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Boiling in an unconstricted granular medium

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Abstract—Boiling in an unconstricted bed with 65% porosity formed by spherical nickel particles with 28.3 μm mean diameter was studied in two sets of experiments. In the first set, the granular bed had the shape of a cylindrical annulus and heat was added through the outer cylinder surface with a heat flux up to 1 kW m^{-2}. Visual observation established in ascending order the evidence of a dry-out region at the bottom of the column, a capillary region in which liquid, as well as vapor, occurred in the voids of the bed, and a chimney region with essentially horizontal cracks and vertical channels and with this uppermost region in a heaving motion. Whether all of these regions existed depended on the total height of the bed. In the second set of experiments, performed in a pressure vessel containing an array of nine heated tubes with the granular medium outside the tubes, the establishment of a dry region below the wetted region (comprising the capillary and chimney regions) was determined by the measurement of the vertical temperature profile along the tube wall at a heat flux up to 50 kW m^{-2}. The wetted region in the bed is independent of the pressure level and of the total height of the bed. The dry region forms when the total bed height is larger than the wetted region. The height of the capillary region changes inversely proportional to the square root of the heat flux whereas the chimney region is essentially independent of it.

INTRODUCTION

COMBINED heat and mass transfer processes in porous media can be ordered into several groups. In the first one, the voids in the porous matrix are completely filled with a single-phase fluid, liquid or gas, and movement as well as energy convection are generated by buoyancy forces or by external pressure differences. A considerable amount of information is available, obtained analytically or experimentally, which describes the flow path and its stability as well as the heat transfer characteristics.

In the second group, the voids are only partially filled with a liquid (usually water) and the rest is occupied by a gas (usually air) and by a vapor of the liquid. Movement of the components in the voids is influenced and sometimes dominated by capillary forces. Such processes are the backbone of the drying industry. Our understanding and ability to analyze them is largely due to the pioneering work of Alexei Vasilievich Luikov in the Soviet Union [1] and of Otto Krischer in Germany [2], started by both researchers in the 1930s independently of one another.

More recently, a third group of heat and mass transfer processes has gained interest in which the voids are partially filled by liquid and partially by its vapor which is generated by evaporation. Such processes occur in various recent technologies, for instance, in geothermal energy utilization and in thermal recovery of oil. A model studied with the intention to simulate the basic processes is a horizontal layer of granular material constricted between two horizontal planes and filled with water [3]. Heat is added through the lower plane and removed through the upper plane which is porous to provide for expansion of the liquid.

In other applications, the granular bed may be unconstricted as in post-accident heat removal in liquid cooled nuclear reactors [4] or in the ground adjacent to geothermal or volcanic activity. The present paper deals with boiling in an unconstricted granular medium. It was instigated by difficulties arising in the steam generators of nuclear power plants where corrosion was found to occur on the tubes in regions where sludge was deposited. The results of such a study with various types of sludge are described in ref. [5].

The present investigation also deals with boiling in an unconstricted granular medium. The geometry for the experimental models was selected to simulate a steam generator. There are, however, also similarities to other situations as well, for instance, to an unconstricted horizontal layer with boiling caused by internal heat sources. The experimental study consisted of two parts. In one, the behavior of an unconstricted granular bed was examined visually under steady boiling conditions. In the second set, the extent of the dry-out region which was observed in the first study was measured at higher heat fluxes and at various pressures under conditions which simulated more closely those existing in the steam generator of a nuclear reactor.

THE GRANULAR BED

A granular bed was formed of nickel particles with a mean equivalent diameter of 28.3 μm. The particles with approximately spherical shape had the tendency to form clusters as could be observed in microphotographs. Reproduction of such a photo at 450 × magnification is presented as Fig. 1. Because of the clustering, the bed had a high porosity of 65%, even

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NOMENCLATURE

b	gap width (thickness of annulus)
d_p	particle diameter
f	porosity
g	gravitational acceleration
h	height
h_b	heat transfer coefficient to the boiling fluid
h_{lv}	heat of evaporation
K_w	liquid permeability
l_c	height of capillary region
l_d	height of dryout region
l_{ch}	height of chimney region
l_t	total bed height
l_w	height of wetted region ($l_w = l_c + l_{ch} = l_t - l_d$)
p, P	pressure
q	heat flux per unit area
$\dot{q}$	heat addition per unit volume of granular bed
R	ratio of capillary to gravity forces
R_i	thermal resistance causing the temperature difference, $t_b - t_w$
r_m	mean radius of curvature of interface between liquid and vapor
r	mean radius of particles
t_b	bulk temperature
t_h	temperature of the heating fluid (Therminol)
t_s	saturation temperature
t_w	wall temperature
U	overall heat transfer coefficient.

Greek symbols

ρ_b	bulk density
ρ_l	density of liquid
ρ_v	density of vapor
ρ_s	density of solid
σ	surface tension.

when it was well settled. A size distribution curve of the nickel particles is shown in Fig. 2. A curve for copper particles is included. Reference to it will be made later on. The density of the solid nickel is 8906 kg m^{-3}, its specific heat is 44 W kg^{-1} K^{-1}, and its heat conductivity is 69 W m^{-1} K^{-1}.

FLOW VISUALIZATION EXPERIMENTS

The particles were placed in the annular space between two concentric glass tubes welded together at the bottom (Fig. 3). Two of these vessels were made so that granular beds with the shape of an annulus having thicknesses of 0.42 cm or 1.02 cm and an outer diameter of 3.01 cm could be studied. The particles filled the annular space to heights of 5.1, 10.2, or 15.2 cm. Water was added carefully to fill the voids of the bed and to create a water column with a height well above the upper surface of the bed.

