POLSKA AKADEMIA NAUK

INSTYTUT MASZYN PRZEPŁYWOWYCH

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

96

GDAŃSK 1993

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

*

THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

REDAKCJA – EDITORIAL OFFICE

Wydawnictwo Instytutu Maszyn Przepływowych
Polskiej Akademii Nauk
ul. Gen. Józefa Fiszera 14, 80-952 Gdańsk, skr. poczt. 621,
tel. (0-58) 41-12-71 wew. 141, fax: (0-58) 41-61-44,
e-mail: tjan@imppan.imp.pg.gda.pl

ISBN 83-01-94610-1
ISSN 0079-3205

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

1994 Zeszyt 96

ZBIGNIEW ZAPAŁOWICZ[1]

The Effect of Droplet Volume on the Droplet Spreading Ratio

The paper presents experimental investigations into the process of spreading of a liquid droplet over the surface. The wall area covered by the droplet is characterized by a spreading ratio β_R. It has been confirmed that the value of β_R increases when the initial droplet volume increases and the droplet-wall-environment system is in the quasi-static state. However, the influence of the initial surface temperature on β_R has not been found.

Nomenclature

c	–	specific heat, $J/(kgK)$,	V	–	volume , m^3 or nm^3 ,
C	–	constant, $C = (\sigma' - \sigma'')/\sigma$,	We	–	Weber number,
d	–	droplet diameter, m,			$We = d\rho_l u^2/\sigma_l$,
D	–	wetted area diameter, m,	Z	–	contact reduce temperature,
Eo	–	Etvös number, $Eo = d^2 \rho_l g/\sigma_l$,			$Z = T_c/T_b$,
Fr	–	Froud number,	β	–	droplet spreading ratio,
		$Fr = Eo/We = dg/u^2$,	ρ	–	density, kg/m^3,
g	–	acceleration of gravity, m/s^2,	λ	–	thermal conductivity, $W/(mK)$,
Re	–	Reynolds number, $Re = du/\nu_l$,	ν	–	kinematic viscosity, m^2/s,
t	–	temperature, ^oC,	σ	–	liquid-gas surface tension, N/m,
T	–	absolute temperature, K,	σ'	–	solid-liquid interfacial tension, N/m,
u	–	droplet velocity, m/s,	σ''	–	solid-gas interfacial tension, N/m.

Subscripts

b	–	boiling,	R	–	charact. quasistatic state of the droplet-: -surface-environment system,
c	–	contact,	o	–	initial,
l	–	water,	w	–	surface.

1. Introduction

Processes where streams of droplets interact with surfaces are very frequent in many fields of technology. Thus, it seams to be crucial to find out how a single

[1] Katedra Techniki Cieplnej Politechniki Szczecińskiej

droplet behaves, after it has been deposited on the surface.

A liquid droplet falling on a flat horizontal surface spreads over it. The wall area covered by a single droplet is characterized by the wetted area diameter or by the nondimensional parameter β [1] which is given by:

$$\beta = D/d \tag{1}$$

The above value is called the wetting parameter [2] or the spreading ratio [3]. The latter name will be used in this paper.

The value of β has been investigated theoretically and experimentally. Assumptions and analytical models of the spreading of a liquid droplet over a flat surface are presented in [3,4,5,6,7]. The simplest model has been formulated by Ueda *et al.* [6]. Ueda *et al.* have assumed that, if the energy losses during the deformation process are neglected, the initial droplet energy (which is the sum of kinetic and surface energies) is equal to the energy of a very thin liquid disc. In their model, a liquid disc with diameter D has formed on the surface. Another analytical model, proposed by Trela [5], considers the lateral disc surface. Trela has also introduced a parameter C to account for the influence of the material the surface is made of. Madejski [3,4] has described a dynamic model of the phenomenon. He also considers friction forces in the equation of conservation of energy. The integro-differential energy conservation equation derived by Madejski has analytical solutions only for several particular cases. In [7], the author assumes that when the droplet-surface-environment system has the minimum of total energy, it achieves the stationary state . The model in consideration here is valid for droplets *softly* deposited on the surface. It take into account the gravity effects on the spreading process.

