EXPERIMENTAL STUDY OF BOILING ON HEATING SURFACES DURING THE THERMAL FLUIDIZATION OF A BED OF PARTICLES

Z. R. Gorbis and M. I. Berman

UDC 536.423:532.545

The results of an experimental investigation into the boiling of distilled water, aqueous solutions of NaCl, and sea-water brine on heating surfaces situated in a bed of mutually-disconnected particles at atmospheric and reduced pressures are presented.

In this paper we shall consider certain basic results of an investigation into the phenomenon which has come to be known as the thermal fluidization of solid particles. In contrast to the ordinary process of fluidization [1] in the present case, the means of fluidization is not independent of the processes taking place in the surrounding medium; fluidization is, in fact, generated by the boiling of a liquid in the form of vapor bubbles. Depending on the degree of thermal loading, either a two-component or a two-phase system is formed; the structure of this system governs the intensity of heat exchange with the heating surface. Since in the boiling of liquids $q = f(\alpha)$, a feedback effect is created; this does not occur in heat transfer induced by ordinary fluidization.

During the last ten years considerable interest has arisen in the use of dispersed systems for organizing transfer processes during phase transformations; in the majority of cases stationary dispersed system are employed [2-5]. Boiling on the surface of mobile metal particles fluidized by water were studied in [6]. The boiling of water containing particles $1.5 \cdot 10^{-5}$-$6 \cdot 10^{-5}$ m in size was studied in [7]. The boiling of water and sugar solutions containing corn flour particles was considered in [8]. The latter two papers bore a qualitative character, the particle concentrations being very low. A slight increase in heat transfer was explained in [7] as being due to the appearance of additional centers of vaporization by virtue of particles settling on the heating surface, and in [8] as being due to turbulization of the liquid in the main volume by the particles.

The results about to be presented were obtained experimentally in the course of boiling on a heating surface situated in a liquid-covered bed of mutually disconnected particles, held on the heating surface by gravitational forces. The vapor formed on the hot surface passes through the particle bed and sets the particles in motion. The presence of the particle bed sets strict conditions for the motion of the liquid and vapor on the hot surface. The experiments are concerned with the boiling of liquids at the saturation temperature T_{sat}, both on a plane heating surface and in an evaporator containing a five-row battery of tubular coils. The conditions of all the series of experiments are given in Table 1.

The arrangement of the working section with the plane heating surface, the boiling vessel, and the experimental method were set out in [9]. In contrast to [9] the granular bed was not pressed down at the top but had a free surface. The boiling vessel was placed in a stainless steel thermostating vessel provided with an illumination system. Using a vacuum pump and a needle-valve leak, the pressure in the vessel could be held constant within the range 0.035-1.0 bar. The results of our experiments relating to the boiling of distilled water on a horizontal heating surface under large-volume conditions (Fig. 1a) agree closely with the results presented in [10, 11].

In the presence of a bed of particles, vaporization starts for temperature heads (differentials) much smaller than under large-volume conditions. It was found that for boiling on a horizontal heating surface,

---

Odessa Technological Institute of the Refrigeration Industry. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 27, No. 3, pp. 389-396, September, 1974. Original article submitted January 31, 1974.

TABLE 1. Experimental Conditions

Particle material	d_T, m	ρ_T, kg/m³	β^*, m	Liquid, heating conditions	p, bar
Glass	$6{,}2\cdot10^{-4}$ $1{,}3\cdot10^{-3}$ $2{,}3\cdot10^{-3}$	2500	$0-1{,}12\cdot10^{-1}$	Distilled water, electric heating	0,035–1,0
Aluminosilicate	$3{,}0\cdot10^{-3}$	1700	$6\cdot10^{-2}$	Distilled water, electric heating;	0,035–1,0
			$4\cdot10^{-1}$	solutions of 2, 4, 6, 8, 11, 15, 20% NaCl; 11% sea brine, convective heating	0,117–0,460
Electrocorundum	$1\cdot10^{-4}$ $5\cdot10^{-5}$	4000	$0-7{,}15\cdot10^{-2}$	Distilled water, electric heating	1,0
Silica	$2\cdot10^{-6}$	2900	$0-1{,}1\cdot10^{-1}$	Distilled water, electric heating	1,0