The glass vessel with the granular bed was placed into a container with glass walls (Fig. 3) which was connected to a thermostat containing Therminol 55

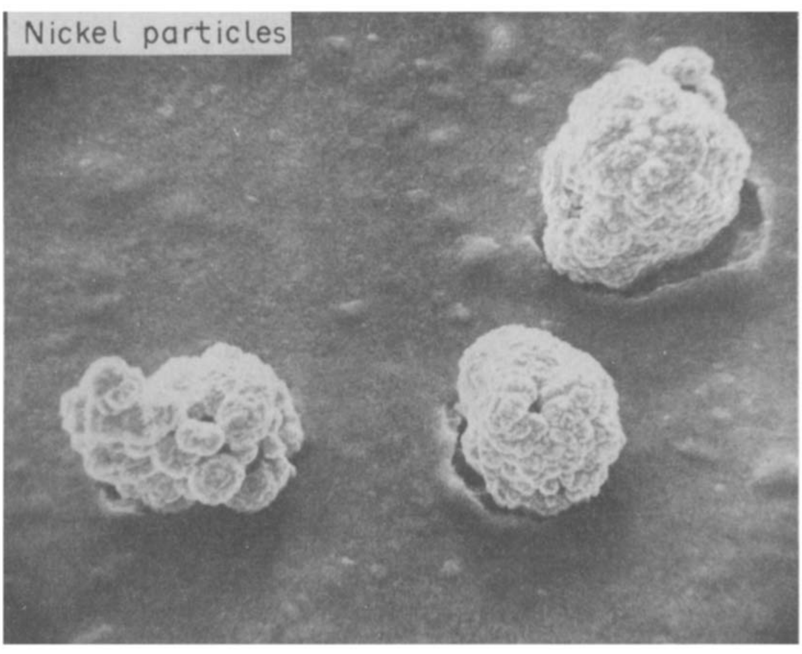

FIG. 1. Microphotograph showing three clusters of nickel particles with 450 × magnification.

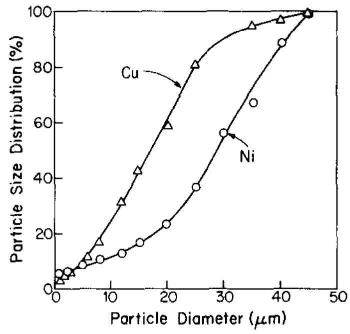

FIG. 2. Size distribution (fracture of particles smaller than a certain diameter) of nickel and copper particles.

(Monsanto Corporation) a liquid with a boiling point above 200°C at atmospheric pressure. This heating fluid could be brought to any selected temperature by an electric heater with temperature control. In this way a heat flux could be generated from the Therminol to the water in the granular bed and boiling could be initiated. The heat flux q per unit area of the circular outer surface of the granular bed in the boiling region was obtained from the equation

$$q = U(t_h - t_s) \quad (1)$$

in which t_h is the temperature of the Therminol measured by the thermocouple which is indicated in Fig. 3 and t_s is the saturation temperature of the water at atmospheric pressure above the liquid column. The heat transfer coefficient U was calculated with the convective heat transfer coefficient on the outer surface of the glass tube, the boiling heat transfer coefficient on the inner surface, and the heat conductivity of the glass wall. Values for these parameters were taken from the literature. A value

$$U = 26.7 \text{ W m}^{-2} \text{ K}^{-1} \quad (2)$$

was obtained in this way. The temperature in the granular bed was measured along a vertical line by a series of thermocouples attached to a thin Teflon rod (Fig. 3). A more detailed description of the apparatus, instrumentation and experimental procedure is contained in [6]. The details of the boiling process were observed visually and recorded in photos and video

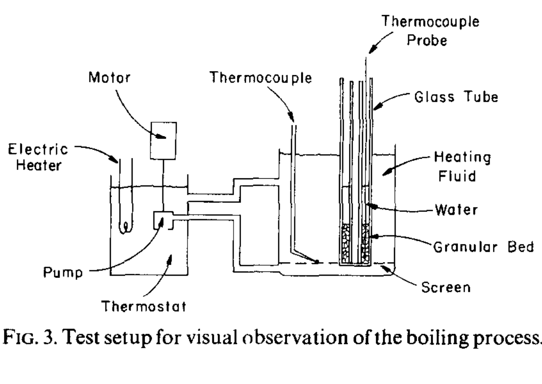

FIG. 3. Test setup for visual observation of the boiling process.

tapes which documented the dynamics of the boiling process.

An example of such a photo is shown in Fig. 4. The photo was taken at a gap width (thickness of the granular annulus) of 1.02 cm and a temperature of the heating fluid of 143°C. One observes a number of essentially horizontal cracks in the upper part of the bed (above plane A in Fig. 4). These cracks increase in time and collapse again in an irregular slow sequence with periods of the order of minutes. This action causes the bed above the cracks to move up and down in an irregular heaving motion. The column below the cracks, on the other hand, remains stationary. The vapor is observed to escape from the surface of the bed in a sequence of bubbles which originate at a few discrete places indicating that more or less vertical channels also are formed in the upper part. This was verified by looking from above at the bed surface after the boiling was terminated and the water above the bed was removed. A small number of particles is carried into the water above the upper surface of the bed and oscillates in the liquid as in a fluidized bed. Such channels have also been observed at the Argonne National Laboratory [7] in particulate beds of heat generating uranium oxide UO_2.