Experimental investigations have been carried out to find the relationship between the spreading ratio β and time [6] . It has also been an aim of research to determine special values of β_R corresponding to the maximal wetting of the surface by a single droplet [6] and to evaluate the spreading ratio β_{max} corresponding to the quasi-static system of the liquid droplet wall surface and environment [2] (Fig. 1). It should be noted that the values of β in the range between 1.2 and 1.5 [2] refer to the characteristic quasi-static state of the system ($\tau = \tau_R$). They do not refer to the initial state of the system ($\tau = 0$) as it has been suggested by the above mentioned authors (Fig. 1).

The purpose of the present investigation is an experimental verification of the influence of droplet volume onto the spreading ratio β and determination of the relationship between the spreading ratio β and crucial parameters expressed by dimensionless numbers. The investigation has been carried out for water droplets larger in volume than those presented by: Bonacina *et al.* ($V_0 = 6.95 \cdot 10^{-4} \div 5.08 \cdot 10^{-4}\ nm^3$) [1] , Ueda *et al.* ($V_0 = 0.38 \div 14.14\ nm^3$ [6] and di Marzo and Evans ($V_0 = 10 - 50\ nm^3$) [2]. Droplets have been dropped from the same height onto a nickel plated flat surface with its initial temperature lower than the water boiling point.

2. Droplet Impact History

Successive stages of the liquid droplet-wall interaction are shown in Fig. 1. The interaction occurs in several phases. In the initial phase, that is in the

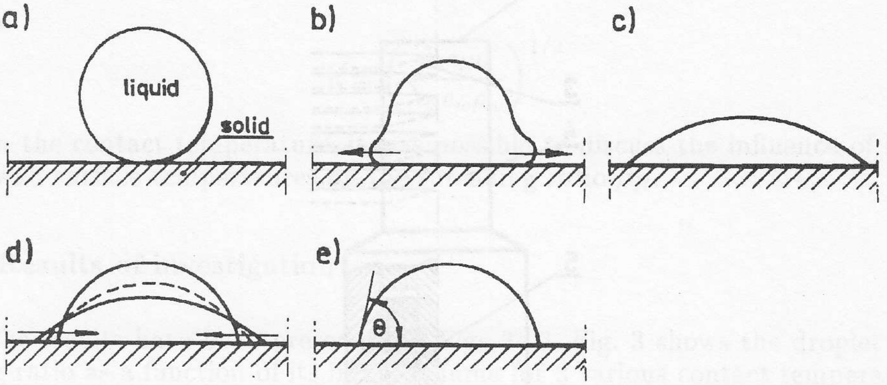

Fig. 1. Phases of liquid droplet spreading over the surface with temperature not higher than the boiling point
a) $\tau = \tau_0 = 0$; $D = 0$; $\beta = 0$, b) $\tau_0 < \tau < \tau_1$, c) $\tau = \tau_1$, $D = D_{max}$, $\beta = \beta_{max}$ d) $\tau_1 < \tau < \tau_R$; $\beta_{max} > \beta > \beta_R$, e) $\tau = \tau_R$; $D = D_R$; $\beta = \beta_R$

moment of dropping ($\tau = \tau_0 = 0$), the droplet wetting area is just a point, with the spreading ratio equal to zero (Fig. 1a). In the next phase, the droplet spreads over the wall surface and the wetted area increases (Fig. 1b). The process occurs until an instantaneous equilibrium of the droplet-wall surface-environment system is reached. At this moment the wetted area is maximal and the spreading ratio reaches its maximum: β_{max} (Fig. 1c). In the next phase, the wetted area decreases (Fig. 1d) until the characteristic quasi-static state of the system is obtained (Fig. 1e) . Since that moment, the wetted area remains constant within 70-80 % of the total time of evaporation, the spreading ratio being equal to β_R. Droplet formation on the wall surface is very fast if compared with the total evaporation time . Mass change of the droplet in the process of its spreading over the wall surface, caused by its evaporation, is relatively small and can be neglected.

3. Experimental Procedure

The essential part of the experimental stand is shown in Fig. 2. The detailed description and the operational principle are presented in [8,9,10]. Only the film camera in the stand presented in [8,9,10] has been replaced with a video-camera CCD V700E Sony.