according to the particular characteristics of the bed and the degree of thermal loading, a variety of structures might develop in the granular bed; these include dense beds allowing filtration of the vapor, nonuniformly and quasi-uniformly fluidized beds, and beds involving periodic and stable-channel formation. In the latter case a vapor—liquid zone occurs at the heating surface. Fluidized beds of large particles have a fairly sharp upper boundary. As particle size diminishes there is a transition to fluidization of the bed over the whole volume of the liquid in the boiling vessel. $\beta^* \equiv G_T/g\rho_T F_H$ values in the range $3\cdot10^{-3}$–$3\cdot10^{-2}$ m, as q increased (quite independently of d_T) there was a transition from the vapor-filtration mode to modes of fluidization, while for $\beta^* > 3\cdot10^{-2}$ m there was a transition from filtration to channeling. Boiling with a particle bed having $d_T < 10^{-4}$ m was accompanied by considerable foaming.

For a vertical disposition of the heating surface, vapor cavities and bed particles tended to rise in the region close to the wall, while there was a downward movement of the particles in the core of the layer. The boundary of the bed close to the wall pulsated under the influence of moving vapor cavities. With increasing q the frequency and amplitude of the pulsations also increased.

Figure 1 shows the characteristic heat-transfer curves for boiling with a flooded granular bed. The initial parts of the heat-transfer curves for $\beta^* < 3\cdot10^{-2}$ m correspond to a transition from filtration to the fluidized state. In the fluidized states, for particle sizes greater than $1\cdot10^{-3}$ m the boiling curves $q = f(\Delta T)$ exhibit vertical sections (Fig. 1a). Boiling curves for $d_T < 1\cdot10^{-3}$ m have no such sections (Fig. 1b). With falling pressure there is a reduction in the intensity of heat transfer on the initial sections of the boiling curves.

An increase in β^* leads to an intensification of the heat-transfer process. The curves corresponding to $\beta^* > 3\cdot10^{-2}$ m are the limiting members of the set describing heat transfer with fluidization, and for $\beta^* > 3\cdot10^{-2}$ m the heat transfer is automodel relative to the quantity β^*. The dependence of heat transfer in the initial sections of the boiling curve on β^* is illustrated in Fig. 2. With diminishing d_T the influence of particle size on the heat transfer weakens, the increase in heat transfer starts at larger values of β^* while for $d_T < 6\cdot10^{-4}$ m the heat transfer is automodel with respect to the size of the particles.

With increasing q the boiling curves develop sections in which α depends very little or not at all on q. The appearance of these sections precedes the onset of surface overheating by the electrical heater. Before overheating sets in, considerable nonuniformities appear in the temperature distribution over the heating surface, amounting to hundreds of degrees. This indicates the appearance of dry spots on the heating surface. The regions of heat transfer with a weak dependence of α on q are characteristic of boiling under restricted conditions [12-14]. The existence of such modes of heat transfer may be explained by the merging of vapor cavities on the heating surface. The evaporation of the liquid film under the merging vapor cavities becomes dominant in this process.

Figure 2b shows the β^* dependence of the critical-thermal fluxes determined from the overheating of the surface. An increase in β^* leads to a reduction in q_{cr} for cases of fluidization. In cases of channeling q_{cr} is independent of β^*. As in the case of heat transfer, the influence of d_T on q_{cr} weakens as the particle size diminishes for cases of fluidization.

The heat-transfer curves obtained for a vertical disposition of the heating surface (Fig. 1c) coincide qualitatively with the heat-transfer curves obtained for the case of a horizontal disposition in the channeling mode.