A singular inclined crack which can be observed at some distance below A in Fig. 4 is interpreted as a rare

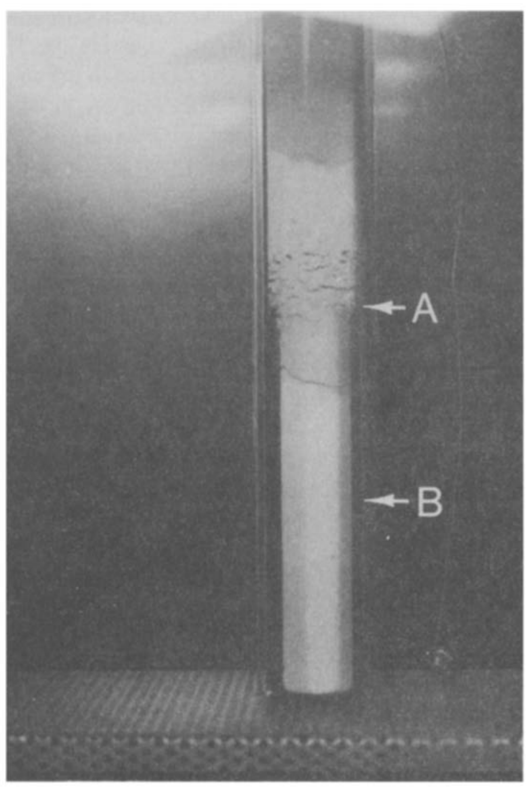

FIG. 4. Photograph of the annular bed of nickel particles during boiling, for a bed height of 15.2 cm and an annular width of 1.02 cm.

occurrence which does not bear on the general behavior of the granular bed.

Figure 5 presents the results of the temperature measurements by the thermocouple probe in the porous bed (see Fig. 3). The temperature is quite high above the bottom over a height of 5 cm at the Therminol bath temperature of 143°C, indicating a dry-out region in which the voids between the grains are filled with superheated vapor.

There exist, according to this observation, in the bed three regions with different characteristic features. Starting at the bottom, there is a *dry-out region* extending to the height indicated by an arrow denoted by B in Fig. 4, which is 5 cm above the bottom of the column. Its extent is deduced from Fig. 5. During the physical observation, and in some of the photos, this region is also distinct from the rest of the column by a brighter color. The column above location B is filled partially with liquid and partially with vapor. The granular bed between the locations B and A is stationary; we will call it *capillary or packed region*. The bed above location A is in the heaving motion described above and contains cracks and channels. We will call it *chimney region*.

The distinction between these regions is facilitated by a peculiar optical effect. One can observe in Fig. 4 two strips on both sides of the column which are dark near the bottom, become gradually brighter when they approach the plane A, and disappear above this plane. It is concluded that they are caused by the reflection characteristics at the interface between the granular bed and the inner surface of the glass wall. The reflection makes the strip appear dark when the voids close to the interface contain vapor and bright when they contain liquid. The gradual decrease in the darkness in the direction from B towards A indicates that the liquid content increases in an upward direction in the capillary region. This feature was observed consistently in all of the photos.

Schematically, these regions are illustrated in Fig. 6, which presents a cross-section through one side of the annulus with thickness b. The granular bed with a total height l_t consists of the dryout region with height l_d, the capillary region with height l_c, and the chimney region with height l_{ch} which also includes the region with horizontal cracks. The sum of the capillary and chimney regions is the *wetted region* with height $l_w = l_c + l_{ch}$. Above the upper surface of the bed is a layer of water of height l_f traversed by steam bubbles and with solid particles in fluidized motion. Only a small fraction of the granular material of the bed was in fluidized motion as evidenced by the fact that the bed height l_t receded by a very small amount only at the beginning of the boiling process.

The following mechanism of the boiling process is deduced from these observations: the voids in the *dry-out region* are filled with superheated vapor. There is no or little movement in this region. The heat flux into the granular bed is very small near the bottom and increases with height as the temperature difference between the heating fluid and the vapor increases. Heat is transferred essentially by conduction in this region.

In the wetted region, liquid and vapor co-exit in the voids. The temperature difference between the heating fluid and the boiling liquid as well as the overall heat transfer coefficient are practically constant along the

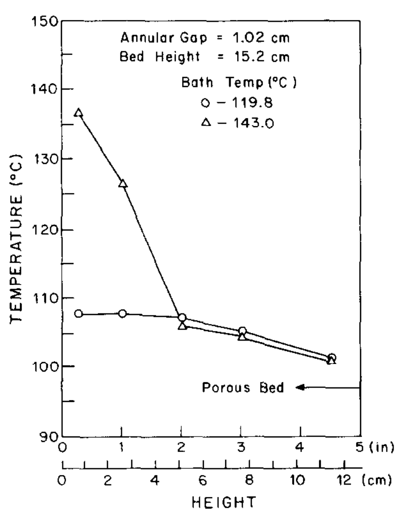

FIG. 5. Vertical temperature profiles along the height of the granular bed.

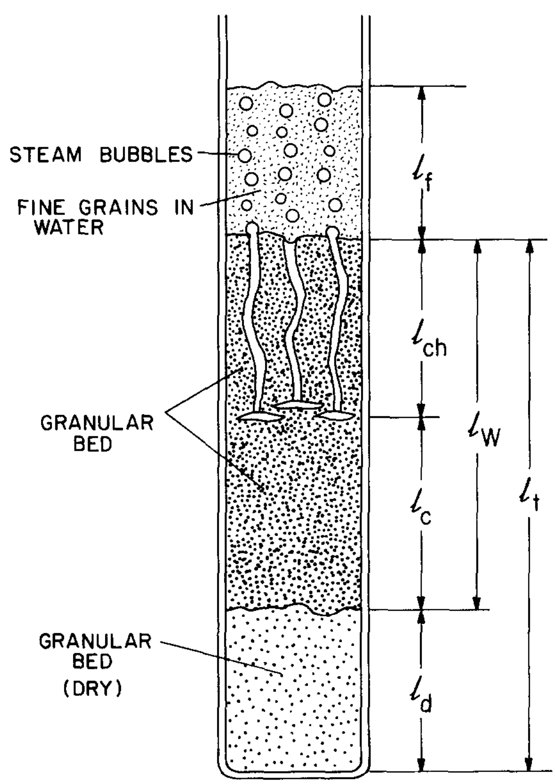

FIG. 6. Sketch of boiling granular bed with different regions.