Water droplets with volumes in the range of $5 \div 300\ nm^3$ were dropped by

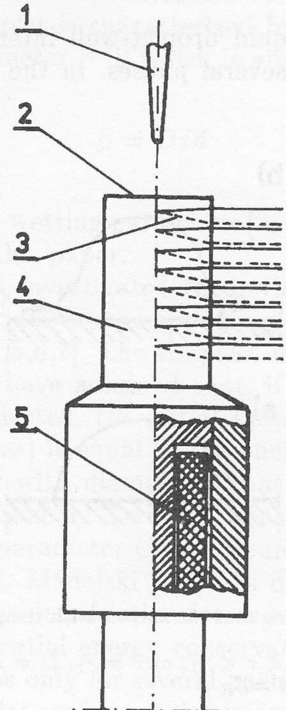

Fig. 2. Principal part of the apparatus
1. Micropipette, 2. Test surface, 3. Thermocouples Cu-Konst, 4. Heater, 5. Heating element

means of a micropipette on the flat horizontal test surface of a heater that had been coated with a very thin nickel layer. Thermocouples Cu-Konst were placed in the cylindrical part of the heater. The initial surface temperature was determined by means of extrapolation from the equation which defined the temperature distribution in the symmetry axis of the heater . The evaporation of water droplets was recorded by the video-camera. Video-film analysis of the initial moment of the evaporation ($\tau = \tau_R$) allowed us to determine the characteristic geometric dimensions of the droplet, that is, the diameter of wetted area and the height. It was assumed that the droplet had the shape of a spherical cap. Later, the droplet volume was calculated. Thus, the diameter of the spherical droplet, equal in volume with that of the spherical cap, could be found. Then, the spreading ratio β_R was computed from the respective diameter values, according to Eq. (1).

Velocity of the falling droplet was approximately constant at $0.524\ m/s$ which is equal to the velocity of the droplet falling from the same height, that is the distance between the micropipette outlet and the heater surface ($H = 0.014\ m$). Density, surface tension, and liquid viscosity given in dimensionless numbers were determined for the contact temperature. It was assumed that the contact temperature was achieved immediately after the droplet reached the wall surface. The contact temperature was computed from the following equation [3]:

$$t_c = \frac{t_l \kappa + t_w}{1 + \kappa} \tag{2}$$

where

$$\kappa = \left(\frac{\lambda_l c_l \rho_l}{\lambda_w c_w \rho_w} \right)^{1/2} \tag{3}$$

Given the contact temperature, it was possible to discuss the influence of liquid and wall surface temperatures on the spreading ratio β_R.

4. Results of investigation

The results have been presented in Figs 3÷6. Fig. 3 shows the droplet spreading ratio as a function of its initial volume for 3 various contact temperatures. It is difficult to estimate the influence of the initial wall surface temperature onto the spreading ratio from the distribution of measurement points in Fig. 3. As a result of approximation, the following equation was obtained:

$$\beta_R = 1,15294\, V^{0,05795} \tag{4}$$

when: $u = const$; $t = const$.

The research results can be presented in the form of a non-dimensional equation. On the basis of the dimensional analysis [11] it has been established that the droplet spreading ratio can be determined as a function of the following dimensionless numbers (see Appendix):

$$\beta_R = G \cdot We^a \cdot Eo^b \cdot Re^c \cdot Z^d \tag{5}$$

The numerical form of the Eq. (5) can be represented by an approximate formula:

$$\beta_R = 0.1857 \cdot We^{-0.1519} \cdot Eo^{0.0279} \cdot Re^{0.2711} \cdot Z^{-1.5021} \tag{6}$$

This formula has been established by means of the numerical program STATISTICA (with the option for nonlinear models). The correlation coefficient of the equation is 0.7852.

