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REMOVAL OF POWER FROM THE HOMOGENEOUS PLANT

Gale Young

July 13, 1943

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Abstract

Consideration is given to several ways of extracting power from the homogeneous plant. For those in which boiling occurs, estimates are given for the effect of decreased density upon the amount of material needed.

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REMOVAL OF POWER FROM THE HOMOGENEOUS PLANT

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The homogeneous plant has a number of attractive features and is being favorably considered at present in view of Fermi's recent measurement of the oxygen cross-section. One of the major questions is the removal of heat from the mixture, and the purpose of the present note is to give some consideration to this problem.

Bubble Rise

One way in which heat may be removed is by the formation of steam bubbles which rise to the surface and escape, carrying their latent heat with them, to be condensed elsewhere and returned to the tank. While the bubbles are in the liquid they decrease its density and the value of $K = \frac{k - 1}{M^2}$, and thus increase the amount of material needed to make the pile operate. We seek, therefore, a relation between the power output and the effective decrease in density.

Consider a column of liquid of height H in which bubbles form at the rate of p cm.^{3} of vapor per second per cm.^{3} of liquid and move upward at speed v. Let δ be the fraction of the volume which is occupied by bubbles. Denoting by x the distance from the bottom of the column, and supposing that $p = p_o \sin \frac{\pi x}{H}$, it is seen that

$$\delta(x) = \frac{1}{v}\int_0^x p\, dx = \frac{Hp_o}{\pi v}\left(1 - \cos\frac{\pi x}{H}\right) \qquad (1)$$

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The effective average value of δ for estimating the loss in K is gotten by weighting with p^2; thus for the entire column

$$\bar{\delta} = \frac{\int_0^H p^2 \delta \, dx}{\int_0^H p^2 \, dx} = \frac{Hp_o}{\pi v} = \frac{H \bar{p}}{2 v} \tag{2}$$

where $\bar{p} = \frac{2}{\pi} p_o$ is the average over the column. The same result is obtained if p = constant = $\bar{p}$ along the column. This result is also the ordinary average of δ over the column, as well as its value at the center.

Now consider the above to be but one of many vertical columns comprising a pile, and for convenience in the immediate calculation, suppose the horizontal cross-section of the pile to be rectangular. Then $\bar{p}$ follows a cosine cosine variation over this cross-section and the p^2 weighting gives a factor of

$$\frac{\int_0^{\pi/2} \cos^3 x \, dx}{\int_0^{\pi/2} \cos^2 x \, dx} = .85 \tag{3}$$

for each of the two directions. Thus for an average power rate $\bar{p}$ in the central column the effective average value of δ for the entire pile is

$$\Delta = (.85)^2 \bar{\delta} = .72 \frac{H \bar{p}}{2 v} \quad . \tag{4}$$

To reduce the volume occupied by bubbles, and the resultant K loss, the system may be operated under pressure. At 10 atmospheres water boils at 180°C., and at this temperature its density is reduced to .89 of the density at room temperature. The various neutron lengths in the system vary inversely as the density, and thus the volume required to

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make the pile operate varies as the inverse cube of the density, so that the mass required goes with the inverse square of the density. Thus the above temperature expansion alone increases the mass by a factor of 1.27.

Suppose we say that we will allow the mass of the pile to be doubled by the cooling provision. Then the density will be .71, the fraction of the volume occupied by water will be $\frac{.71}{.89} = .8$, and the effective fraction occupied by bubbles is .2.

According to observations by Cooper and others the rate of rise of bubbles relative to water is low, being of the order of 20 cm. per second for the size of bubbles which actually occur. Inserting in (4) the values $\Delta = .2$, $v = 20$, $H = 400$ gives $\bar{p} = 0.028$. The average value of p throughout a cylindrical pile without reflector is therefore $\frac{.028}{2.32} = 0.012$.

At 10 atmospheres the heat of vaporization of water is 2.5 cal. per $cm.^3$ of steam formed, so that in the present case the average power is 0.03 cal. per sec. per $cm.^3$ of pile. The density of moderator water is $1.1 \times .71 = .78$ grams per $cm.^3$, so that the power production is 0.038 cal. per sec. per gram of water, or 160 Kw per ton.

Thus the rate of bubble rise through stationary water is not in itself sufficient to get much power out of the pile.