height of this region causing near constant heat flux. Accordingly, the upward flow of the vapor increases nearly linearly with height in this region. This upward flow of vapor has to be compensated by a flow of liquid in a downward direction. In steady state, both of these fluxes must be equal in any horizontal plane. In the capillary region the vapor flows steadily through the voids between the grains. It is believed that the vapor moves through this part of the bed in continuous channels and does not form discrete bubbles. The flow of the vapor is caused by buoyancy and by a pressure drop in the upward direction. The liquid flow is generated by gravitational and capillary forces. An estimate of the relative magnitude of the two forces will indicate that, in the range of the experiments, capillary forces are dominating. The order of magnitude of the buoyancy pressure is

$$(\rho_l - \rho_v)gh \qquad (3)$$

where ρ_l indicates the density of the liquid, ρ_v the density of the vapor, g the gravitational acceleration. h the height of the capillary region and r_m the mean radius of curvature of the liquid–vapor interface. The capillary force per unit area is

$$\frac{\sigma}{r_m} \qquad (4)$$

with σ denoting the surface tension. The ratio of the capillary to the gravitational force, therefore, is

$$R = \frac{\sigma}{r_m(\rho_l - \rho_v)gh}. \qquad (5)$$

With the values $\sigma = 59.3 \times 10^{-3}$ kg s^{-2}, $r_m \approx r/4 \approx 7$ μm, $\rho_l - \rho_v = 1000$ kg m^{-3}, $g = 9.81$ m s^{-2}, $h = 5$ cm corresponding to the conditions of the experiments, the ratio of the two forces is 17, indicating that the capillary force is considerably larger than the gravity force. Movement by capillary forces requires that the liquid content in the voids decreases in downward direction. This restricts the cross-section available for vapor movement near the upper surface of the capillary region and causes near this surface a pressure gradient of such magnitude that it is able to lift the bed above and to cause the cracks. Dhir and Catton [4] described dryout experiments at 1 b pressure for inductively heated, unconstricted beds of steel and lead particles in a size distribution of 295 to 787 μm. The bed height varied from 1.9 to 8.9 cm and the bed porosity from 0.38 to 0.45. They compared the results with those of an analysis in which the counterflow of liquid and vapor in the bed is postulated to be caused by gravitational forces. Equation (5) results for these parameters in a ratio of capillary to gravity forces equal to 0.5–2. This indicates that capillary forces probably have contributed to the circulation of water. In general one has to expect that gravity dominates for larger particles and bed heights whereas capillarity dominates for small particles and bed heights. In a constricted bed, no movement of the particles is possible and the height of the capillary region is also the height of the wetted region in which counterflow between vapor and liquid can exist in steady state.

In an unconstricted bed, however, the wetted region can expand and create the *chimney region.* The vapor creates passages for itself by forming chimneys and the horizontal cracks duct the vapor, which leaves the capillary region uniformly distributed, into the chimneys. The height of the chimney region is again determined by the capillary suction potential which the menisci in the granular material can develop. The height of the wetted region in which counterflow of the vapor and liquid can exist is now the sum of the heights of the capillary and the chimney regions.

No dry region was observed in the bed with a total height of 10.2 cm and no chimney region in the 5 cm high bed. It is concluded that the heights of the chimney region and of the capillary region may be a function of the geometry, the heat flux and the pressure in the bed but that they do not depend on the *total bed height.* A dry region is formed when the total bed height is larger than the sum of the heights of the capillary and the chimney regions. The formation of the chimney region permits counter current flow to heights which cannot be achieved in a fixed bed.

A special series of experiments was performed for a bed with 15.2 cm height. Care was taken to insure that steady state was obtained. The temperature of the heating fluid was raised in steps and was at each step held constant for 45 min before the bed was photographed. The heights of the various layers were measured in the photographs and are plotted in Fig. 7 over the heat flux q, per unit area of the cylindrical interface between the outer glass tube and the bed in the flooded region, calculated with equation 1. There is

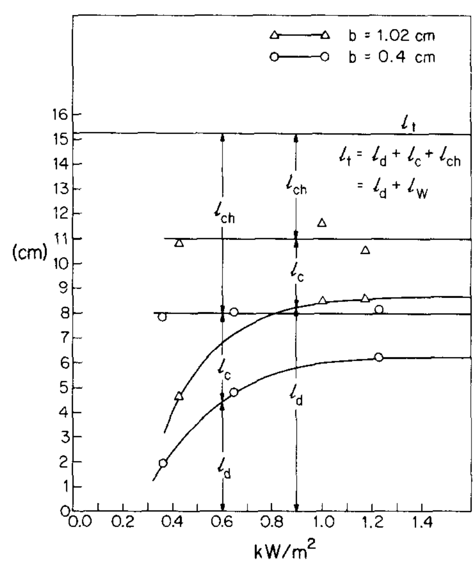

FIG. 7. Height of dry-out region l_d, capillary region l_c, and chimney region l_{ch}, for 15.2 cm total bed height l_t, as function of the heat flux q through the outer cylinder surface of the bed.

some scatter in the data representing the height of the chimney region for $b = 1.02$ cm. A horizontal line was used to interpolate those. It can be observed that the height l_c of the capillary region decreases with increasing heat flux, whereas the height l_{ch} of the chimney region is essentially independent of the heat flux. In using this figure one has to keep in mind that experiments discussed before indicate the heights of the capillary region and the chimney region to be independent of the total height of the bed whereas the heights of the dryout region in the figure are restricted to a total bed height of 15.2 cm only.