Figs. 4 to 6 present a comparison of the experimental and analytic values of droplet spreading ratio. Solid lines are plotted through the points calculated according to Eq. (6) for three different values of the contact reduce temperature. Of course, the droplet spreading ratio increases with the increase of the dimensionless numbers We, Eo, Re. However, the influence of the contact reduce temperature (a ratio between contact temperature and boiling temperature) is clear only in Fig. 6. The influence of the initial surface temperature onto the coefficient β_R was

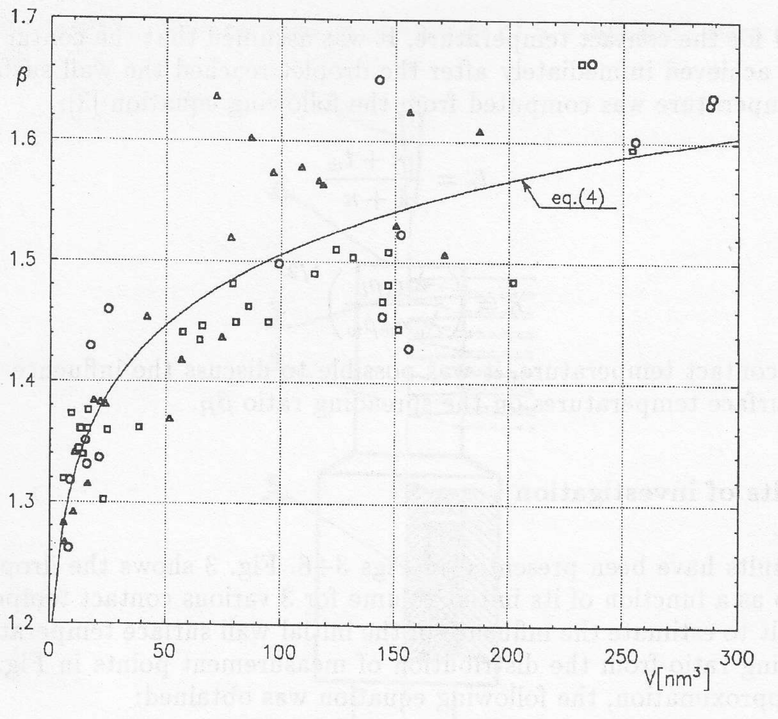

