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LIQUID BOILING PROCESS IN ROTATING VESSELS AND CHANNELS

S. I. Sergeev, O. M. Popov,
and I. P. Vishnev

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Results of visual observations of water boiling in rotating vessels and channels are presented. The existence of various forms of nucleate boiling is established. Simplified calculations of single phase and boiling liquid thermal convection are performed.

In order to construct high-power electric generators with rotors cooled by cryogenic liquids [1], information is required on the motion of heated and boiling liquid in rotating cavities and channels of various configurations. Reviews of studies of the boiling process in rotatint vessels can be found in [2-5]. Visual observations of liquid flow in such vessels were described in [6] and other studies. In view of the shortcomings and contradictions of the available studies, the present authors carried out test stand studies in which the convection and boiling of heated water in rotating glass vessels and channels of various form were observed (Fig. 1). Test stand parameters were as follows: radial distance from bottom of vessel or channel wall to axis of rotation $r_2 \approx 12$ cm, radial distance from edge of vessel or beginning of channel to axis of rotation $r_1 \approx 2$ cm, channel diameter D = 0.3 or 0.5 cm, vessel diameter 4 or 7 cm, heater, externally heated sleeve around channel section L_2 = 8 cm long, or 3 cm diameter plane heater immersed to bottom of vessel, occupying from 18 to 56% of bottom area. Experiments were performed both with and without transparent screens to protect the rotating vessels and channels from cooling by the air through which they moved. The screenless experiments produced additional heat losses, but simplified observations. Angular rotation frequency $\omega \leqslant 157\ \sec^{-1}$ (or $\leqslant 1500$ rpm). This corresponded to a maximum centripetal acceleration of $r_2\omega^2 \leqslant 3 \cdot 10^3$ m/sec^2 or relative acceleration of $G = r_2\omega^2 g^{-1} \leqslant 300$, and an excess pressure produced by centrifugal forces of $P_+ = 0.5\rho\omega^2 \times (r_2^2 - r_1^2) \leqslant 0.17$ MPa, with increase in the water boiling point at the bottom of the vessel to 130°C.

Visual observations and photography of the motion of vapor bubbles and plastic shavings with a density close to that of water were carried out under stroboscopic illumination. The rotation frequency and thermal heating power Q were measured.

Boiling in a free volume was studied in a glass vessel 9 cm high with axis oriented along the normal to the axis of rotation (8, Fig. 1), with water supplied through collector 4.

Observations of the convective motion of the single phase liquid not heated to the boiling point ($Q \leqslant 50$ W) were performed under normal conditions $G > 30$ and $Ra_\omega = D^3\omega^2 r_2 \beta T_+ (\nu a)^{-1} \backsim 10^8 - 10^{10}$. In this case it was evident from the motion of the suspended particles that the usual (in the absence of rotation) two-loop convection with a flow of hot liquid departing from the center of the heater did not occur. Instead, a one-loop circulation convection was established with cold flow directed along the pressure wall of the vessel to the bottom and heater located there, with heated flow directed along the pressure wall of the vessel to the bottom and heater located there, with heated flow directed from the heater along the nonpressure wall toward the axis of rotation (1, Fig. 2). The direction of the

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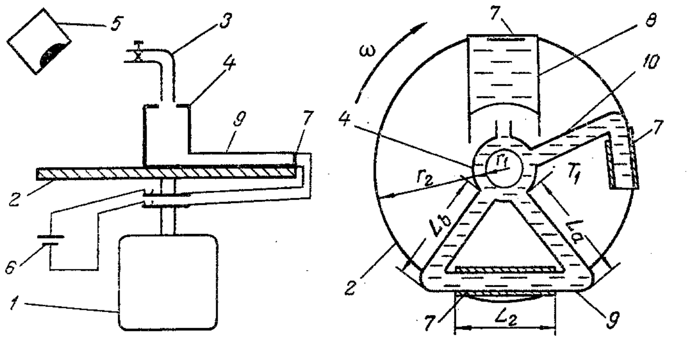

Fig. 1. Diagram of experimental test stand: 1) dc electric motor; 2) faceplate; 3) water supply; 4) distributing collector; 5) stroboscope; 6) current source; 7) heaters; 8) vessel; 9, 10) channels.

circulation can be explained by the action of Coriolis forces which force apart the hot and cold branches of the flow and press them to the vessel walls, thus producing partial thermal insulation between them. If oppositely directed circulation were to develop at random, then the Coriolis forces would force together the branches of such a flow, leading to equalization of temperatures in the branches and reduction in temperature head. With increase in rotation frequency and Rayleigh number, together with this first type of circulation there developed a form consisting of two independent vortices separated at the midpoint of the vessel height, after which higher forms of several more or less ordered vortices appeared.

