Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Mass Transfer 51 (2008) 1628–1632

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Peculiarities of boiling of emulsions with a low-boiling disperse phase

N.V. Bulanov [a,*], B.M. Gasanov [b]

[a] Ural State University of Railway Transport, Kolmogorova Street, 66 Ekaterinburg 620034, Russia
[b] Institute of Thermal Physics of Ural Branch of Russian Academy of Sciences, Amundsena Street, 106 Ekaterinburg 620016, Russia

Received 8 February 2007; received in revised form 10 April 2007
Available online 17 October 2007

Abstract

The heat transfer from thin wires to emulsions with a disperse phase formed from a liquid whose boiling temperature is much lower than the boiling temperature of the disperse medium was investigated. Experiments were conducted at atmospheric pressure on vertical and horizontal wires from 50 to 100 μm in diameter with *n*-pentane/glycerine, diethyl ether/water, and freon-113/water and water/oil emulsions.

It was possible to describe the experimental data obtained by one analytical dependence $Nu = AArPrM^{-1}[1 - \exp(-JVt)]$. The dependence presented was obtained from the proposed model of the chain branched activation of boiling centers in droplets of a superheated liquid. In this case the coefficient J acquires the meaning of the activation rate of these centers.

Keywords: Boiling; Nucleation site; Heat transfer; Activation of nucleation sites; Superheated liquid

---

1. Introduction

The boiling intensity of any heat-transfer agent depends on the number of nucleation sites. As their number increases, so do the heat-flow density and the heat-transfer coefficient α. However, the nature of formation of nucleation sites remains to be explored [1]. When an emulsion with a low-boiling disperse phase boils, the heating surface is wetted with a high-boiling disperse phase, whose temperature of saturated vapors is higher than the heating surface temperature. Therefore the formation of nucleation sites at the heating surface is hampered, and they do not exert any noticeable effect on the process of boiling the disperse phase. The boiling-up of droplets of the disperse phase takes place not at the heating surface, but in the thermal boundary layer, in which droplets of the disperse phase are easily heated to a temperature exceeding the temperature of their saturated vapors. Since the boiling-up of every droplet occurs only in the event that at least one nucleation site is activated in it, this leads to some peculiarities of the boiling process. The main of them are a wide temperature range of bubble boiling and a considerable temperature difference ΔT_i that is necessary for starting of intense boiling [2,3]. This delay in emulsions reaches considerably higher values (up to 150 °C) as compared with conventional heat-transfer agents (pure liquids and solutions) and is an undesirable phenomenon. It should be noted that during the boiling of conventional heat-transfer agents the delay ΔT_i [4] is observed only at the initial instant of time ($\tau = 1$–10 s) and disappears with the activation of the first nucleation site.

2. Boiling model for an emulsion with a low-boiling disperse phase

To describe experimental data, formulae were obtained on the basis of the following assumptions [5]:

- the boiling-up of disperse-phase droplets takes place on activated low-temperature nucleation sites [6,7] inside disperse-phase droplets of an emulsion, nucleation sites at the surface being cooled were not activated;

---

[*] Corresponding author. Tel.: +7 9222106520; fax: +7 343 2678800.
E-mail address: bulanov@itp.uran.ru (N.V. Bulanov).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.07.027

Nomenclature

A	adjustment coefficient depending on the geometric form of the heater, dimensionless
C	volume concentration of the emulsion disperse phase, m^3/m^3
c_e and c_{dph}	heat capacity of the emulsion and the disperse phase, J/(kg °C)
D	bubble diameter, m
d	disperse phase droplet diameter, m
g	gravitational acceleration, m/s^2
J	adjustment coefficient and activation rate of nucleation sites, $m^{-3}\ s^{-1}$
r	disperse phase evaporation heat, J/kg
T_W, T_{WB}, T_S and T	temperatures of a heat-transfer surface, the beginning of intense boiling, disperse phase saturated vapors and a heat-transfer agent (emulsion), °C
t and t_a	time of emulsion residence in the thermal boundary layer and time of activation of a nucleation site, s

Dimensionless numbers

Ar	Archimedes
M	metastability
Nu	Nusselt
Pr	Prandtl

Greek symbols

α, α_b and α_c	heat-transfer coefficient under measurement and its components – boiling and convective, W/(°C m^2)
Δp	pressure amplitude, Pa
$\Delta T_i = T_{wbi} - T_S$	temperature difference that is necessary for starting of intense boiling, °C
$\Delta T = T_w - T_0$	temperature drop, °C
η_e	emulsion dynamic viscosity, N s/m^2
λ_e	emulsion thermal conductivity, W/(m °C)
v_m and v	average and true volume of disperse phase droplets, m^3
ρ_e, ρ_{ph} and ρ''_{ph}	densities of emulsion, disperse phase and forming vapor, kg/m^3

- when an emulsion boils, the heat removed from the surface is first absorbed by a thin emulsion layer in contact with the surface being cooled, and then goes into the evaporation of disperse-phase droplets brought to the boiling;
- under the action of the buoyancy force forming vapor bubbles leave the thermal boundary layer, together with a certain amount of the heat-transfer agent, and the vacant space is filled with a new portion of the emulsion.