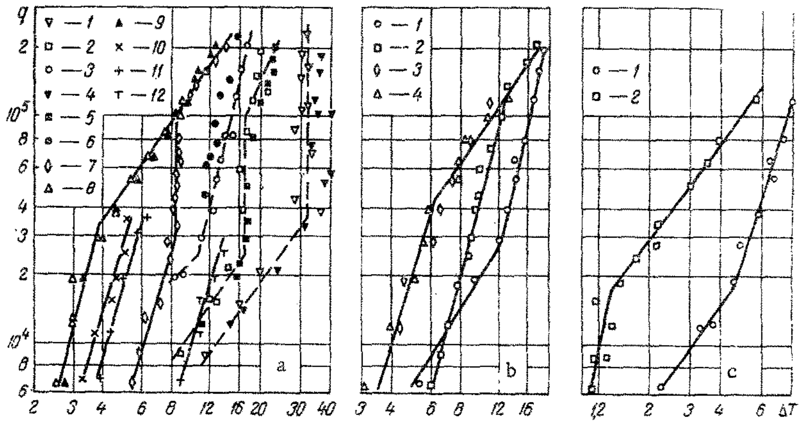

Fig. 1. Thermal flux as a function of the temperature head during the boiling of distilled water on a plane heating surface under free conditions and under conditions of thermal fluidization (q, W/m^2; ΔT, °K): a) Horizontal position, free volume 1, 2, 3) p = 0.035; 0.2; 1.0 bar; 4, 5, 6) p = 0.036; 0.2; 1.0 bar [11]; glass spheres $d_T = 2.3 \cdot 10^{-3}$ m; 7, 8, 9) p = 1 bar, $\beta^* = 5.6 \cdot 10^{-3}$; $3 \cdot 10^{-2}$; $1.1 \cdot 10^{-1}$ m; 10, 11, 12) $\beta^* = 1.1 \cdot 10^{-1}$ m, p = 0.5; 0.2; 0.035 bar; b) Horizontal position, electrocorundum d_T $1 \cdot 10^{-4}$ m, p = 1 bar; 1, 2, 3, 4) $\beta^* = 1.8 \cdot 10^{-3}$; $8.9 \cdot 10^{-3}$; $2.7 \cdot 10^{-2}$; $7.2 \cdot 10^{-2}$; $7.2 \cdot 10^{-2}$ m; c) vertical position: 1) free volume; 2) glass spheres $d_T = 2.3 \cdot 10^{-3}$ m.

These characteristics of the influence of β^* and d_T may be explained on the following basis. The heat transfer and the critical-thermal fluxes in the granular bed depend, as in other cases of boiling under restricted conditions, on the degree of restriction of the motion of the liquid and vapor in the zone close to the wall. As a measure of the restriction influencing the thermal characteristics we may, to a first approximation, use the porosity of the bed. If as a qualitative analogy we make use of the relationship representing the condition of uniform fluidization for a single-phase liquid [15]

$$m = \left(\frac{18\mathrm{Re} + 0.36\mathrm{Re}^2}{\mathrm{Ar}}\right)^{0.21}, \tag{1}$$

then for different d_T and ρ', ρ'', ν', q, $v_f \sim q/r\rho''$ idem we have, by analogy with [1]:

$$\frac{m_2}{m_1} = \left(\frac{18\nu'/d_{T_2}^2 + 0.36 v_f/d_{T_2}}{18\nu'/d_{T_1}^2 + 0.36 v_f/d_{T_1}}\right)^{0.21}. \tag{2}$$

According to Eq. (2), with increasing d_T the restriction increases over a certain range of values (other conditions being equal); as in other cases of boiling under restricted conditions this leads to an intensification of heat transfer in the initial parts of the boiling curves and to a reduction in the critical-thermal fluxes. Particles of small dimensions, for which the hovering velocity is smaller than v_f, are fluidized over the whole volume of liquid, and only the existence of a free liquid surface prevents their escape. Here the dispersed medium may be regarded as a quasi-homogeneous liquid; the influence of the particles appears through the effective properties of the liquid. In the case of coarse particles, for which d_T greatly exceeds the separation diameter of a bubble under free conditions, the bubbles will pass unimpededly through the porous space of the bed, not producing any fluidization. In both cases the influence of d_T on the thermal characteristics degenerates.