At low rotation frequency ($G > 10$) and sufficiently high heater power ($Q = 200$ W) nucleate boiling close to conventional form (under stationary conditions) was observed, with formation of vapor bubbles on the heated surface, but with the bubbles being carried to the nonpressure side of the vessel due to thermal convection. The bubbles are concentrated less densely on the heater near the pressure wall and more densely near the opposite wall, and ascend at some distance from the wall with the convective flow (Fig. 2, zone 2; Fig. 3a). This same pattern is observed when the heater was shifted toward the pressure side of the vessel. In this case bubbles were formed only on the portion of the heater furthest removed from the pressure wall and then moved toward the axis of rotation, which was accompanied by boiling up of the superheated liquid on the heater, so that the bubble flow was in the form of a funnel directed toward the free surface of the water. The development of bubbles intensified and stabilized the basic single loop form of the circulation and inhibited the development of higher multivortex forms. With the heater power maintained constant, at increased rotation frequency the thermal convection increased so intensely that bubble formation on the heater stopped, first near the pressure side, then over the entire heater surface. In addition, the water temperature near the heater increased to a point, which although less than the boiling point under the excess pressure P_+ at the vessel bottom, $T_s(P_a + P_+) \infty 110$–$130$°C, significantly exceeded the atmospheric boiling point P_a ($T_s(P_a) = T_s = 100$°C) at the free surface. The hot water at temperature T, $T_{s0} < T < T_s(P_s)$ then convectively flowed toward the axis of rotation from the increased pressure zone into an area of reduced pressure $P_a + P_+(r)$, $P < P_a + P_+(r) < P_a + P_+$ and boiled up. With further increase in rotation frequency the zone of vapor bubble formation within the liquid moved further from the heater (over which completely transparent single-phase water flowed) and approached the free liquid surface near the non-pressure wall (Fig. 2, zones 3, 4, 5; Fig. 3b, c). At $\omega > 100$ sec^{-1} ($G > 120$) and a heater power $Q = 100$–180 W there was intense bubble boiling within the water volume exclusively near the free surface, with the water in all remaining parts of the vessel including the volume near the heater remaining completely transparent, without a single bubble.

Although such boiling processes have been described previously [3] and can be explained quite simply, nevertheless the clearly expressed boiling of the portion of the liquid volume opposite the heater appears quite effective.

With increase in heater power at constant rotation frequency ($\omega = 50$–100 sec^{-1}) a reverse sequence of similar phenomena was observed. With low heat levels insufficient for boiling ($Q < 100$ W) the thermal circulation convection described above developed, then broke into several vortices with increase in heater power. With further increase in heat

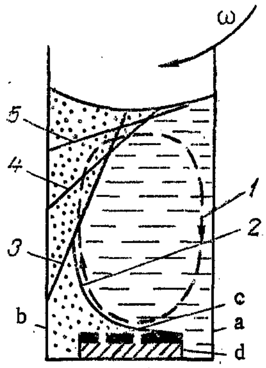

Fig. 2. Boiling zones in rotating vessels: 1) one-loop convective circulation; 2-5) boundaries of vapor formation zone for successive increases in centripetal acceleration; a) pressure wall; b) nonpressure wall; c) heaters; d) thermal insulation.

(Q = 100-180 W) fully developed boiling of the water near its free surface was observed, beginning with weak bubble formation at the free surface, appearing like ripples on the surface, then expanding into intense nucleate boiling in the liquid volume. The basic single-loop circulation existed, and the vapor bubble diameter was 3-5 times larger than in conventional boiling on a heated surface under static conditions. With increase in heating (Q = 200-300 W) the nucleate boiling zone in the volume expands along the nonpressure wall, but does not yet reach the heater surface. At Q = 310 W with further expansion of the boiling zone vapor bubbles began to be formed on the heater surface near the nonsupply wall. Subsequent increase in thermal loading caused this zone to expand, and at Q ≈ 450 W the two bubble boiling zones on the free and heater surfaces joined together. With further increase in thermal load the nucleate boiling zone increased still further, and at Q = 700 W boiling occurred over the entire vessel volume and on the heater surface.