A numerical analysis based on the model of the boiling and transport mechanism in a granular bed as described in this paper has been presented for a slab of thickness b in [8]. According to this analysis, the height of the *capillary region* is given by the equation

$$l_c = \sqrt{\frac{2\rho_l^2 K_w h_{lv} f}{\rho_s \dot{q}}} \tag{6}$$

where the heat flux through the bottom of the region can be neglected. In this equation, K_w denotes the permeability of the porous bed containing the liquid, h_{lv} is the heat of evaporation, f the porosity, and $\dot{q} = q/b$ the heat addition per unit volume of the granular bed. According to the equation, the height of the capillary region changes inversely proportional to the square root of the heat addition $\dot{q}$ per unit volume of the bed, and is independent of the thickness b of the bed and almost independent of pressure. The experimentally determined height of the capillary region is plotted in Fig. 8 vs the heat addition $\dot{q}$, which for the annular bed is defined by the equation $qd_o = \frac{1}{4}\dot{q}(d_o^2 - d_i^2)$ with d_o and d_i denoting the outer and inner diameter of the annulus respectively. The points are for the two thicknesses of the annular bed. The two curves drawn through the experimental points do not collapse into a single one as required by the theory. This probably is due to an unequal distribution of the liquid and vapor velocities throughout the crossections of the annulus whereas the analysis is based on the assumption of a uniform distribution. The theory predicts that the height l_c should vary inversely proportional to the square root of the heat generation rate $\dot{q}$. The experimental curves are somewhat steeper. Experimental data have also been used in ref. [8] to calculate the value of the permeability K_w describing the movement of liquid in an unsaturated porous medium. An error has occurred in the selection of the heat flux $\dot{q}$. The calculation will, therefore, be repeated here. The height of the capillary region in the experiments was approximately 5×10^{-2} m at a heat flux of about 1000 W m^{-2}. This leads in Fig. 3, of ref. [8], to a value between 10^{-6} and 10^{-7} m^2 s^{-1} for K_w which is in the right order of magnitude according to values in the literature for similar porous media.

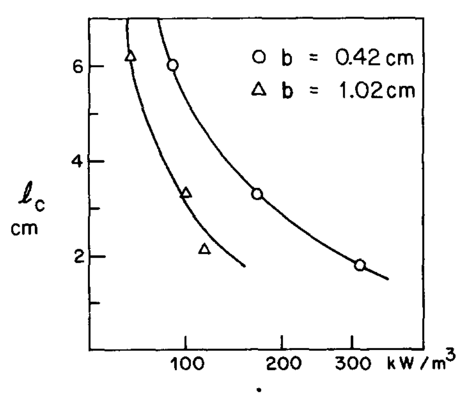

FIG. 8. Height l_c of the capillary region as a function of the heat addition $\dot{q}$ per unit volume of the bed for two thicknesses b of the annular bed.

According to the analysis, the height of the *chimney region* should also be essentially inversely proportional to the heat addition $\dot{q}$. The experimental points in Fig. 7 indicate a height which is independent of the heat flux.

S. W. Jones *et al.* performed an analysis [9] of the chimney region based on a model which assumes that regions of the granular bed surrounding the channels are in a state of incipient fluidization whereas the bulk of the bed is still packed. The pressure drop Δp_f caused by the flow of vapor through the channels is in equilibrium with the hydrostatic pressure in these layers

$$\Delta p_f = \rho_b g h \tag{7}$$

with g denoting the gravitational acceleration and h the height of the channels. The average density of the bed in fluidization is given by the equation

$$\rho_b = f\rho_l + (1-f)\rho_s. \tag{8}$$

The pressure drop through the channel is also equal to the sum of the hydraulic pressure in the liquid moving downward through the packed bed and the pressure increase due to capillary action at the interphase between liquid and vapor when the pressure drop in the liquid is neglected. This is expressed in the equation

$$\rho_b g h = \rho_l g h + \frac{\sigma}{r_H}. \tag{9}$$

The symbol σ denotes the surface tension and r_H the average radius of the capillaries. The following equation for the hydraulic radius is used in [9]

$$r_H = \frac{d_p f}{6(1-f)}. \tag{10}$$

Equations (7)–(10) result in the following relation for the height of the channels which can be equated to the height of the chimney region

$$l_{ch} = \frac{6\sigma}{(\rho_s - \rho_l) g f d_p}. \tag{11}$$

This equation makes the height of the chimney region independent of the heat flux and also practically independent of the pressure level in agreement with the results of the experiments which will be discussed later on. The magnitude of l_{ch} [0.25 m, according to equation (11)] is larger than the values in Fig. 7. This figure also shows the height of the chimney region to be larger for the small thickness b of the annulus than for the larger one, which may again be due to the nonuniform distribution of the velocities over the annular cross section.

A few experiments were performed with a bed of approximately spherical *copper particles* with a mean diameter of 17.3 μm forming a bed with 39% porosity. The particle size distribution is shown in Fig. 2. The experiments demonstrated the appearance of cracks and the heaving motion of the bed, however, the process is more vehement and a larger fraction of the particles move into the fluidized state. These differences in comparison to the nickel bed are probably a consequence of the smaller bed porosity.

