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REACTORS--POWER

LOS ALAMOS SCIENTIFIC LABORATORY
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AN ESTIMATE OF THE LAPRE
POWER AND STEAM FLOW CHARACTERISTICS

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(Los Alamos Power Reactor Experiment)
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ABSTRACT

A method of numerical solution is developed for calculating the LAPRE coolant pressure drop and power output with variable coolant inlet pressure, flow rate, and reactor solution temperature. The results of a series of calculations are presented that show excessive pressure drops and sonic exit flow as the flow rate is increased and the inlet pressure is decreased. Both supercritical and subcritical coolant flow regions are investigated. Reactor power is shown to be strongly dependent on the solution temperature in the region of 700-750°F. At the design flow of 12 gal/min, excessive coolant pressure drops are encountered at inlet pressures of 2000 lb/in.² and below.

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Symbols

A = heat exchanger area
c = speed of sound
 c_p = specific heat at constant pressure
C = ρV = constant for a given flow rate
D = heat exchanger tubing diameter
f = fanning friction factor
 g_c = gravitational conversion factor
h = enthalpy
K = head loss coefficient
P = pressure
 $\dot{Q}$ = reactor heat output (power)
T = coolant temperature
 ΔT_m = log mean temperature difference
U = overall heat transfer coefficient based on outside tube area
v = specific volume
V = velocity
 $\dot{W}$ = coolant mass flow rate
x = flow path length
 ρ = density
 ϕ = pressure drop coefficient defined by Eq. (16)

Subscripts

f = saturated liquid
g = saturated vapor
i = inside
is = isentropic
o = outside
s = reactor solution

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1. INTRODUCTION

The heat exchanger for the LAPRE (Los Alamos Power Reactor Experiment) was designed for operation with supercritical water as a coolant and 2 Mw heat output. This heat exchanger configuration consists of 22 flat helical coils or pancakes in parallel. The length of tubing in each coil is 35 ft and the average total length of each tube is approximately 45 ft. The outside coil diameter is approximately 14 in. and the tubing inside diameter is 0.125 in. with 0.030 in. wall thickness. The heat exchanger is immersed in the reactor solution which is circulated from the reactor core past the heat exchanger and returned to the core at a rate of two cycles per second.

This compact arrangement coupled with a high solution temperature is unique for a power reactor and offers the possibility of producing high pressure superheated steam within the reactor that would lend itself to a highly efficient thermodynamic cycle. The factor limiting the amount of superheat that can be obtained for any given solution temperature is the pressure drop in the coolant flow through the heat exchanger, which in the extreme will lead to sonic outlet flow velocities and low outlet pressures. This report presents an analysis of the power, flow, and steam characteristics for the LAPRE with coolant flow rate, inlet pressure, and reactor solution temperature as independent variables. The method used is a numerical stepwise integration of the heat transfer and momentum equations.

2. METHOD

The momentum equation for a one-dimensional steady flow is

$$dP = -\rho V dV - \frac{4f}{D_i} \frac{1}{2} \rho V^2 dx \quad (1)$$

For a constant area flow, however, from the continuity relation

$$\rho V = C \quad (2)$$

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Making use of this relation Eq. (1) becomes

$$dP = -CdV - \frac{4fC}{D_i} \frac{1}{2} V dx \quad (3)$$

In terms of specific volume, Eq. (2) may be rewritten as

$$V = g_c v C \quad (4)$$

Making use of Eq. (4), Eq. (3) becomes

$$dP = -g_c C^2 (dv + \frac{2f}{D_i} v dx) \quad (5)$$

where v is a function of P and T and f is a function of Reynolds number. In the form of a difference equation this is

$$\Delta P = -g_c C^2 (\Delta v + \frac{2f}{D_i} v \Delta x) \quad (6)$$

The heat transfer equation for a one-dimensional steady flow of the coolant is

$$dh = \frac{U\pi D_o}{\dot{w}} (T_s - T) dx \quad (7)$$

If no change in phase occurs

$$dh = c_p dT \quad (8)$$

and Eq. (7) becomes

$$dT = \frac{U\pi D_o}{\dot{w}c_p} (T_s - T) dx \quad (9)$$

where c_p is a function of P and T , and U is essentially constant. The heat balance for the coolant and reactor solution gives the auxiliary