In a loop- or horseshoe-shaped channel (9, Fig. 1) joined to the supply collector 4 near the axis of rotation with heater 7 at the periphery, similar phenomena were observed with some differences. The loop form of the channel stabilized the circulation convective flow. For strictly symmetric location of the heater the circulation direction was the same as for convection in a vessel (1, Fig. 2). When the symmetry was disrupted by locating the heater closer to one or the other radial portion of the channel, the circulation direction could be changed, so that the flow toward the axis of rotation occurred in that portion of the channel which was partially heated. In such channels the circulation velocity was higher than in vessels and at times superheated liquid was carried into reduced pressure zones located away from the axis of rotation, where abrupt periodic removal of superheating occurred, manifesting itself through violent boiling up of the liquid volume with formation of vapor bubbles which coalesced into a vapor plug within the channel.

The frequency of such boilups was 0.2-0.5 Hz with relatively weak heating, increasing to 2-5 Hz with intense heating, accompanied by sonic effects — noise and crackling. At a sufficiently high rotation rate ($\omega > 80\ \text{sec}^{-1}$), stable rolling boiling in a channel zone ∿ 1 cm long far from the heater near the collector was observed. This zone increased in size with increase in heater power.

In intense centrifugal force fields there was no regime with formation of fine bubbles (diameter < 1 mm). As they move toward the reduced pressure zone, the bubbles which developed almost instantaneously increased in size, reaching the diameter of the channel.

In a deadend channel (10, Fig. 1), heated near the closed end, liquid circulation was significantly hindered, and surface tension forces manifest themselves more intensely, encouraging occlusion of the channel by rising vapor bubbles. In a stationary channel (at $\omega = 0$) unstable boiling with periodic flares was observed, water being expelled by rising vapor bubbles. But even at a low rotation rate ($\omega \approx 30\ \text{sec}^{-1}$, $G \approx 10$), despite the small channel diameter (0.5 cm or even 0.3 cm) liquid motion was stabilized due to circulation. At increased rotation rates the forms of boiling were similar to those in loop channels, but less stable.

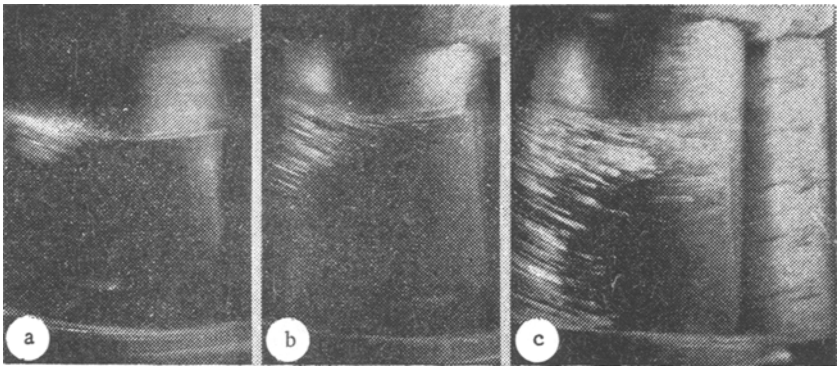

Fig. 3. Photographs of the boiling process in a rotating vessel: a) $\omega = 45\ \text{sec}^{-1}$; b) 65; c) 80 (Q = const).