The analogy with the state of uniform fluidization cannot be regarded as quite complete. Equations (1) and (2) were derived on the assumption of identical conditions of interaction between all the solid particle of the bed and the fluidizing medium. Under the conditions in question the fluidizing effect arises as a result of the growth of vapor cavities on the heating surface and their subsequent motion through the bed. The motion of the curvilinear vapor—liquid interface of the vapor cavity causes filtration of the liquid at a velocity which falls on moving away from this interface. The nonuniformity of the liquid velocity distribution in the granular layer, together with the contribution from the piston-type action of the vapor cavities,

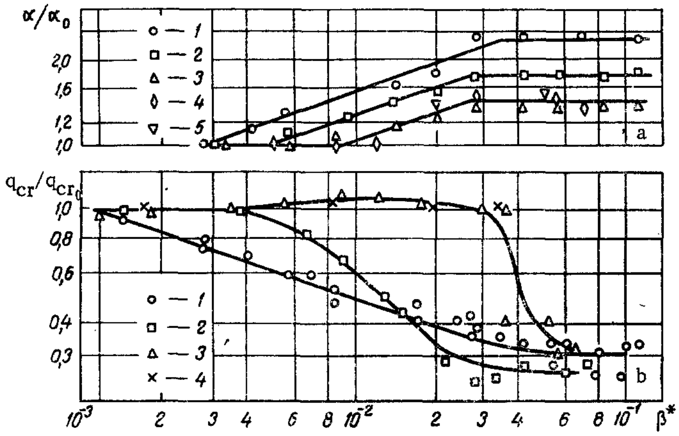

Fig. 2

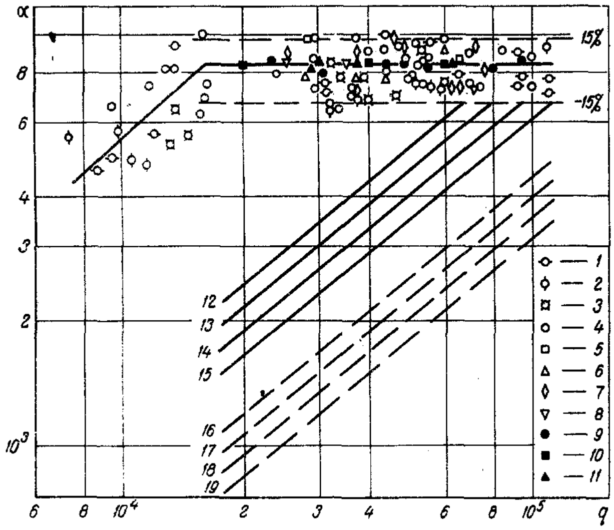

Fig. 3

Fig. 2. Influence of the characteristics of the granular bed on the heat-transfer and critical-thermal fluxes during the boiling of water on a horizontal-plane surface under conditions of thermal fluidization. $p = 1$ bar (β^*, m); a) $q = 3 \cdot 10^4$ W/m^2; 1, 2, 3) glass spheres $d_T = 2.3; 1.3; 0.62 \cdot 10^{-3}$ m; 4, 5) electrocorundum $d_T = 1 \cdot 10^{-4}$; $5 \cdot 10^{-5}$ m; b) 1, 2) glass spheres $d_T = 2.3; 1.3 \cdot 10^{-3}$ m; 3) electrocorundum $d_T = 5 \cdot 10^{-5}$ m; 4) silica $d_T = 2 \cdot 10^{-6}$ m.

Fig. 3. Heat-transfer coefficient as a function of the specific thermal flux obtained in a vacuum evaporator (α, W/m^2·deg; q, W/m^2). Evaporator with a granular bed, data from all rows of coils: 1, 2, 3) distilled water, $p = 0.117$; 0.298; 0.460 bar; 4, 5, 6, 7, 8, 9, 10, 11) $p = 0.182$ bar, concentration of NaCl solution 0; 2; 4; 6; 8; 11; 15; 20%. Evaporator under ordinary conditions, data from the lower row of coils: 12, 13, 14, 15) $p = 0.460$; 0.298; 0.182; 0.117 bar, distilled water, 16)–19) represent a recalculation of 12)–15) for an NaCl concentration of 20% on the basis of [17].

is evidently responsible for the experimentally-observed dependence of m, and hence α and q_{cr}, on β^* which does not follow from Eqs. (1) and (2).