Fig. 3. Dependence of the spreading ratio β_R on the initial droplet volume V_0

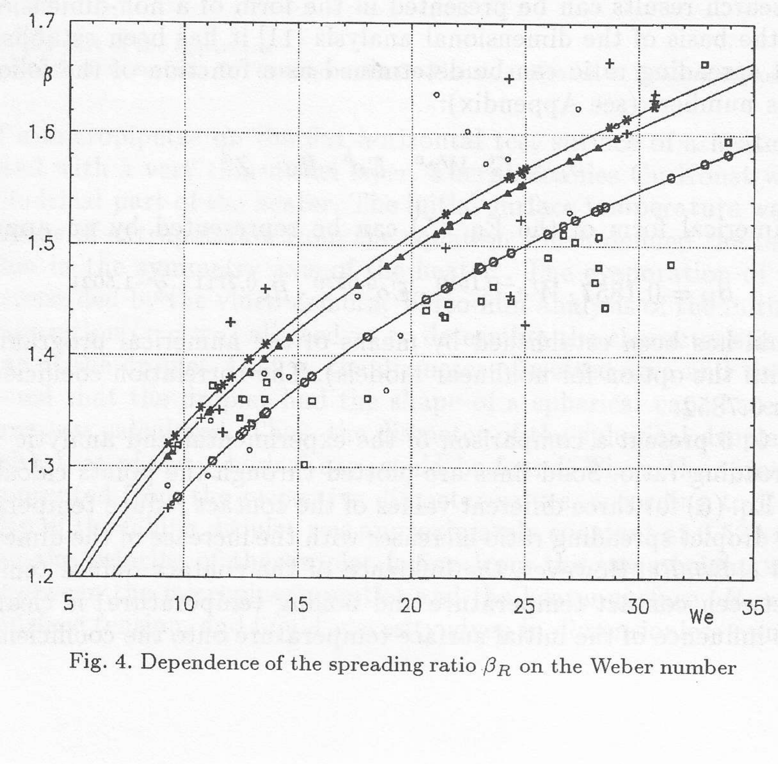

Fig. 4. Dependence of the spreading ratio β_R on the Weber number

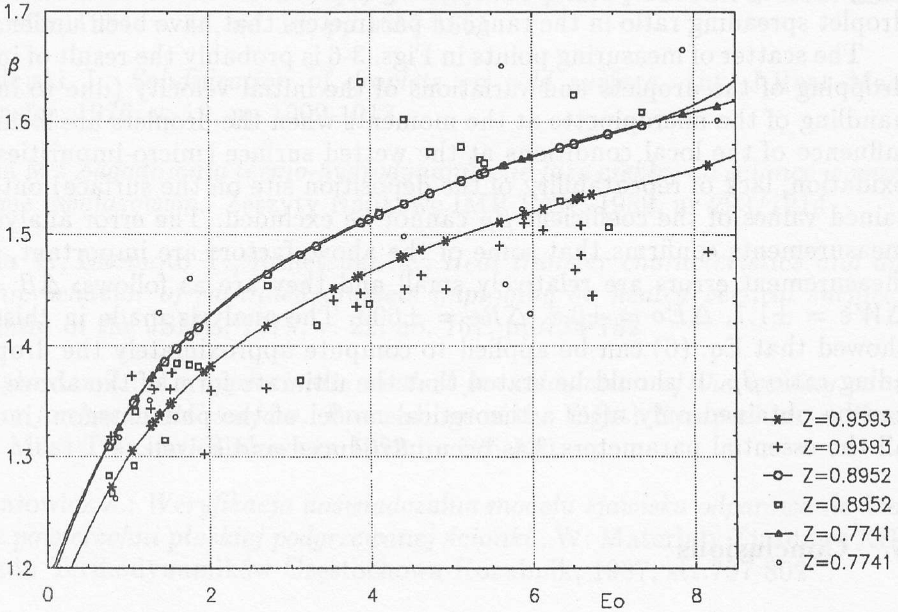

Fig. 5. Dependence of the spreading ratio β_R on the Etvös number

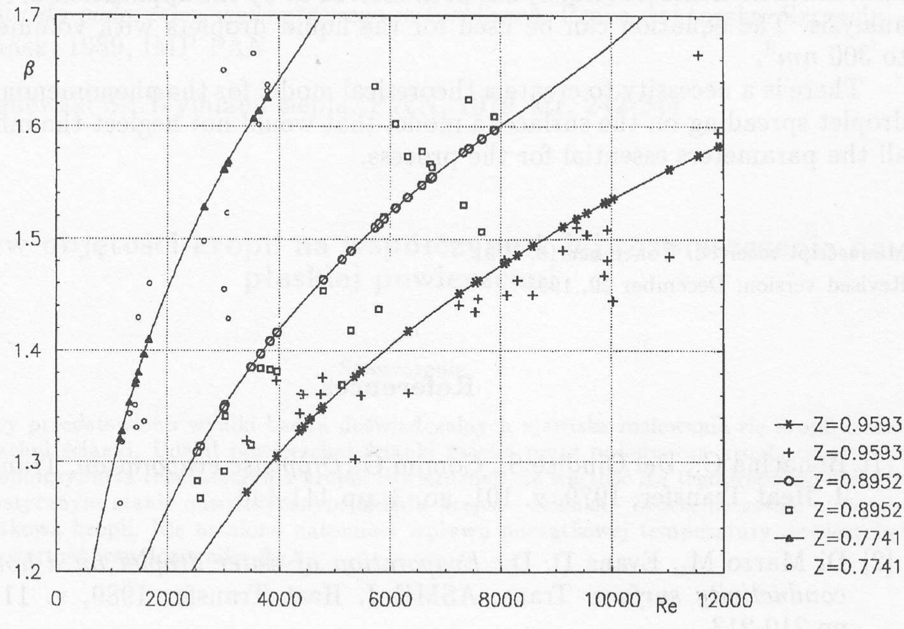

Fig. 6. Dependence of the spreading ratio β_R on the Reynolds number

suggested by di Marzo and Evans [2]. Eq. (6) enables one to determine values of droplet spreading ratio in the range of parameters that have been under research.