The formula [5] was obtained for calculating the contribution of boiling (α_b) to heat transfer. The value of α_b was found from the relation $\alpha = \alpha_c + \alpha_b$, where α_c and α are the convective component and the measured value of the heat-transfer coefficient. For concentration of the disperse phase $C > 1.0\%$ the formula takes the form

$$Nu = AC_0 Ar Pr M^{-1}[1 - \exp(-J v_m t)], \tag{1}$$

where A and J are adjustment coefficients, $C_0 = c_e\rho_e(T - T_S)/[\rho_{dph}r + (c_e\rho_e - c_{ph}\rho_{ph})(T - T_S)]$, $Nu = \alpha D/\lambda_e$, $Ar = (\rho_e - \rho''_{ph})\ g\rho_{ph}D^3/\eta_e^2$, $Pr = \eta_e c_{dph}/\lambda_e$, $M = c_{ph}(T - T_S)/r$, v_m – is the average volume of droplets of the emulsion disperse phase,

$$t = 18\rho_{ph}D^2/(Nu Ar \eta_e) \tag{2}$$

is the duration of stay of disperse droplets in the thermal boundary layer. Eqs. (1) and (2) are solved by the method of successive approximations. From formulae (1) and (2) it follows that the heat-flow density, all other things being equal, essentially depends on the coefficient $J = J(p,T)$.

3. Results of an experimental investigation

Fig. 1 gives initial experimental data for the emulsion water/(oil PES-5).

The segments ΔT_1 and ΔT_2 on the abscissa axis correspond to temperature range at which one can observe the temperature difference that is necessary for starting of intense boiling, i.e. droplets of the emulsion disperse phase rarely boil up in the thermal boundary layer and do not make any considerable contribution to the density increase of a convective heat flux. The experimental data processing according to correlation (1) (Fig. 2) came to finding the adjustment coefficients A and J. The value of A depends on the shape of the heating surface and its orientation in space, the quantity J has the physical meaning of the activation rate of nucleation sites [6,7] in disperse-phase droplets. For the investigated emulsions and a vertical wire about 50 mm in length and from 0.050 to 0.200 mm in diameter it was found that $A = 0.038$. The values obtained for J are given in Fig. 3. It should be noted that in the temperature ranges ΔT_1 and ΔT_2 (Fig. 1) the obtained values of J coincide with reference data [6,7], and then with

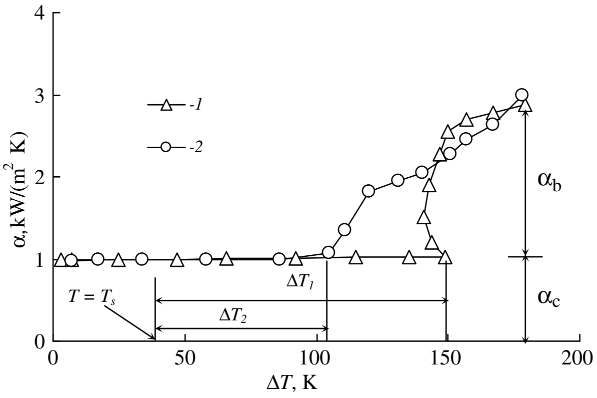

Fig. 1. Temperature difference ΔT_i that is necessary for starting of intense boiling of water/(oil PES-5) emulsion for a horizontal platinum wire of diameter 0.1 mm in addition to $C = 1.0$ vol.%, $T_0 = 60$ °C. 1: a small-grained ($d = 0.0015$ mm) emulsion, ΔT_1; 2: a large-grained ($d = 0.035$ mm) emulsion, ΔT_2.