Bubble Convection

It appears, however, that another mechanism may intervene to considerably increase the speed at which the bubbles move to the surface, namely currents set up in the tank water by density differences. More bubbles are produced in the central part of the tank, so that the density of the mixture is less there than it is near the walls. The lighter

material in the center is thus continually displaced upward by the heavier material flowing downward in the outer regions.

To get an idea of the convective speed V which may be developed consider that if ρ is the density of the mixture without bubbles in the outer part of the tank, then the mean density in the central part of the tank is $\rho(1 - \bar{\delta})$ where $\bar{\delta}$ is given by (2) with v replaced by V, it being supposed that V is large compared to v. Around a circuit which passes downward along the edge of the tank and upward through the center there is thus an effective pressure increment equal to $\rho\bar{\delta}gH$, and this is the work done upon unit volume of liquid in one revolution of the circuit. The kinetic energy of this amount of liquid is $\frac{1}{2}\rho V^2$, and if the liquid loses f velocity heads per revolution we obtain

$$fV^3 = \bar{g}p\, H^2 \quad . \tag{5}$$

When a bubble is produced it has potential energy by virtue of the depth beneath the surface at which it is created. Apart from a factor $\frac{\rho}{2}$ the right side of (5) is the rate at which potential energy is being thus supplied within a stream of unit cross-section extending around the entire circuit. Denote by L the length of this circuit. Then the number of revolutions made by the liquid per second is V/L, the mass of liquid in the stream described above is ρL, its kinetic energy is $\frac{1}{2}\rho LV^2$, the energy loss per revolution is $\frac{\rho}{2}\, fLV^2$, so that the energy loss per second is $\rho/2$ times the left side of (5).

Substituting V from (5) for v in (2) gives

$$\bar{\delta} = .5\, g^{-1/3}\, f^{1/3}\, \bar{p}^{2/3}\, H^{1/3} \tag{6}$$

to be compared with (2) for the non-convective case. Instead of (3) we now have the weighting factor

$$\frac{\int_0^{\pi/2} \cos^{8/3} x \, dx}{\int_0^{\pi/2} \cos^2 x \, dx} = .89 \qquad (7)$$

for each of the two horizontal directions, and the result corresponding to (4) is

$$\Delta = .4 \, g^{-1/3} \, f^{1/3} \, \bar{p}^{2/3} \, H^{1/3} \qquad (8)$$

Setting $\Delta = .2$, $H = 400$, and guessing $f = 1$ gives $\bar{p} = .55$. This is about 20 times the result in the non-convective case, or 3200 Kw per ton of water. These same values in (5) give $V = 440$ cm. per sec., which is about 22 v. The difference between the factors 20 and 22 arises from the difference in (3) and (7).

In the above it has been assumed that the bubbles are carried completely to the surface by the convective velocity V. This can hardly be the case, and it would seem that some of the bubbles will have to make the last part of their rise at the lower speed v. It is hoped that experiments will be made by blowing in air through nozzles distributed over the bottom of a tank, to study the water currents set up and the way in which the bubbles disengage at the top.

Heat Removed from Walls of Tank

Consider the tank cross-section to be divided into 2 parts of equal area, an inner core where the liquid flows upward and an outer annulus where it flows downward. The hydraulic diameter of the stream

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which touches the sides of the tank will be taken to be twice the radial thickness of this annulus. For a cylindrical tank of 220 cm. radius this hydraulic diameter is 130 cm.

The bulk of the tank water is at 180°, and let us imagine that the tank walls can be kept at 60°. Then with the above diameter and velocity a standard (Marks, p. 398) transfer formula gives h = 1/3 cal. per sec. per cm.^{2} per degree, or a flux of 40 cal. per sec. per cm.^{2} into the wall.

The total side plus bottom area of such a tank 400 cm. high is 7×10^5 cm.^{2}, giving a total heat output through the wall of 120,000 Kw. or about 2000 Kw. per ton of water.

Pump Circulation

The calculation of the previous section shows that water kept at high temperature under pressure can transfer appreciable amounts of heat to cooled surfaces at moderate velocity. By installing cold water pipes around the sides of the tank the area of the cooled surface can be increased several fold, and by forcing the tank water past these with pumps it is possible to avoid bubbles entirely. This is the line of approach favored by Wigner, who considers that radioactivity in the pumps may be less objectionable than the splattering about of active particles in violent boiling.

This amounts to a pump and heat exchanger circuit operated under pressure. The power removal possibilities are very good, and the main limitation appears to be in the direction of holdup in the pumps and piping. Chapin and Huffman propose to investigate this in some detail.

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