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relation

$$dh_s = \frac{\dot{w}}{\dot{w}_s} dh \quad (10)$$

If no phase change occurs, Eq. (10) becomes

$$dT_s = \frac{\dot{w}_c}{\dot{w}_s} \frac{c_p}{c_{p_s}} dT \quad (11)$$

In the form of difference equations Eqs. (9) and (11) become

$$\Delta T = \frac{U \pi D}{\dot{w}_c} (T_s - T) dx \quad (12)$$

$$\Delta T_s = \frac{\dot{w}_c}{\dot{w}_s} \frac{c_p}{c_{p_s}} \Delta T \quad (13)$$

The method of solution in a single phase region is to solve Eqs. (6), (12), and (13) simultaneously, taking small differences in the flow path length x as the independent variable and obtaining values of v , Δv , and c_p from tables of thermodynamic properties.¹

In general, the solution involves three coolant flow conditions - compressed liquid, two-phase, and superheated vapor. The momentum relation, Eq. (6), applies for each of these conditions, but Eqs. (12) and (16) lose significance in the two-phase region and Eqs. (7) and (10) must be used. The two-phase problem may be simplified, however, by using the integrated results of Martinelli and Nelson.²

In the compressed liquid region numerical solution of Eqs. (6), (12), and (13) is carried out until the saturated liquid condition is reached. For the two-phase flow region, two possibilities exist - either a saturated vapor exit followed by some degree of superheat, or a wet vapor exit leaving the heat exchanger. The investigation of which of these conditions applies is as follows:

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The heat exchanger area required for producing dry saturated vapor is

$$A = \frac{\dot{w}(h_{g2} - h_{f1})}{U\Delta T_m} \quad (14)$$

where $(h_{g2} - h_{f1})$ and ΔT_m are values obtained from an assumed pressure drop and the steam conditions entering the two-phase flow section. If the area determined from Eq. (14) is less than the available heat exchanger area from saturated liquid to the exit, the two-phase flow length required to produce dry, saturated steam can be found as the flow length corresponding to this area. If the area determined from Eq. (14) is greater than the available heat exchanger area, wet vapor will leave the heat exchanger with a quality approximately equal to the ratio of the available area to the area determined from Eq. (14).

The pressure drop for the two-phase flow region can be determined from integration of Eq. (6)

$$P_1 - P_2 = g_c C^2 \left[v_2 - v_{f1} + \phi \frac{2f_1}{D_1} v_{f1} (x_2 - x_1) \right] \quad (15)$$

where the subscripts 1 and 2 refer to entering and leaving the two-phase flow region, respectively, and ϕ is a coefficient obtained from Fig. 4 of reference 2 which is equal to

$$\phi = \frac{\int_{x_1}^{x_2} f v dx}{f_1 v_{f1} (x_2 - x_1)} \quad (16)$$

Since v_2 is not initially known it should be obtained from an assumed two-phase flow exit condition. The assumed value can be checked from the resulting exit pressure.

In the superheat region numerical solution of Eqs. (6), (12), and (13) is carried out to the end of the heat exchanger. The flow from the end of the heat exchanger to the end of the flow path is assumed to be

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adiabatic. For this length Eq. (6) is integrated numerically with the enthalpy of the fluid held constant.

The entering and leaving losses can be obtained from the relation

$$\Delta P = K g_c C^2 v \quad (17)$$

where K is the head loss coefficient for a sudden enlargement or contraction.

The reactor power in megawatts is found after the coolant exit pressure and temperature have been determined from the following relation

$$\dot{Q} = \frac{\dot{w}(h_2 - h_1)}{3.414(10)^6} \quad (18)$$

where the subscripts 1 and 2 refer to coolant conditions entering and leaving the reactor, respectively, and $\dot{w}$ is the coolant flow rate in lb/hr.

3. LIMITING FLOW

The velocity of the coolant increases in passing through the heat exchanger as a result of the increase in specific volume caused by friction, heat addition, and the accompanying pressure drop. When the local velocity increases to a value where it is equal to the speed of propagation of weak pressure waves within the medium, the so-called "sonic" condition exists and the velocity cannot increase further in a constant area flow. The sonic condition, if present, will always exist at the downstream end of a constant area flow and in effect acts as a throttle on the flow.