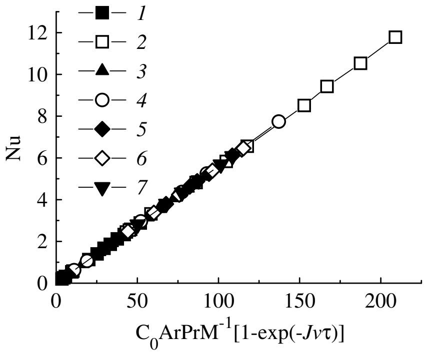

Fig. 2. Dependence $Nu = AC_0ArPrM^{-1}\ [1 - \exp(-Jvt)]$ for bubble boiling of emulsions: 1: *n*-pentane/glycerine; 2: freon-113/water; 3: water/(oil PMS-300); 4: water/(oil PES-4); 5: water/(oil PES-5); 6: water/(oil VM-1 C); 7: alcohol/(oil VM-1C).

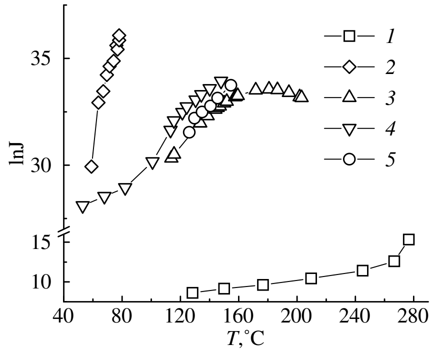

Fig. 3. Rate of formation of nucleation sites J in the disperse phase versus temperature T. 1: water in usual conditions [6]; liquids in a drop of phase of intense boiling of emulsions; 2: freon-113; 3: water; 4: *n*-pentane; 5: ethanol.

increasing temperature, abruptly, stepwise, increase by several orders (curves 2–5, Fig. 3).

The inconsiderable scatter of experimental data (Fig. 2) with respect to the generalizing curve shows the legitimacy of the chosen technique of treatment of the experimental data obtained. It also indicates that the observed jump in dependence $J = J(p,T)$ reflects the valid dependence $J = J(p,T)$, which we explain by the initiation of chain formation of nucleation sites [8] at a certain temperature of liquid superheat. One can observe a temperature delay ΔT_i and chain activation of the number of nucleation sites at a heat-transfer surface when operating with pure liquids [4], but only at the initial instant of time in passing from convective heat exchange to boiling.

Fig. 4 presents the comparative efficiency of heat-transfer to emulsions 4 and 5 and pure liquids 1, 2 and 3. The broken curves 1 and 2 show characteristic heat-transfer coefficients for pure water and freon-12, the line 3 has been built by our experimental data for the silicon organic liquid PES-5 during convective heat exchange. The curve segments a_1b_1, a_2b_2 and the curve 3 correspond to convective heat transfer, the segments b_1c_1 and b_2c_2 to bubble boiling, c_1d_1 and c_2d_2 to mixed (bubble and film) boiling. The mixed boiling regime with increasing surface temperature transforms into the regime of less efficient film boiling – segments d_1c_1 and d_2c_2 – at which the values of the heat-transfer coefficient are minimum. When the film regime develops, one can observe an abrupt increase in the temperature of the heating surface, which often results in its destruction because of its burn. It is seen from the figure that regimes of highly efficient bubble boiling for pure liquids have very narrow temperature ranges, which often makes it impossible to use them in heat-exchange equipment. The use of the emulsions under study allows increasing the temperature range of a stable bubble boiling regime several times, and this makes it possible to avoid an accidental transition to the film boiling regime and failure of heat exchange apparatus.

Noteworthy is the following advantage of the emulsions under consideration over conventional heat-transfer

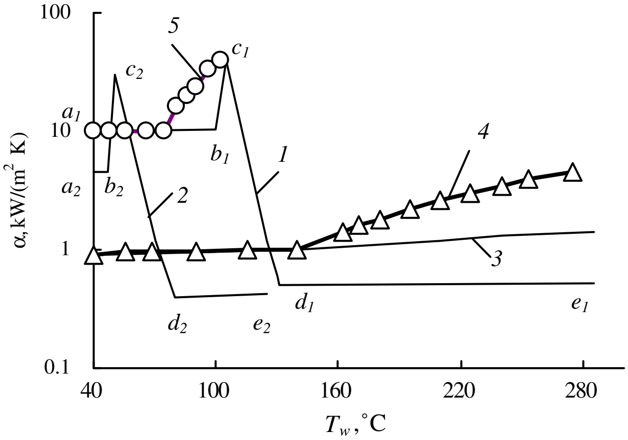

Fig. 4. Comparative efficiency of heat transfer to emulsions and pure liquids. Pure liquids: 1: water; 2: freon-113; 3: transformer oil. Emulsions: 4: water/(transformer oil); 5: freon-113/water.

agents: a high heat-transfer coefficient in regions where for conventional heat-transfer agents they are low.

