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OAK RIDGE NATIONAL LABORATORY
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POST OFFICE BOX P
OAK RIDGE, TENNESSEE

ORNL
CENTRAL FILES NUMBER

CF-52-10-79

DATE: October 9, 1952
SUBJECT: POWER REMOVAL FROM
A BOILING REACTOR

COPY NO.

REACTORS—POWER

TO:
FROM: P. C. Zmola, E. N. Lawson

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The work reported here was done about six months ago. Originally, it was to be included in a status report of the Boiling Reactor Program. Since that time R. V. Bailey has reviewed the problem of power removal from boiling reactors and placed evaluations on a more general basis. It is expected that a report covering Bailey's work will be available shortly.

The work reported here is based on a rather specific and simplified model of the reactor core in which internal circulation exists. Because of the model simplicity, the influence varying some of the parameters appears more directly. In particular, calculation of the circulation factor, which is important in determining the need for vapor separators, is included in this study but has been omitted in the later work. On this basis it was felt desirable to make the results of this study available even though they have been largely superseded by the later work.

P. C. Zmola
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POWER REMOVAL FROM A BOILING REACTOR

P. C. Zmola
E. N. Lawson

1/ The ultimate utility of a boiling reactor depends upon the removal of an appreciable amount of energy from the core of the unit without decreasing the mean density to the extent of requiring an excessive size or fuel enrichment. The calculation presented here is an attempt to relate the mean density to the specific power and the pertinent parameters on the basis of a simplified hydrodynamic model of the reactor core. *and*

Calculations are based on a cylindrical core. It is postulated that the boiling liquid flows upward in the center, liberates a substantial part of the vapor at the top surface, and flows downward in an annular region along the wall of the containing vessel. There is some experimental evidence to support the realism of this flow pattern. Other postulations and simplifications are:

1. Uniform specific power distribution.
2. Bubbles are small relative to the scale of the flow pattern so that the core fluid may be considered homogeneous.
3. Cross sectional area of rising and downcoming region are equal.
4. Average values are used for the density in the rising and downcoming regions.

The idealized system is represented in Figure 1. The core fluid will circulate under steady state conditions at such a rate that the natural convection driving forces resulting from the density difference between the rising and downcoming regions is balanced by the flow resistance of the system. Equations for both the driving and resisting systems will be written as expressions for the maximum rising velocity, V_{max} . As customary in performance problems, the two systems are calculated separately so they can be combined in graphical form.

Consider the driving system first. For a steam flow rate W , the circulation rate W_c can be expressed

$$W_c = nW = \frac{A_1 V_3}{v_3} = \frac{A_1 V_3}{v_f + w_3 v_{fg}} \quad (1)$$

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where w_3 is the top dryness fraction (quality of the soup near the top surface). If a fraction, η , of the bubbles remain in the soup for every circulation pass, the relation between the steam rate and the circulation rate will be

$$W = W_c(1 - \eta)w_3 = \frac{W_c}{n}$$

or

(2)

$$w_3 = \frac{1}{(1 - \eta)n}$$

The heat power output is

$$q_o''' V_o = W h_{fg} \quad (3)$$

Solving (1) for V_3 and combining with (2) and (3) gives

$$V_3 = \frac{n q_o''' V_o}{h_{fg} A_1} [v_f + w_3 v_{fg}] \quad (4)$$

Postulating a uniform specific power distribution the specific volume at points 1, 2, and 3 (Figure 1) can be written

$$v_1 = v_f + w_1 v_{fg} = v_f + w_3 \eta v_{fg}$$

$$v_2 = v_f + w_2 v_{fg} = \frac{1}{2} (v_1 + v_3) \quad (5)$$

$$v_3 = v_f + w_3 v_{fg}$$

Defining γ

$$\gamma = \left(1 - \frac{\rho_1}{\rho_o}\right) = 1 - \frac{v_1 + v_2}{v_2 + v_3} \quad (6)$$

and substituting for the specific volume from (5) gives

$$\gamma = 1 - \frac{4 v_f + w_3 v_{fg} [1 + 3\eta]}{4 v_f + w_3 v_{fg} [3 + \eta]} \quad (7)$$

Solving for w_3

$$w_3 = \frac{4 v_f \delta}{v_{fg} [2(1 - \eta) - \delta(3 + \eta)]} \quad (8)$$

and substituting into (2)

$$n = \frac{v_{fg}}{v_f} \frac{\left[\frac{2(1 - \eta)}{\delta} - (3 + \eta) \right]}{(1 - \eta)^4} \quad (9)$$

Substituting (8) and (9) into (4)

$$V_3 = \frac{q_0''' V_0}{h_{fg} A_i} \cdot \frac{v_{fg}}{(1 - \eta)} \left[\frac{\frac{2(1 - \eta)}{\delta} - (3 + \eta)}{4} + 1 \right] \quad (10)$$

For all cases considered here $V_3 = V_{\max}$.