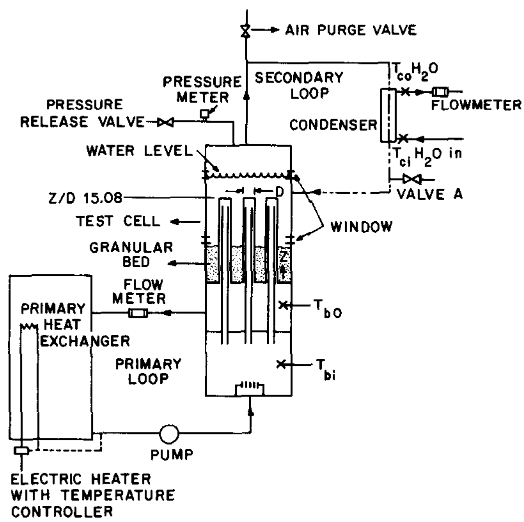

FIG. 9. Test setup for the second set of experiments.

EXPERIMENTS AT HIGH HEAT FLUX AND VARYING PRESSURE

A second series of experiments was performed in a test setup which permitted higher heat fluxes and a pressure range of the boiling liquid from 1 to 4.5 b. The geometry was also different and simulated more closely the geometry in nuclear reactor steam generators. Nine tubes with circular cross-section are in a square arrangement with a central tube surrounded by eight outer tubes. Each of the nine tubes has an inner tube inserted permitting an upward flow of the heating fluid in the inner tube and a downward flow in the annular space between both tubes. The main attention was focused on the central tube. The diameter of each tube is 2.03 cm. They were arranged with their axes at the corners of squares with a side length of 2.78 cm. The tubes were 30.6 cm long. The same granular material as used in the first group of experiments (nickel particles) occupies the space between the tubes which are heated by Therminol 60 on the inside whereas the boiling occurs on the outside and in the space between the tubes filled with the same nickel particles as used in the first series of experiments. Bed heights of 7.6 cm and 15.2 cm were used. The tubes are arranged inside a test cell, shown in Fig. 9. The cell is connected to a primary heat exchanger in the way that the heating fluid can be pumped from the heat exchanger into a lower chamber of the test cell. From there it flows through the inner concentric tubes in an upward direction, turns around at the closed top of the outer tubes and returns through an annular space between the tubes into a second chamber and from there through a flow meter to the primary heat exchanger. The bulk temperature t_b of the fluid entering and leaving the tubes is measured by thermocouples located close to the inlet and outlet of the tubes. The heat flux to the boiling water is calculated from the mass flux measured by the flow meter and the bulk temperatures. Water fills the voids of the granular bed and extends to the level indicated in the figure. Vapor generated on the outer surface of the tubes and in the voids of the bed leaves at the top of the test cell. The mass flux of the water cooling the condenser is measured by a second flow meter. This measurement together with the measured inlet and outlet temperature of the cooling water provides a check on the heat flux to the boiling water. Windows are provided to allow observation of the boiling process. The pressure in the test cell is measured with a pressure gage indicated in the figure. Forty-one copper–constantan thermocouples in inconel sheaths are soldered into the wall of the tubes as close as possible to the outer surface on which boiling occurs. Thirty-five of these are arranged on the central tube.

A test is started by providing electric energy to the primary heat exchanger. Air is removed from the test cell through the air purge valve and steady state is established by a proper balance of the electric heat supplied to the heat exchanger with the heat removed in the condenser. A more detailed description of the test setup, instrumentation, and experimental procedure is contained in [5].

The temperature field on the outer surface of the tubes was measured together with the entering and leaving bulk temperatures of the heating fluid flowing through the annular channel of the concentric tubes and the saturation temperature of the water above the granular material as functions of the heat flux per unit area of the outer surface of the tubes and the vapor pressure above the water. Typical results of these measurements are shown as Figs. 10–12. Figures 10 and 11 are for 15.2 cm bed height, Fig. 12 is for 7.6 cm bed height. The wall temperature t_w in these figures was measured along a vertical line in the central tube wall. The bulk temperature of the heating fluid was obtained by linear interpolation between the inlet temperature t_{bi} and the outlet temperature t_{bo}. The saturation temperature is obtained as a function of the measured pressure p from steam tables. The abscissa is the ratio of

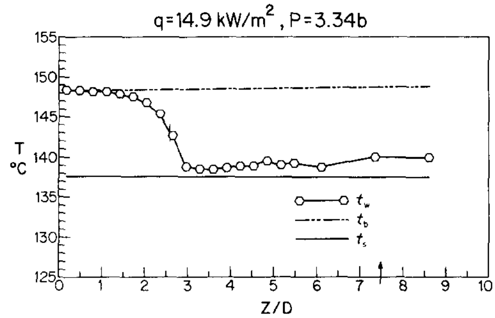

FIG. 10. Profiles of wall temperature t_w, heating fluid bulk temperature t_b, and saturation temperature t_s along a vertical line in the wall of the central tube, bed height is 15.2 cm (the arrow indicates the total bed height).

the distance Z from the bottom of the granular bed to the tube diameter D (2.03 cm). An arrow on the abscissa indicates the location of the upper surface of the granular bed at the beginning of the test. Measurements of the vertical temperature profile on the outer tubes agreed well with those on the central tube. The wall temperature in the figures is quite close to the bulk temperature near the bottom of the bed and experiences a sharp drop-off with increasing height indicating that a dry-out region has been established. In the upper part of the bed, the wall temperature is almost constant and closer to the saturation temperature. In Fig. 11, however, a bump in the wall temperature occurs near the value $Z/D = 5$. This is interpreted as indicating a partial dry-out region at that location.