The thermal circulation processes described for liquid boiling can be calculated approximately, using channel 9 of Fig. 1 as a basis, if we assume that the channel segment near the axis of rotation, is in contact with the liquid in the collector or with an external medium and has a temperature T_1 equal to or less than the boiling temperature under atmospheric conditions T_{s0} and that the lateral portions of the channel L_a and L_b ($L_a = L_b$) are thermally insulated (not an obligatory condition), and that the peripheral segment of length L_2 is uniformly heated by a distributed heat source of known power Q. Then in the process of circulation formation the liquid approaches the heater at temperature T_1 through channel L_a and leaves the heated region at temperature $T_1 + T_+$, while

$$T_+ = Q(SV\vartheta)^{-1}. \tag{1}$$

In single phase motion of the liquid due to thermal expansion, a pressure head

$$P_V = \beta T_+ P_+,\ P_+ = 0.5\rho\omega^2(r_2^2 - r_1^2) \tag{2}$$

develops, which compensates the friction resistance P_f, equal for the turbulent regime to

$$P_f = 0.5k\rho V^2 L D^{-1},\ L = L_a + L_2 + L_b. \tag{3}$$

From this it is evident that the centripetal pressure P_+ appears in the expression for the presssure P_V which excites the circulation, and this is more important than the increase in hydrostatic pressure on the vessel bottom under the action of P_+. The resistance coefficient k for flow in the radial channels is not known reliably. Under the action of Coriolis force it may be tens of times larger than the usual value of 0.02 and may approach $1.5 \cdot 10^{-3} D\omega^{1/2}\nu^{-1/2}$ [7].

From the equation $P_V = P_f$ we find the mean liquid velocity V and the amount by which it is heated T_+:

$$V = (8\beta Q P_+)^{1/3}(k\pi\rho\vartheta DL)^{-1/3},$$
$$T_+ = (8kQ^2\rho L)^{1/3}(\pi^2 D^5\vartheta^2\beta P_+)^{-1/3}. \tag{4}$$

If the liquid heating T_+ is sufficiently large, so that $(T_1 + T_+) > T_{s0}$ (where T_{s0} is the boiling point under atmospheric pressure), then in the centripetal flow along channel L_b the liquid will boil up in the decreasing pressure field at some radial coordinate r_b and then boils over the entire extent of the channel up to the free surface near the axis of rotation. Significant increases then occur in both the Archimedean pressure head P_V, due to reduction in density of the two-phase medium, and the friction resistance P_f, due to increase in the velocity of the two-phase medium as compared to the liquid velocity V in channel segments L_a and L_2. Calculation of such flows is quite complicated. For simplicity, we will assume that $T_1 = T_{s0}$, that the vapor in the boiling zone $r_1 \leqslant r \leqslant r_b$ occupies a constant fraction η of the channel area, that the free liquid surface is close to the axis of rotation, so that $r_1 \approx 0$, and that the resistance to the two-phase flow is described in the same manner as for the single-phase flow, with the density and velocity ρ and V being replaced by the two-phase medium density and velocity ρ_2 and V_2, and that the circulation velocity is so high that as before only single-phase liquid flows over the heater. Then Eq. (1) remains valid. With further liquid motion along the channel L_2 this heating leads to evaporation of a fraction of the liquid ξ, so that

$$\begin{gathered}\xi = Q(\delta SV)^{-1}, \quad 0.5\rho\omega^2 r_b^2\gamma = T_+,\\ r_b^2 = 2T_+(\rho\omega^2\gamma)^{-1} = 2Q(SV\vartheta\gamma\rho\omega^2)^{-1} \text{ at } r_b < r_2,\\ \rho_2 V_2 = \rho V = (\rho_V\eta + \rho - \rho\eta)V_2, \ \rho_V\eta V_2 = \xi\rho V,\\ 0.5\rho\omega^2 r_b^2\eta \approx 0.5kD^{-1}[\rho V^2 L + \rho_2 V_2^2 r_b].\end{gathered} \tag{5}$$

Here ρ_V is the vapor density in the region $0 < r < r_b$, where the pressure is not much more than atmospheric; in the last equation the left side represents the pressure which produces liquid motion, and the right side is the resistive pressure. From Eqs. (1), (5), neglecting terms of second order smallness, we have

$$\begin{gathered}\eta \approx \rho\xi(\rho\xi + \rho_V)^{-1} \approx 1,\\ Q\eta(S\vartheta\gamma)^{-1} \approx 0.5k\rho D^{-1}[V^3 L + 2^{1/2}V^{3/2}\rho\rho^{-1}Q^{3/2}(\eta^2\delta^2 S^3\rho\omega^2\vartheta\gamma)^{-1/2}].\end{gathered} \tag{6}$$