Under operating conditions involving channel formation, all the vapor formed on the heating surface is removed through vapor channels without causing vigorous motion of the liquid in the vapor-free regions of the granular bed. For these conditions no influence of β^* on the heat transfer and critical-thermal fluxes appears (Fig. 2).

The effectiveness of these processes of thermal fluidization increases under conditions leading to the contamination of the heating surfaces (incrustation, oil films, in the shell-and-tube evaporators of refrigerators, etc.). In order to study the influence of the thermal fluidization of the granular bed on the operation of a boiling evaporator, we carried out some experiments in a vacuum evaporator with a five-row battery of tubular copper coils. The arrangement of the apparatus and the measuring method were the same as in [16]. The experimental conditions are indicated in Table 1. The results of the experiments carried out in distilled water under ordinary evaporator operating conditions agree closely with the results of [16, 17]. For studying the operation of an evaporator with a granular bed, the liquid space of the evaporator was filled with a bed of aluminosilicate particles having a mean diameter of $3.0 \cdot 10^{-3}$ m. The total height of the bed was $7 \cdot 10^{-1}$ m. When boiling occurred there was a rise of the particles in the center of the evaporator and a downward motion close to the walls. The temperature head for the onset of boiling was under 5°K for all cases involving a granular bed.

Figure 3 illustrates the influence of the granular bed on heat transfer for boiling in the coils of the evaporator. Starting from values of $q \simeq 1.5 \cdot 10^4$ W/m^2 there was a state in which α remained independent of q. We see from Fig. 3 that for this case of heat transfer α was also independent of the pressure, the NaCl concentration, and the number of rows of coils, in contrast to the ordinary conditions of evaporator operation, in which there was a considerable fall in the intensity of heat transfer with increasing rarefaction and concentration (curves 12-19 in Fig. 3). This fact may be considered as yet another confirmation of the decisive influence of the evaporation of the liquid film (under conditions of merging

TABLE 2. Influence of the Granular Bed on the Efficiency of a Sea-Water Evaporator under Conditions of Incrustation

τ, h	ω_0, liters/h under ordinary condition	ω, liters/h in a granular bed	$\frac{w-w_0}{w_0}$, %	τ, h	ω_0, liters/h under ordinary condition	ω, liters/h in a granular bed	$\frac{w-w_0}{w_0}$, %
0	16,7	17,1	2,4	70	13,8	22,1	60
10	17,2	18,3	6,5	80	13,3	22,1	66
20	16,1	19,4	21	90	13,2	21,4	62
30	15,4	19,9	29	100	12,9	21,6	67
40	15,0	20,0	33	110	12,7	22,0	73
50	14,8	20,9	41	120	12,9	22,1	71
60	14,3	21,8	52				

vapor cavities) on the heat-transfer process. The fact that the number of rows in the battery had no effect supports earlier data as to the automodel nature of heat transfer relative to β^* for $\beta^* > 3\cdot10^{-2}$ m. In agreement with the general run of the heat-transfer curves, an increase in the (productivity) of the evaporator was in fact observed.

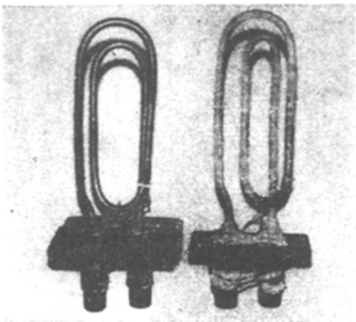

Fig. 4. Evaporator coils after five days of operation in sea-water brine with a concentration of 11%. Left, coil after operating the evaporator with a granular bed; right, coil covered with incrustation after working under ordinary conditions.