Plots like the ones presented in Figs. 10–12 can also be used to obtain information on the variation of the heat transfer coefficients describing the heat flux q from the cylinder wall into the granular material in the following way. Two equations can be written for the heat flux q

$$q = \frac{1}{R_i}(t_b - t_w) \quad (12)$$

$$q = h_b(t_w - t_s) \quad (13)$$

R_i denotes the overall resistance to heat flux including the effect of the film heat transfer coefficient of the heating fluid and of the temperature drop in the wall up to the location where t_w is measured. The film heat transfer coefficient h_b to the boiling water is obtained from equations (12) and (13)

$$h_b = \frac{1}{R_i} \cdot \frac{t_b - t_w}{t_w - t_s}. \quad (14)$$

The thermal resistance R_i is practically independent of Z. The ratio of the two temperature differences in Figs. 10–12, therefore, describes the variation of h_b with the location along the tube wall.

The height of the dry-out region is defined in the figures as that value of Z/D at which the wall temperature has a value halfway between the bulk temperature and the saturation temperature. Vertical lines in the figures indicate this height. The results of two test runs are plotted in Fig. 12. They demonstrate the reproductibility of the experiments. Thermocouples arranged around the periphery of the central tube indicated that the temperature was constant around the periphery except at heights Z/D at which the wall temperature drops sharply in the Z direction indicating that the surface describing the height of the dry-out region is somewhat curved.

The difference between the total bed height and the height of the dry-out region constitutes the wetted region in which liquid and vapor co-exist. The experiments give no indication how this region is subdivided into a capillary and a chimney region. From the trend of the heights l_c in Fig. 7, however, it is concluded that most, if not all of this region is in a heaving motion.

The ratio of the height l_w of the wetted region to the diameter D obtained from the experiments is presented in Fig. 13 over the heat flux q. Circles indicate data obtained from experiments with 7.5 cm total bed height and triangles are for 3.75 cm bed height. The experimental points arrange themselves around the interpolating line inserted in the figure except for a number of points in the range of smaller heat fluxes which are higher. Some of these symbols are filled out. They are the ones in which humps, as shown in Fig. 11,

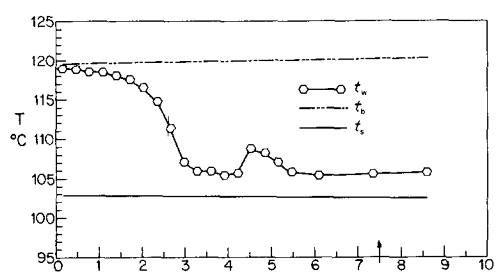

FIG. 11. Profiles of wall temperature t_w, heating fluid bulk temperature t_b, and saturation temperature t_s along a vertical line in the wall of the central tube, bed height is 15.2 cm (the arrow indicates the total bed height).

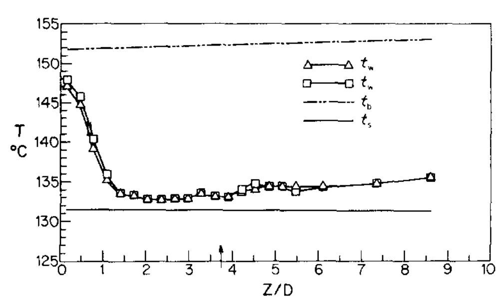

FIG. 12. Profiles of wall temperature t_w, heating fluid bulk temperature t_b, and saturation temperature t_s along a vertical line in the wall of the central tube, bed height is 7.6 cm (the arrow indicates total bed height).

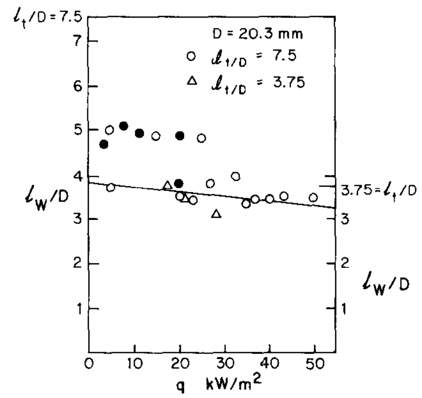

FIG. 13. Height of the wetted region for 3.75 and 7.5 cm bed height as a function of the heat flux q through the outer surface of the central tube. The total bed heights are indicated by horizontal lines on the left and right ordinate respectively.

have been observed. The data in the figure were obtained at various pressures between 1 and 4.5 b. They do not exhibit any consistent influence of the saturation pressure and they also demonstrate that the dry-out region is independent of the total height of the bed.

A comparison between the height of the dry-out region in Fig. 13 with that in Fig. 7 is made difficult by the fact that the geometry of the granular bed is different in both situations. However, if one assumes that the width of the smallest gap between the tubes in Fig. 9 (0.75 cm) is equivalent to the thickness b of the annular layer in Fig. 7, then a comparison can be made. The height of the wetted region which is the sum of the capillary and the chimney regions for a width b of 0.7 cm is found in Fig. 7 by linear interpolation between the corresponding heights at 0.42 and 1.02 cm to be 7.5 cm. This agrees well with the height of $l_w = 3.8 \times 7 = 7.6$ cm obtained from Fig. 13 at $q = 10^3$ W m^{-2}. The hydraulic diameter of the tube array is 1.92 cm when based on the total circumference belonging to the cross-sectional area and even larger when based on the circumference of the tubes. It leads to a poorer correlation for the two geometries than the use of the width of the smallest gap.

CONCLUSIONS

Boiling of water in an unsaturated granular bed of 0.65 porosity formed by nickel particles with an average size of 29.8 μm was studied experimentally. Two shapes of the bed were investigated: an annulus between two vertical concentric cylinders and a bed occupying the space between an array of vertical tubes. In both cases, the bed height was large compared to the horizontal dimensions.

Visual observation and temperature measurements established the formation during boiling of a *wetted region* which contained liquid and vapor and had a height which was independent of the total bed height and independent of pressure but decreased somewhat with heat flux.