In the case where the entire liquid tract is located on the rotor periphery, i.e., $(r_2 - r_1) \ll r_1$, we obtain similar expressions with the parameters ξ, η, ρ_2, V_2 also expressed by Eq. (5), with the radius at which boiling commences r_b and the flow velocity V being defined by expressions (second-order terms omitted)

$$\begin{gathered}r_b \approx r_1 + Q(r_1 SV\vartheta\gamma\rho\omega^2)^{-1} \text{ at } r_b < r_2,\\ Q\eta(S\vartheta\gamma)^{-1} \approx 0.5k\rho D^{-1}[V^3 L + VQ^2\rho\rho_V^{-1}(r_1\rho\omega^2\eta S\delta\vartheta\gamma)^{-1}].\end{gathered} \tag{7}$$

From this it follows that if the thermal load and vapor formation rate are low, for any r_1, as before (Eq. (4)) the flow velocity V will be approximately proportional to the heater power raised to the 1/3 power, but in contrast to Eq. (4), it is practically independent of rotation frequency ω:

$$V \approx (8Q\eta)^{\frac{1}{3}}(\pi kDL\rho\vartheta\gamma)^{-\frac{1}{3}}, \ \eta = 1. \tag{8}$$

With increase in power Q and vapor formation the boiling zone in the channel L_b expands at $0 < r < r_b$ while the resistance to the two-phase flow increases more rapidly than the driving pressure, defined by the left side of the last expression of Eq. (6). As a consequence, the flow velocity V as a function of heater power Q increases, reaches a maximum, and then falls. On the falling branch of this dependence

$$V \approx [\pi\rho_V^2\delta^2\omega^2 D^4\eta^4(\rho^2k^2Q\rho\vartheta\gamma)^{-1}]^{\frac{1}{3}}, \ \eta = 1 \text{ at } r_1 \approx 0, \tag{9}$$

$$V \approx 0.5k^{-1}\pi\rho_V\rho^{-1}D^3 r_1\delta\eta^2\omega^2 Q^{-1}, \ \eta \approx 1 \text{ at } (r_2 - r_1) \ll r_1. \tag{10}$$

Here the velocity V again increases with increase in rotation frequency. However, the decrease in circulation with increase in power creates conditions for a boiling crisis.

To describe flow in vessels, in the first approximation we may use the same expressions, taking D equal to half the vessel diameter, while $L_\alpha = L_b$ is the height of the liquid layer and L_2 is the extent of the heater.

Equations (4), (5), (7)-(10) show that with increase in channel rotation velocity the liquid circulation velocity increases, its temperature decreases, the boiling zone decreases in size and approaches the free surface, while all these phenomena depend on heater power in a complex manner.

The above expressions can be refined by considering the dependence of vapor content η and velocity V_2 on radial coordinate r, the inertial resistance of the vapor flow, temperature conditions on the channel walls, etc., which naturally leads to some complication of the dependence of V and T_+ on system parameters.

According to the observations reported and calculations performed, in rotating channels and vessels with G > 10 and $Ra_\omega > 10^4$ the following regimes may occur, gradually changing with increase in heater power.

1. Intense circulation of single-phase liquid with temperature below the boiling point. In vessels such circulation occurs at low heat levels in the form of a single vortex with thermal flux from the heater toward the axis of rotation along the wall not under pressure, with this circulation breaking up into several vortices upon increased heating.

2. The same type of circulation, accompanied by boiling in a zone near the axis of rotation and removed from the heater.

3. Expansion of the boiling zone and its approach toward the heater, accompanied by reduction in circulation velocity.

4. Extension of the boiling zone to the liquid surface, beginning on the pressure-free side of vessel or channel, with breakup of the circulation into disordered jets or a chain of gas bubbles.

Similarity of the various flows considered for channels and vessels with different parameters is determined by equality of the Reynolds numbers $Re = VD\nu^{-1}$ for the various flow regimes and constructions and equality of the relative length of the boiling zone $X = (r_b - r_1)(r_2 - r_1)^{-1}$.