4. Mechanism of activation of nucleation sites

When disperse-phase droplets boil up, their volume increases abruptly, which results in the initiation of a sound shock wave with an amplitude Δp. The greater is the thermal energy Q, which can turn into the energy of the sound shock wave, the larger is the amplitude Δp. For Q we have the relation $Q = c_{\mathrm{dph}}(T - T_{\mathrm{S}})\rho_{\mathrm{ph}}v_{\mathrm{m}}$. The initiated shock wave, if it has a sufficient amplitude, leads to activation of closely spaced potential (which may appear) nucleation sites. As a result, new disperse-phase droplets boil up on these sites, which initiate activation of the next portion of nucleation sites, and so on. The process of boiling-up of droplets becomes self-maintaining and is no longer random.

The following model and mechanism of activation of a potential nucleation site are suggested. Usually a heat-transfer agent before and during experiments is in contact with the atmospheric air; therefore it always contains dissolved air, namely, its components – nitrogen and oxygen. We shall assume, as is generally done [1], that nucleation sites are activated on solid particles that contaminate a liquid. In any, even quite thoroughly purified, liquid there are always particles with a characteristic dimension d of less than 10^{-7} m. It is very difficult to get rid of such particles as they neither sink nor float up, but move chaotically in a liquid under the action of Brownian forces. It is well known that the surface of practically any solid adsorbs a gas, the adsorbing capacity decreasing with increasing temperature. The particle surface is always covered with a layer of gas adsorbed from a heat-transfer agent. If particles get into the thermal boundary layer, where they and the surrounding liquid heat up, it leads to a decrease of both the gas solubility in a heat-transfer agent and the adsorbing capacities of particles. In this case gas bubbles begin to grow at the surface of particles, which, according to our calculation, grow up to critical-size bubbles in a time t_{a} of the order of 0.5 s. By the order of magnitude, this time coincides with the emulsion duration of stay t in the thermal boundary layer. At a time t_a shorter than t, one can observe a temperature difference that is necessary for starting of intense boiling (segment ΔT_1 and ΔT_2 in Fig. 1, 5). At a future increase of the surface temperature the chain mechanism of activation of nucleation sites comes into force.

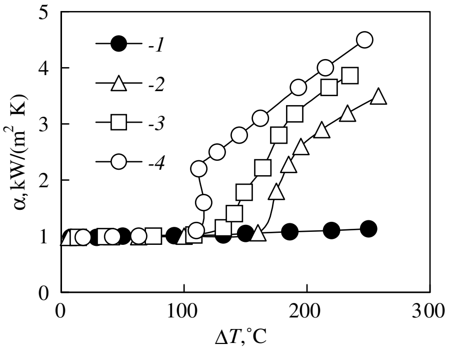

Fig. 5. Effect of surface-active substances on the heat-transfer intensity and the temperature difference that is necessary for starting of intense boiling, $C = 1.0$ vol.%, $T_0 = 36$ °C: 1: pure PES-5. Water/PES-5 emulsion: 2: with addition of 1.0 vol.% of trisodiumphospate; 3: with addition of 1.0 vol.% of caustic soda; 4: without addition of surface-active substances.

5. Model of nucleation sites activation by the chain mechanism

It is well known that under the action of surface (adhesive) forces particles in a liquid unite into flocculas. The unification of particles is aided by the gas adsorbed on them – oxygen and nitrogen; in this case the space between particles is filled with a gas, and its total amount exceeds the amount of the gas adsorbed on a separate particle. Under the action of pressure and/or rarefaction pulses of a sufficient amplitude (which arise, for instance, during the boiling-up of a disperse-phase droplet) on a floccula, this floccula decays into separate particles, and the liberated gas, at once or some time later, forms a new nucleation site. As a result a new disperse-phase droplet boils up, which leads to the next pressure pulse and boiling-up of the next series of disperse-phase droplets. One can observe the chain activation of nucleation sites.

6. Effect of small additions of surface-active substances (SAS)

Additional experiments were run for checking the adopted model: small additions of gas adsorbents (activated carbon, zeolites and natural adsorbers) or surface-active substances (SAS) were introduced into emulsions.

On the basis of the adopted model of a nucleation site it may be assumed that the introduction of a surface-active substance into a liquid will result in enveloping particles and gas bubbles in a continuous layer of SAS, which essentially complicates gas adsorption by solid particles and, therefore, the activation of nucleation sites.