The scatter of measuring points in Figs. 3-6 is probably the result of inaccurate dropping of the droplets and variations of the initial velocity (due to inaccurate handling of the micropipette at the moments when the droplets are formed). The influence of the local conditions at the wetted surface (micro-impurities, surface oxidation, lack of repeatability of the deposition site on the surface) onto the obtained values of the coefficient β_R cannot be excluded. The error analysis of the measurements confirms that some of the above factors are important. Maximal measurement errors are relatively small and they are as follows: $\Delta\beta = \pm 0.02$, $\Delta We = \pm 1.7$, $\Delta Eo = \pm 0.8$, $\Delta Re = \pm 600$. The analysis made in this research showed that Eq. (6) can be applied to compute approximately the droplet spreading ratio β_R. It should be stated that the ultimate form of the above equation can be obtained only after a theoretical model of the phenomenon, inclusive of all the essential parameters, has been introduced and solved.

5. Conclusions

Within the investigated range of parameters, it has been confirmed that the spreading ratio β_R of the liquid droplets depends on their initial volumes. No influence of the initial wall surface temperature onto the spreading ratio β_R has been observed.

The approximate equation describing the spreading ratio β_R as a function of dimensionless numbers (Eq. 6) has been arrived at by the application of regression analysis. The equation can be used for the liquid droplets with volumes from 5 to 300 nm^3.

There is a necessity to create a theoretical model for the phenomenon of liquid droplet spreading on the surface, a model that would not neglect the influence of all the parameters essential for the process.

Manuscript received: Nonember 18, 1991
Revised version: December 20, 1993

References

[1] Bonacina C., Del Giudice S., Comini G.:*Dropwise evaporation.* Trans. ASME J. Heat Transfer, 1979, v. 101, no. 3, pp.441-446

[2] Di Marzo M., Evans D. D.: *Evaporation of water droplet on a hot thermal conductivity surface.* Trans. ASME J. Heat Transfer 1989, v. 111, no. 1, pp.210-213

[3] Madejski J.: *A new criterion of dry-out in two-phase flow.* Int. J. Heat Mass Transfer, 1981, v. 24, no. 10, pp.1657-1665

[4] Madejski J.: *Solidification of droplets on cold surface..* Int. J.Heat Mass Transfer, 1976, v. 19, pp.1009-1013

[5] Trela M.: *Zagadnienia termo-hydrodynamiczne fazy ciekłej na ściance w przepływie dwufazowym..* Zeszyty Naukowe IMP PAN, 1989, nr 293/1214

[6] Ueda T., Enomoto T., Kanetsuki M.: *Heat transfer characteristics and dynamic behavior of saturated droplets impinging on heated vertical surface..* Bulletin of the JSME, 1979, v. 22, no. 167, pp.724-732

[7] Zapałowicz Z.: *An approximate method for calculation of the wetting parameter for horizontal surface..* Proceedings of the Eighth Symposium on Heat and Mass Transfer. Białowieża 1992, p. 525-530

[8] Zapałowicz Z.: *Weryfikacja doświadczalna modelu zjawiska odparowania kropli z powierzchni płaskiej podgrzewanej ścianki..* W: Materiały Zjazdowe XIII Zjazdu Termodynamików Częstochowa-Kozubnik, 1987, str.797-802

[9] Zapałowicz Z.: *Badania doświadczalne odparowania kropel z podgrzewanej powierzchni. Badania filmowe odparowania kropel z płaskiej podgrzewanej powierzchni..* Raport 7/89. Szczecin, 1989 (praca wykonana na zlecenie IMP PAN w ramach RPBP-02.8 zadanie 2.5.3.1. etap II)

[10] Zapałowicz Z.: *Odparowanie kropel z podgrzewanej powierzchni w zastosowaniu do podgrzewu wewnętrznego w turbinach.* Praca doktorska. Szczecin – Gdańsk, 1989, IMP PAN

[11] Wiśniewski S.: Wymiana ciepła. PWN, 1979, str. 242-244

Wpływ objętości kropli na współczynnik jej rozpłaszczenia na płaskiej powierzchni

Streszczenie

W pracy przedstawiono wyniki badań doświadczalnych zjawiska rozlewania się kropli cieczy po powierzchni ścianki. Udział powierzchni ścianki zajętej przez pojedynczą kroplę opisano za pomocą współczynnika rozpłaszczenia kropli. Stwierdzono, że wartość β_R tego współczynnika w charakterystycznym stanie qusistatycznym układu kropla - ścianka - otoczenie rośnie z objętością początkową kropli. Nie ustalono natomiast wpływu początkowej temperatury powierzchni ścianki na wartość współczynnika β_R.