The influence of incrustation on the productivity of the evaporator with a granular bed was studied over five days continuous operation in sea-water brine at a concentration of 11% and T_{sat} = 333°K. Measurements were made every hour. Table 2 compares the resultant data with the results of experiments carried out by some of our colleagues in the faculty under the same initial conditions, but using the ordinary evaporator operation procedure. According to Table 2, at the end of the five days the relative increase in the productivity of the evaporator with the granular bed was 70%. An inspection of coils taken out after the experiments (Fig. 4) confirmed the view that the particles of the granular bed under conditions of thermal fluidization impeded the deposition of incrustation on the heating surfaces. Only in places in which stagnant zones existed as a result of constructional aspects of the coils were there appreciable regions of (easily-removed) scale. In general the coils had a clean, lustrous surface.

The foregoing data indicate that the process of thermal fluidization promotes an intensification of heat transfer in boiling on heated surfaces and also efficiently combats contamination of the heating surfaces.

NOTATION

ΔT, temperature head; T_{sat}, saturation temperature; p, pressure in the system; ρ', ρ'', ρ_T, density of the liquid, vapor, and particle material; d_T, particle diameter; G_T, weight of particles in the granular bed; g, gravitational acceleration; F_H, area of heating surface; $\beta^* \equiv G_T/g\rho_T F_H$, characteristic dimensions of the bed with respect to height; q, specific thermal flux (heat flow); q_{cr}, critical thermal flux; α heat transfer coefficient; ν', ν'', kinematic viscosity of the liquid and vapor respectively; r, latent heat of vaporization; m, porosity of the bed; v_f, liquid filtration velocity; $Re = v_f d_T/\nu'$, Reynolds number; $Ar = g d_T^3/\nu'^2 (\rho_T - \rho')/\rho'$, Archimedes number; w, productivity (delivery) of the evaporator.

LITERATURE CITED

1. S. S. Zabrodskii, High-Temperature Devices with Fluidized Beds [in Russian], Énergiya, Moscow (1971).
2. A. V. Lykov, Heat and Mass Transfer (Handbook) [in Russian], Énergiya, Moscow (1972).
3. Heat Tubes (Collection) [Russian translation], Mir, Moscow (1972).
4. V. A. Maiorov and L. L. Vasil'ev, Inzh.-Fiz. Zh., 25, No. 2 (1973).
5. T. A. Kolach, R. Kh. Shapirov, and V. V. Yagov, Inzh.-Fiz. Zh., 14, No. 6 (1968).
6. F. M. Young and J. R. Holman, Industr. and Engng. Chem. Fundamentals, 7, No. 4 (1968).
7. N. Kh. Afran and P. M. Anastasievich, in: Heat and Mass Transfer, Vol. 2 [in Russian], Minsk (1968).
8. G. M. Pludovskaya, Trudy Tsent. Kot. Turb. Inst., No. 101 (1970).
9. M. I. Berman and Z. R. Gorbis, Teploénergetika, No. 11 (1973).

10. D. A. Labuntsov, Teploénergetika, No.9 (1972).
11. V. V. Yagov, Author's Abstract, Candidate's Dissertation, Moscow Power Institute, Moscow (1971).
12. D. A. Labuntsov, Izv. Vyss. Ucheb. Zaved., Mashinostroenie, No.7 (1970).
13. G. I. Bobrova and L. A. Stasevich, Inzh.-Fiz. Zh., 25, No.2 (1973).
14. E. Ishibashi and K. Nishikawa, Internat. J. Heat Mass Trans., 12, 886-894 (1969).
15. V. D. Goroshko, R. B. Rozenbaum, and O. M. Todes, Izv. Vyss. Ucheb. Zaved., Neft' i Gas, No.1 (1958).
16. V. N. Skripnik, Author's Abstract, Candidate's Dissertation, OVIMU, Odessa (1972).
17. V. F. Kovalenko, Thermal Desalination of Seawater [in Russian], Transport, Moscow (1966).