Experiments were made with addition to emulsions of sodium oleate, trisodiumphosphate and caustic soda [2]. From the experimental results it follows (Fig. 4) that at a small concentration C of the disperse phase addition of SAS causes a considerable additional temperature difference that is necessary for starting of intense boiling. With increasing concentration C the effect of SAS on this temperature difference weakens. At high temperature drops (heads) and large c's an addition of SAS results in a considerable increase of the heat-transfer coefficient (not shown in the figure).

7. Effect of small addition of adsorbents on the boiling of emulsions

If a powder of activated carbon, whose particles are capable of adsorbing a gas, is introduced into an emulsion of the water/oil type, the temperature difference that is necessary for starting of intense boiling is bound to decrease and the heat-transfer coefficient to increase. This is confirmed by experimental results [9,10]. It is necessary to pay attention to the fact that while an addition of activated carbon to emulsions of the water/oil type results in decreasing temperature difference that is necessary for starting of intense boiling, the same addition to emulsions of the oil/oil type (for example, *n*-pentane/glycerine or diethyl ether/glycerine) gives the opposite effect. This is caused by the fact that activated carbon adsorbs organic substances quite well, which results in a decrease of the average size of disperse-phase droplets, and this, according to Fig. 1, leads to an increase of the temperature difference that is necessary for starting of intense boiling.

Similar results were obtained with the use of zeolites of the NaX type and natural adsorbers.

8. Conclusion

The paper presents experimental data on the boiling of emulsions whose disperse phase is low-boiling as compared with its dispersion medium. It shows the advantages of their use as heat-transfer agents as compared to the use of pure liquids and solutions, Fig. 4. Formulae (1) and (2) for calculating coefficients of heat transfer from wires to emulsions are given. Methods of controlling the boiling intensity are suggested. To increase the heat-transfer coefficient (and decrease the delay of the boiling beginning) one should introduce in an emulsion some gas adsorbent, for example, a powder of activated carbon. The opposite effect is achieved by the introduction of surface-active substances.

References

[1] Y.H. Mori, E. Inui, K. Komotori, Pool boiling heat transfer to emulsion, J. Heat Transfer 100 (4) (1978) 613–617.

[2] B.M. Gasanov, N.V. Bulanov, V.G. Baidakov, Peculiarities of boiling of emulsions with a low-boiling disperse phase and addition of SAS, Inzhenerno-fizicheskiy Zhurnal 70 (2) (1997) 185–187 (Rus).

[3] N.V. Bulanov, B.M. Gasanov, V.G. Baidakov, Regime of bubble boiling of an emulsion with a low- boiling disperse phase, in: Proceedings of the 3-d Minsk International Heat-Exchange Forum (Trudy 3 Minskogo mezhdunarodnogo foruma po teploobmenu), Minsk, 1996, vol. 4 (1), pp. 54–57 (Rus).

[4] V.P. Skripov, N.V. Bulanov, Convective heat transfer of metastable liquids at boiling delay, Inzhenerno-fizicheskiy Zhurnal 22 (4) (1972) 614–617 (Rus).

[5] N.V. Bulanov, An analysis of the heat flux density under condition of boiling internal phase of emulsion, High Temp. 39 (3) (2001) 462–469.

[6] V.P. Skripov, E.N. Sinitsyn, P.A. Pavlov, Thermophysical Properties of Liquids in the Metastable (Superheated) State, Gordon and Beach Science Publishers, New York, London, Paris, 1988.

[7] A.V. Reshetnikov, O.A. Isaev, N.A. Mazheiko, N.V. Bulanov, Beak-up of a jet of boiling-up water, Teplomassoobmen MMF-92. Teploobmen v dvukhfaznikh sistemakh, Minsk, 1992, vol. 4, Part 1, pp. 111–114 (Rus).

[8] N.V. Bulanov, B.M. Gasanov, Experimental setup for studying the chain activation of low-temperature nucleation sites in superheated liquid droplets, Colloid J. 67 (5) (2005) 531–536.

[9] N.V. Bulanov, B.M. Gasanov, T.V. Drugomilova, Activation of nucleation sites and their effect on heat-exchange intensity in boiling of emulsion with a low-boiling disperse phase, Metastabilnie sostoyaniya i fazovie perehodi, No. 6. Ekaterinburg, 2003, pp. 95–105.

[10] M.G. Buivid, M.V. Sussman, Superheated liquids containing suspended particles, Nature 275 (1978) 203–205.