The Reynolds number can be found by multiplying the right sides of the expression for V in Eqs. (4), (8)-(10) by $D\nu^{-1}$, as a result of which we obtain the numbers N_1, N_2, N_3, N_4, respectively. The relative extent of the boiling zone is expressed by

$$\begin{gathered} X = 0 \text{ or } X^2 = N_5 N_2^{-1}, \text{ or } X^2 = N_5 N_3^{-1}, \\ N_5 = 8Q(\pi r_2^2 D\rho\nu\omega^2\vartheta\gamma)^{-1} \text{ for } r_1 \approx 0, \\ X = 0 \text{ or } X = N_6 N_2^{-1}, \text{ or } X = N_6 N_4^{-1}, \\ N_6 = 4Q(\pi r_1 D\rho\nu\omega^2\vartheta\gamma)^{-1}(r_2 - r_1)^{-1} \text{ for } r_2 - r_1 \ll r_1. \end{gathered} \tag{11}$$

We note that according to similarity theory, we obtain a significantly larger number of dimensionless parameters $\gamma^* = \vartheta\gamma$, $\delta^* = \delta P_+^{-1}$, $Q^* = Q(P_+ r_2^3 \omega)^{-1}$, $\nu^* = \nu(r_2^2\omega)^{-1}$, $\beta^* = \beta P_+ \vartheta^{-1}$, G, Ra_ω and simplexes $r_1 r_2^{-1}$, Dr_2^{-1}, Lr_2^{-1}, $\rho\rho_V^{-1}$, $T_1 T_{S_0}^{-1}$, the meaning of which is unclear and the use of which is inconvenient.

As is well known [8], the relative heat-liberation coefficient for heated channels with turbulent liquid flow is proportional to the Reynolds number raised to the 0.8 power. Hence, for the regimes considered with circulation or convection of continuous liquid or boiling outside the heating zone (regimes 1, 2, 3) according to Eqs. (4), (9), the heat-liberation coefficient proves to be proportional to the rotation frequency ω to the power n = 0.53, or proportional to the centripetal acceleration to the power m = 0.265, while in accordance with Eq. (10), we may expect that at $(r_2 - r_1) \ll r_1$ these exponents will increase by a factor of three. In addition, there are possible zones (Eq. (8)) where the circulation velocity V and heat-liberation coefficient are practically independent of rotation frequency and even decrease somewhat with increase in ω due to increase in the resistance coefficient k. The authors of [3-6] and others, measuring the heat-liberation coefficient under experimental conditions most frequently refer to similar expressions $Nu \propto \omega^n$ or G^m, or Ra_ω^m, n = 2m = 0.5-0.66, which correspond to the same dependence of Nu on Ra_ω as under stationary conditions. In addition, some authors maintain [3, 4] heat liberation depends more intensely on rotation frequency ($n \leqslant 1$) or that it is completely independent of that parameter (n = 0). However [9] presented the opposite conclusion, 0.3 < n < 0. Many studies have noted the significant dependence of experimental data on vessel and heater form.

We note that use of the relative acceleration G or the Rayleigh number Ra_ω as an argument, as practiced in [3-5], is not justifiable, since under usual conditions in rotating channels, G > 50, $Ra_\omega > 10^6$ the acceleration of gravity g has no effect whatever on the character of flow or heat exchange, and liquid circulation or convection with or without boiling occur under different conditions than those present at the commencement of convection at $Ra_\omega \approx 2 \cdot 10^3$. The regimes of intense circulation and boiling outside the heating zone considered in more detail in the present study (regimes 1-3) have attracted the interest of other researchers [10], who have indicated that such regimes are intrinsic to the operation of electrical machinery cooled by liquid helium.

NOTATION

a, thermal diffusivity; D, diameter; g, acceleration of gravity; G, relative acceleration; k, resistance coefficient; L, length; N, number; P, pressure; Q, heater power; Re, Reynolds number; Ra_ω, Rayleigh number; r, radial coordinate; S, cross-sectional area; T, temperature; V, mean (over section) velocity; β, volume coefficient of thermal expansion; γ, boiling point-temperature coefficient; δ, specific volumetric heat of vaporization; ξ, vaporization coefficient; η, volume vapor content; ϑ, volumetric heat capacity; ν, kinematic viscosity; ρ, density; X, relative length of boiling zone; ω, angular rotation velocity.

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