The average density in the core becomes

$$\rho_{av} = \frac{1}{v_{av}} = \frac{2}{v_3 + v_1} = \frac{1}{v_f + w_3 v_{fg} \left(\frac{1 + \eta}{2} \right)} \quad (11)$$

Substituting for w_3 from (2), the average density can be expressed in terms of the circulation factor, n

$$\rho_{av} = \frac{1}{v_f + \frac{v_{fg}}{2n} \left(\frac{1 + \eta}{1 - \eta} \right)} \quad (12)$$

To express V_3 in terms of the average density, define

$$D \equiv \frac{\rho_{av}}{\rho_f} = \frac{v_f}{v_f + w_3 v_{fg} \frac{(1 + \eta)}{2}} \quad (13)$$

Solving for w_3 in terms of D and substituting into (7) yields

$$\gamma = 1 - \frac{2 + \left(\frac{1 + 3\eta}{1 + \eta}\right)\left(\frac{1 - D}{D}\right)}{2 + \left(\frac{3 + \eta}{1 + \eta}\right)\left(\frac{1 - D}{D}\right)} \quad (14)$$

which can be substituted into (10).

The system losses may be evaluated in terms of a head or pressure loss

$$H_{\text{loss}} = \frac{\Delta P_{\text{loss}}}{\rho} = K \frac{v^2}{2g} \quad (15)$$

For simplicity the velocity is taken as V_{max} and the density as ρ_0 . The loss coefficient, K , is defined accordingly. The coupling of (15) with the driving system is

$$\Delta P_{\text{available}} = (\rho_0 - \rho_i) h_0 = \gamma h_0 \rho_0 \quad (16)$$

Equating (15) and (16)

$$\rho_0 K \frac{V_{\text{max}}^2}{2g} = \gamma h_0 \rho_0$$

or

$$V_{\text{max}} = \sqrt{\frac{2gh_0 \gamma}{K}} \quad (17)$$

In the calculation above it is postulated that all of the steam leaving the system was generated in the form of bubbles. For smaller units in which a free surface exists and some interface evaporation can take place, the circulation and mean density can be calculated using the fraction of the steam rate generated in the form of bubbles. If μ is defined as the fraction of the total steam rate, W_T , that results from surface evaporation, the steam rate used for circulation and density calculations can be written

$$W = W_T(1 - \mu) \quad (18)$$

In the case of high steam rates steam separators will be necessary and $\mu = 0$.

A tacit assumption underlying the need for these density calculations is that reduction in mean density will set the limit on specific power at which a boiling reactor can operate. However, attention must also be directed toward the problem of steam separation in the upper region of the core. At present it is not really clear whether steam separation or decrease in mean soup density will set the upper specific power limit.

For this simplified case the complete information on circulation is contained in equations (9), (10), (14), and (17). This system of equations has been plotted in Figures 2 through 4 for the special case of a reactor 20 ft. in diameter and 20 ft. high producing 470 mw (about 2.6 KW/2). A range of values was used for each of the parameters. It should be noticed that since the specific power enters equation (10) linearly, the graphs can easily be modified to give results for other values of total power.

NOMENCLATURE

The following notation is used:

- V_o = Total volume of reactor at operating temperature and pressure but zero power.
- h_o = Height of soup at reactor operating temperature and pressure but zero power.
- q_o''' = Specific power based on V_o
- A_i = Cross sectional area of the rising region (πr_o^2)
- A_o = Cross sectional area of reactor = (πr_o^2)
- ρ_i = Mean density of the fluid in rising region
- ρ_o = Mean density of the fluid in the downcoming region
- ρ_{av} = Average density of fluid in the reactor
- v_f = Specific volume of saturated liquid
- v_g = Specific volume of saturated vapor
- v_{fg} = $v_g - v_f$
- v_{av} = $\frac{1}{\rho_{av}}$
- γ = $(1 - \frac{\rho_i}{\rho_o})$
- D = Ratio of average density to liquid density at operating conditions. $(1 - D)$ is equal to the fraction density decrease.
- w = Quality of the soup, defined by $v_x = v_f + w_x v_{fg}$

- w_3 = Top dryness fraction (quality of the soup at the top surface)
- η = Fraction of the bubbles remaining in the soup flow stream for each pass near the top surface.
- h_{fg} = Heat of vaporization (latent heat)
- g = Gravitational constant
- V = Velocity
- W = Steam rate due to vapor bubbles
- W_T = Total steam rate
- W_c = nW = circulation rate of soup
- n = Circulation factor
- ϕ = Fraction of total steam rate that results from surface evaporation.

Subscripts 1, 2, and 3 refer to positions in the reactor flow stream (see Figure 1).

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Drawing #16553

FIG 1. IDEALIZED BOILING REACTOR SYSTEM.
BAFFLES ARE INCLUDED FOR EASE OF ANALYSIS
AND MAY OR MAY NOT BE INCLUDED IN AN
ACTUAL MACHINE.

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FIG. 2 PERFORMANCE CHART FOR SQUARE RIGHT CIRCULAR CYLINDER BOILING REACTOR, DIA. 20 FT., $n=0$

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FIG. 3 PERFORMANCE CHART FOR SQUARE RIGHT CIRCULAR CYLINDER BOILING REACTOR, DIA 20 FT., $\eta = 0.2$

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FIG. 4 PERFORMANCE CHART FOR SQUARE RIGHT CIRCULAR CYLINDER BOILING REACTOR, DIA 20 FT., $\eta = 0.5$

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