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EXAMPLES FOR PRESSURE DROP CALCULATIONS IN PARALLEL FLOW HELIUM COOLING*

B.T. Feld & L. Szilard

June 18, 1942

With an Addition dated August 10, 1942

ABSTRACT

Pressure drop calculations are shown for He cooled power plants ranging from 400,000 kw to 30,000 kw.

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* For constructional details of parallel flow power unit see L. Szilard -- Memoranda dated June 16, June 24, June 29.

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In this report we calculate some of the dimensions, and also the work done in circulating gas, for a number of helium cooled power plants ranging in output from 400,000 kw down to 30,000 kw. We use helium at 10 atmospheres pressure and at 1 atmosphere pressure.

I. Friction Work.

We allow the gas to have a temperature rise of 300°C at the center of the machine. At the outside of the machine where the output is considerably smaller than at the center (for a cube, the thermal neutron density at the center is four times the average thermal neutron density), we keep the pressure drop the same and achieve a constant temperature rise in the gas of 300°C by putting more than one plug in series; then the ratio of the heat transfer to the friction loss remains constant throughout the machine. And we need calculate it only at the center. We make our estimate a pessimistic one by taking the velocity and density throughout the plug corresponding to the highest temperature of the gas (500°C). The formula for the ratio of heat transfer to friction work is:

$$Ra = 3.842 \times 10^7 \frac{k}{\mu} \quad \frac{c_p \mu}{k}^{0.4} \quad \frac{\Delta H}{v^2} \quad \frac{T_{hot}}{T_{cold}}$$

which becomes for helium

$$Ra = 6 \times 10^7 \quad \frac{\Delta H}{v^2} \quad \frac{T_{hot}}{T_{cold}}$$

k = heat conductivity
μ = viscosity
c_p = specific heat at constant pressure
ΔH = Temperature difference between gas and metal = 300°C
v = velocity of gas at exit from the plug
T_{hot} = maximum temperature of gas = 500°C
T_{cold} = minimum temperature of gas = 200°C

If we take one-half the critical velocity*, or a velocity of 8.85×10^3 cm/sec, this ratio is equal to

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$$6 \times 10^7 \times \frac{300}{v^2} \times \frac{8}{5} = 368$$

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*The critical velocity is defined as the velocity at which the kinetic energy of the gas is equal to 1 percent of the heat transported by the gas.

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or a friction loss of 0.27% of the heat transported. To this must be added ½% for each exit of the hot gas. Hence, if we have two plugs in series, we lose 0.5 + 0.27 = 0.77% in the plug. To this add the friction loss in the duct and at the hot exit from the duct. If the duct is twice the critical** length, the total friction loss for the duct and exit is 0.75%, giving about 1.5% grand total, or, for 300,000 kw, a loss of 4,500 kw. By reducing the velocity in the duct and at the duct exit by a factor of $\sqrt{3}$ we reduce the duct friction loss to 0.75/3 = 0.25, giving a total loss of about 1%, or for a 300,000 kw machine, a loss of 3,000 kw.

II. Power Output.

We will now calculate the heat transfer, using helium at 10 atmospheres pressure with a velocity equal to 1/2 the critical velocity or 8.85×10^3 cm/sec.

1). The Uranium lump or plug consists of 0.6 cm diameter cylindrical sticks, 4.5 cm long, packed so as to have 3/4 of the cross section metal and ¼ empty space. We cool two such plugs in series (at the center of the pile) in order to get a temperature rise of 300°C in the gas. This corresponds to a heat production of 210 calories per double stick; and, since two sticks weigh 50.9 g, to a production of 17.3 watts/g at the center of the pile, or 4.32 watts/g average. For 40 tons of metal this gives a total production of 173,000 kw.