Appendix

Dimensional Analysis

The process of spreading of the liquid droplet on the hot surface is determined by eleven characteristic dimensional quantities. The general relationship between these quantities is as follows [11]:

$$D = f(d_0, u_0, \rho, \nu, \sigma, \sigma', \sigma'', g, T_c, T_b) \tag{1d}$$

Basic units that have been assumed in presented study are:

- temperature – $[T]$,
- distance – $[l]$,
- mass – $[m]$,
- time – $[\tau]$.

From the theorem II of Buckingham, it is evident that the smallest number of dimensionless numbers is seven.

Eq. (ld) is to be dimensionally homogeneous, so it can be written:

$$[D] = [d_0]^a[u_0]^b[\rho]^c[\nu]^d[\sigma]^e[\sigma']^f[\sigma'']^g[g]^h[T_c]^i[T_b]^j \tag{2d}$$

Substituting the above quantities with their basic units gives the following:

$$[l] = [l]^a[l\ \tau^{-1}]^b[m \cdot l^{-3}]^c[l^2 \cdot \tau^{-1}]^d[m \cdot \tau^{-2}]^e[m \cdot \tau^{-2}]^f[m \cdot \tau^{-2}]^g \cdot$$
$$[l \cdot \tau^{-2}]^h[K]^i[K]^j \tag{3d}$$

The comparison of respective exponents gives:

$$\begin{array}{lr} \text{for } l & a + b - 3c + 2d + h = 1 \\ \text{for } \tau & -b - d - 2e - 2f - 2g - 2h = 0 \\ \text{for } m & c + e + f + g = 0 \\ \text{for } K & i + j = 0 \end{array}$$

The above system of equations can be solved with respect to any six exponents (eq. d,e,f,g,h,i). Therefore, it can be expressed as:

$$D = f\left(\frac{d_0 d_0^h}{d_0^d d_0^e d_0^f d_0^g};\ \frac{1}{u_0^d u_0^{2e} u_0^{2f} u_0^{2g} u_0^{2h}};\ \frac{1}{\rho^e \rho^f \rho^g};\ \nu^d;\ \sigma^e;\ \sigma'^f;\ \sigma''^g;\right.$$

$$\left. g^h;\ T_c^i;\ \frac{1}{T^i}\right) \tag{4d}$$

Eq. (4d) can be transformed and written as:

$$\frac{D}{d_0} = f\left(\frac{\nu^d}{d_0^d u_0^d};\ \frac{\sigma^e}{d_0^e u_0^{2e} \rho^e};\ \frac{\sigma'^f}{d_0^f u_0^{2f} \rho^f};\ \frac{\sigma''^g}{d_0^g u_0^{2g} \rho^g};\ \frac{g^h d_0^h}{u_0^{2h}};\ \frac{T_c^i}{T_b^i}\right) \tag{5d}$$

Substitution of the following expressions

$$\beta = \frac{D}{d_0};\quad Re = \frac{u_0 d_0}{\nu};\quad We = \frac{d_0 u_0^2 \rho}{\sigma};\quad We' = \frac{d_0 u_0^2 \rho}{\sigma'};$$

$$We'' = \frac{d_0 u_0^2 \rho}{\sigma''};\quad Fr = \frac{g d_0}{u_0^2};\quad Z = \frac{T_c}{T_b}$$

into Eq. (5d) gives the general form of the dimensionless equation:

$$\beta = f(Re, We, We', We'', Fr, Z) \tag{6d}$$

The number of dimensionless numbers can be reduced by two, because the experiment was conducted for the same surface and the same surface conditions. Therefore, the influence of quantities σ' and σ'' on the phenomenon is neglected. It is possible to substitute the Froude number with the Etvös number. The following expression for the droplet spreading ratio can be written:

$$\beta = G\, We^a\, Eo^b\, Re^c\, Z^d \tag{7d}$$

where: G - constant and a, b, c, d - exponents.

Numerical values of the constant G and exponents are established by means of the numerical program STATISTICA (with the option for nonlinear models). Thus, the above equation can be rewritten as:

$$\beta = 0.1857\, We^{-0.1519}\, Eo^{0.0279}\, Re^{0.2711}\, Z^{-1.5021} \tag{8d}$$