Observation showed that this region consisted of two layers: an upper layer called *chimney region* in which the vapor formed vertical channels through which it escaped in an upward direction whereas the liquid flowed downwards through the voids of the fixed bed porous medium. The height of this layer was independent of the total bed height and independent of heat flux.

Below this was a second layer called *capillary region* in which the counterflow of vapor and liquid occurred through the voids of the fixed bed porous medium. The height of this layer was independent of the total bed height and decreased with increasing heat flux.

A third *dry region* was established below the wetted region when the total bed height was larger than the height of the wetted region. Its height was the difference between the total bed height and the height of the wetted region. In the same way, the capillary region and the chimney regions were not established to their full extent when the total bed height was too short.

Experimental results indicated that the velocities of the vapor and the liquid were nonuniformly distributed throughout horizontal cross sections of the bed.

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EBULLITION DANS UN MILIEU GRANULAIRE SANS CONSTRICTION

Résumé—L'ébullition dans un lit sans constriction à 65% de porosité, formé par des particules sphériques de nickel avec 28,3 μm de diamètre moyen, est étudié dans deux séries d'expériences. Dans la première série, le lit granulaire a la forme d'un milieu annulaire cylindrique et la chaleur est apportée à la surface externe du cylindre, avec un flux allant jusqu'à 1 kW m^{-2}. Une visualisation montre, dans l'ordre ascendant, une région d'assèchement à la base de la colonne, une région capillaire dans laquelle le liquide, aussi bien que la vapeur, trouve dans les vides du lit, et une région de cheminée avec des failles horizontales et des canaux verticaux. Si toutes ces régions existent, elles dépendent de la hauteur totale du lit. Dans la seconde série d'expériences conduite dans un réservoir sous pression contenant une nappe de neuf tubes avec un milieu granulaire extérieur aux tubes, l'établissement d'une région sèche au dessous de la région mouillée (comprenant les régions capillaires et cheminées) est déterminé par la mesure d'un profil vertical de température le long de la paroi du tube, avec un flux thermique allant jusqu'à 50 kW m^{-2}. La région mouillée est indépendante du niveau de pression et de la hauteur totale du lit. La région sèche se forme quand la hauteur totale du lit est plus grande que celle de la région mouillée. La hauteur de la région capillaire est inversement proportionnelle à la racine carrée du flux de chaleur, alors que la région de cheminées est essentiellement indépendante du flux.

SIEDEN IN EINEM NICHTVERDICHTETEN KÖRNIGEN MEDIUM

Zusammenfassung—In zwei Versuchsreihen wurde das Siedeverhalten in einem nichtverdichteten Bett mit 65% Porosität, bestehend aus kugeligen Nickelpartikeln mit einem mittleren Durchmesser von 28,3 μ m, untersucht. Bei der ersten Versuchsreihe hatte das körnige Bett die Form eines zylindrischen Ringraums, wobei über die äußere Zylinderfläche Wärme mit einer Wärmestromdichte bis zu 1 kW m^{-2} zugeführt wurde. Visuelle Beobachtungen brachten in aufsteigender Reihenfolge den Nachweis einer Trockenzone am Grund des Zylinders, einer Kapillarzone, in der sowohl Flüssigkeit als auch Dampf in den Freiräumen des Bettes auftritt und einer Kaminzone mit im wesentlichen horizontalen Spalten und vertikalen Kanälen und mit einer Vertikalbewegung im Bett. Ob tatsächlich alle Zonen auftreten, hängt von der Gesamthöhe des Bettes ab. Bei der zweiten Versuchsreihe, die in einem Druckbehälter mit einer Reihe von neun beheizten Rohren durchgeführt wurde, an deren Außenseite sich das körnige Medium befand, wurde durch die Messung des vertikalen Temperaturprofils entlang der Rohrwand bei Wärmestromdichten bis zu 50 kW m^{-2} die Existenz einer Trockenzone unter der benetzten Zone (einschließlich der Kapillar- und Kaminzone) festgestellt. Die benetzte Zone im Bett ist vom Druck und der Gesamthöhe des Bettes unabhängig. Eine Trockenzone entsteht, wenn die Gesamthöhe des Bettes größer als die der benetzten Zone ist. Die Höhe der Kapillarzone verändert sich umgekehrt proportional zur Quadratwurzel der Wärmestromdichte, wogegen die Kaminzone unabhängig davon ist.

КИПЕНИЕ В ПЛОТНОЙ ГРАНУЛИРОВАННОЙ СРЕДЕ

Аннотация—В двух сериях экспериментов исследовалось кипение в плотном слое с 65%-ной пористостью, образованной сферическими никелевыми частицами со средним диаметром 28,3 мкм. В первой группе опытов гранулированный материал находился в цилиндрическом кольцевом зазоре. Тепловой поток, подводимый через поверхность наружного цилиндра, достигал 1 кВт/м^2. При визуализации обнаружено наличие сухой зоны в нижней части колонны; капиллярной области, в которой жидкость, также как и пар, заполняют пустоты в слое; и зоны с существенными горизонтальными трещинами и вертикальными проходами, в которой слой находится в движении. Существование всех этих зон зависит от общей высоты слоя. Вторая серия экспериментов была проведена в камере высокого давления, в которой расположен ряд из девяти нагреваемых труб, окруженных гранулированной средой. Установлено наличие сухой зоны под влажным участком (включающим капиллярную зону и область трубы) путем измерения вертикального профиля температуры вдоль стенки трубы при тепловом потоке до 50 кВт/м^2. Влажная область не зависит от величины давления и общей высоты слоя. Сухая зона образуется в том случае, когда общая высота слоя превышает высоту влажного участка. Высота капиллярной зоны изменяется обратно пропорционально корню квадратному из величины теплового потока, в то время как высота зоны трубы существенно независима от него.