameters of phenomenon described a.o. in papers [7-15] in the theoretical model allows to describe better the process of wetting the surface by liquid droplets.

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References

[1] Orzechowski Z., Prywer J.: *Liquid spraying*, WNT, Warszawa 1991, (in Polish).

[2] Orzechowski Z., Prywer J.: *Liquid spraying in power engineering applications*, WNT, Warszawa 1994, (in Polish).

[3] Pasandideh-Fard M., Bhola R. Chandra S., Mostaghimi J.: *Deposition of tin droplets on a steel plate: simulations and experiments*, Int. J. Heat Mass Transfer, 41(1998), No. 19, 2929-2945.

[4] Waldvogel J. M., Poulikakos D., Wallace D. B., Marusak R.: *Transport phenomena in picoliter size solder droplet dispension*, Trans. ASME, J. Heat Transfer, 118(1996), 148-156.

[5] Waldvogel J. M., Poulikakos D.: *Solidification phenomena in picoliter size solder droplet deposition on a composite substrate*, Int. J. Heat Mass Transfer, 40(1997), No. 2, 295-309.

[6] Gajewski A., Trela M.: *Dynamic wetting angle in gravitational liquid jets*, Bull. of IFFM PAS, No. 518/1477/2000, Gdańsk 2000, (in Polish).

[7] Van Carey P.: *Liquid-vapour phase-change phenomena: An introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment*, Hemisphere Publ. Corporation, Taylor & Francis, Bristol, Pa 1992.

[8] Wayner Jr P. C.: *Intermolecular forces in phase change in heat transfer: 1998 Kern award review*, AIChE J., 45(1999), No. 10, 2055-2068.

[9] Wayner Jr P. C., Kao Y. K., LaCroix L. V.: *The interline heat-transfer coefficient of an evaporating wetting film*, Int. J. Heat Mass Transfer, 19(1976), 487-492.

[10] Wayner Jr P. C.: *Adsorption and capillary condensation at the contact line in change of phase heat transfer*, Int. J. Heat Mass Transfer, 25(1982), 707-713.

[11] Wayner Jr P. C.: *The effect of interfacial mass transport on flow in thin liquid film*, Colloids and Surfaces, 52(1991), 71-84.

[12] Wayner Jr P. C., Schonberg J.: *Spreading of liquid film on substrate by the evaporation-adsorption process*, J. Coll. Int. Science, 152(1992), 507-520.

[13] Wayner Jr P. C.: *Spreading of liquid film with a finite contact angle by the evaporation/condensation process*, Langmuir, 9(1993), 294-299.

[14] Wayner Jr P. C.: *Thermal and mechanical effects in the spreading of a liquid film due to a change in the apparent finite contact angle*, Trans. ASME, J. Heat Transfer, 116(1994), 938-945.

[15] Zheng L., Wang Y-X, Plawsky J. L., Wayner Jr P. C.: *Effect of curvature contact angle, and interfacial subcooling on contact line spreading in a microdrop in dropwise condensation*, Langmuir, 18(2002), 5170-5177.

[16] Zapałowicz Z.: *Conditions for appearance of a droplet structure and liquid film on a horizontal heated wall surface for selected liquids*, Archives of Thermodynamics, 21(2000), No. 1-2, 73-85.

[17] Staniszewski B.: *Thermodynamcs*, PWN Warszawa 1978, p.149, (in Polish).

[18] Michiyoshi I., Makino K.: *Heat transfer characteristics of evaporation of a liquid droplet on heated surfaces*, Int. J. Heat Mass Transfer, 21(1978), 605-613.

[19] Makino K., Michiyoshi I.: *Discussions of transient heat transfer to a water droplet on heated surfaces under atmospheric pressure*, Int. J. Heat Mass Transfer, 30(1987), No. 9, 1895-1905.

[20] Seki M., Kawamura H., Sanakawa K.: *Transient temperature profile of a hot wall due to an impinging liquid droplet* Trans. ASME, J. Heat Transfer, 100(1978), No. 1, 167-169.

[21] Bonacina C., Del Giudice, S., Comini G.: *Dropwise evaporation*, Trans. of ASME, J. Heat Transfer, 101(1979), 441-446.

[22] Madejski J.: *Solidification of droplets on a cold surface*, Int. J. Heat Mass Transfer, 9(1976), 1009-1013.

[23] Trela M.: *Thermal-hydraulic problems in liquid phase on the wall in two-phase flow*, Bull. of IFFM PAS, No. 293/1214/89, Gdańsk 1989, (in Polish).

[24] Pasandideh-Fard M., Qiao Y.M., Chandra S., Mostaghimi J.: *Capillary effects during droplet impact on a solid surface, Physics of Fluids*, 8(1996), No. 3, 650-659.

[25] Sobolev V. V., Guilemany J. M., Martin A. J.: *Investigation of droplet flattening during thermal spraying*, Surfaces and Coatings Technology, 89(1997), 82-89.

[26] Kim H.-Y., Chun J.-H.: *The recoiling of liquid droplets upon collision with solid surfaces*, Physics of Fluids, 13(2001), No. 3, 643-658.

[27] Zapałowicz Z.: *Macroscopic model of droplet spreading onto horizontal surface*, Archives of Thermodynamics, Vol. 24 (2003), No. 3, 55-68.

[28] Zapałowicz Z.: *Critical contact Weber number for toluene droplets dropping onto heated wall surface*, Experimental Thermal and Fluid Science, 25(2002), 523-528.