2). We decrease the diameter of the sticks to 0.3 cm, hydraulic radius*** 0.05 cm. This gives $h = 4.73 \times 10^{-2}$ calories/cm²/°C/sec, and requires us to cool single plugs of length 4 cm at the center of the pile. For this type of plug we have, at the center of the pile a production of 39 watts/g, or for 40 tons, a total production of 390,000 kw. The friction loss in this case is 0.25 + 0.27 = 0.52% per plug plus 0.75% per duct = 1.25% of the heat transport. This gives the frictional work equal to 4870 kw.

3). If we reduce the output to 300,000 kw (by reducing the velocity of the gas), the friction loss drops by the square of the velocity. However, the heat transfer drops more slowly. If we increase the pencil length in the plug slightly, so that ΔT remains 300°C, then, for a 300,000 kw machine the friction work equals 4870/1.69, or 2880 kw. For 1/2 the critical velocity, 300,000 kw output requires about 9 percent duct area. The friction loss in the ducts can be made smaller if we allow the duct area to go up to about 12 percent, corresponding to the new velocity of $8.85 \times 10^3 \times \frac{3}{3.9} = 6.8. \times 10^3$ cm/sec.

III. Effect of reducing pressure.

If the ducts are unchanged and we keep the same exit velocity, then, dropping the pressure by a factor of 10, reduces the output by a factor of 10.

** The critical length is that length in which the frictional loss in the tube is equal to the kinetic energy of the gas.

*** The hydraulic radius is a measure of the effective radius of the empty space for heat transfer and pressure loss. It is defined as 2 x area/periphery of the space through which the gas flows.

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The friction loss in the ducts is the same fraction of the transported heat as before. We may thus go from a 300,000 kw to a 30,000 kw machine. However, the heat transfer does not decrease with the pressure, but decreases more slowly ($p^{0.8}$) so that for a length of plug equal to 4.7 cm we can take pencils of diameter 0.5 cm and still have the gas temperature rise by 300°C. For this case the friction loss is 0.25 + 0.27 = 0.57% in the plug, and in the duct, for a velocity equal to the critical velocity divided by $2 \times \sqrt{3}$, the friction loss is 0.25%, giving a total friction loss of 0.77%. For a 30,000 kw machine this amounts to 230 kw. If we increase all velocities by a factor of 3, keeping ΔT constant, the friction loss becomes about 6240 kw, and the heat transferred (if the plugs are slightly changed) goes up by a factor of 3, giving an output of 90,000 kw.

Addition Dated August 10, 1942

Previously I calculated the dimensions of a 300,000 kw machine cooled by helium at 10 atmospheres. In this machine we used, at the center, a plug consisting of pencils 0.3 cm in diameter and 4 cm long. The gas was circulated with a velocity of 68 m/sec, or $\frac{1}{2.6}$ x critical velocity. The duct size on this machine is 12 percent of the total area. We now consider a 100,000 kw machine.

The duct size, if we keep the same velocity, goes from 12 percent to 4 percent, and if we take a 20 cm cell, this gives a cross sectional area of 16 cm^2 for each duct, and a critical length of 150 cm for this duct size. Thus, the length of our duct is about 4 critical lengths. Hence, the friction loss in the duct, including the loss upon exit, equals $\frac{4+1}{(2.6)^2}$ percent of the total heat transport--or .74 percent. In the plugs themselves the production of heat is 1/3 as much as previously considered, and so, in order to get a temperature rise of 300°C, we would put 3 plugs in series, at the center of the pile. The friction loss in the plug and on exit, is $\frac{.27 + .25}{1.69} = 0.31$ percent, so that the total loss in this machine is 0.31 + 0.74 = 1.05 percent, or 1,050 kw.

If we reduce the pressure to 7 atmospheres, we would connect two plugs in series at the center of the pile and would have to increase the total duct area to 6 percent. For this size duct the critical length is 200 cm, and so we have a loss of $\frac{3+1}{6.8} = .59$ percent in the ducts. The total loss then for this machine = 0.31 + 0.59 = 0.90 percent of the heat transported, or 900 kw.

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