For a given reactor solution temperature and heat transfer area, reduction of the coolant flow and coolant inlet pressure will ultimately lead to a limiting sonic exit condition. Therefore, the heat exchanger pressure drop that results in sonic exit conditions must be considered

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as the maximum pressure drop for a given set of coolant inlet conditions.

The speed of sound in any homogeneous medium is given by³

$$c = \frac{\sqrt{\left(\frac{\partial P}{\partial v}\right)_{is}}}{\rho} \quad (19)$$

Eq. (19) is equivalent to

$$c = v \sqrt{g_c \left(\frac{\partial P}{\partial v}\right)_{is}} \quad (20)$$

If it is assumed that the two-phase flow is homogeneous, Eq. (20) can be used for the two-phase flow region, as well as for the superheat region, with values of the sonic speed determined from tables of thermodynamic properties.² Figures 1 and 2 show values of sonic speed for both two-phase flow and superheat regions of interest to the LAPRE. In carrying out the numerical pressure drop solution, when the flow velocity as calculated by Eq. (4) is equal to the speed of sound as shown in Figs. 1 or 2, the limiting pressure drop for the given inlet conditions has been reached.

4. RESULTS

A series of calculations was made to determine the LAPRE power and pressure drop characteristics over a rather wide range of coolant flow rates, inlet pressures, and reactor solution temperatures using the method previously described. These results are shown in several performance charts, Figs. 3-13 inclusive.

The overall heat transfer coefficient was found to be essentially constant at a value of 1000 Btu/hr-ft²-°F from a number of calculations for the flow range investigated. The variation of the inside convection coefficient did not have a pronounced effect on the overall coefficient since the fixed thermal resistances of the tube walls and solution-side

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convection were larger than that of the coolant-side convection resistance.

The coolant specific heat values as a function of pressure and temperature were taken from Figs. 4, 6, and 7 of reference 1.

The friction factor f was taken from Fig. 51 of reference 4, corrected for tube curvature by the method of reference 5. It was found that two values of friction factor would cover the normal range of Reynolds numbers encountered. These were $f = 0.0035$ for the wet vapor and superheat regions and $f = 0.005$ for the compressed liquid region.

Other constants used in the calculations were

Tube cross section area = 0.00187 ft^2

Tube inside diameter = 0.125 in.

Tube outside diameter = 0.185 in.

Tube length in heat exchanger = 35 ft

Tube length outside heat exchanger = 5 ft

Contraction and expansion coefficient, $K = 1$

Reactor solution flow rate = 1300 gal/min

The results of typical solutions for supercritical and subcritical operation are shown in Figs. 3 and 4 where coolant temperature, pressure, and velocity are plotted vs heat exchanger length for a flow rate of $12\frac{1}{4}$ gal/min. The inlet pressure for Fig. 3 is 3500 lb/in^2 and for Fig. 4 is 2500 lb/in^2 . It is interesting to note in Fig. 3 that the rate of coolant temperature increase is depressed in the region of the critical temperature similar to that of the two-phase flow region in Fig. 4. The reason for this flat temperature region in Fig. 3 is the high specific heat of the coolant at these temperatures and pressures. There is also a large increase in specific volume in this region as evidenced by the rapid increase in velocity in Fig. 3.

Figures 5-7 show outlet pressure vs inlet pressure for reactor solution temperatures of 850, 750, and 650°F with various flow rates. As shown in these figures excessive pressure drops and sonic exit velocities are reached for all flows with sufficiently low inlet pressures.

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Figures 8-10 show reactor heat output vs inlet pressure for reactor solution temperatures of 850, 750, and 650°F with various flow rates. In all cases the power increases with increasing flow rate. For the 750°F solution temperature a peculiar inflection of the power curve is noted for the 20 gal/min flow rate. The reason for this irregularity is that the specific heat of supercritical water varies considerably between 4000 lb/in.² and 3200 lb/in.² and the heat exchanger is much more effective at 3200 lb/in.². The sharp drop near 3000 lb/in.² is the result of entering the two-phase flow region where the coolant leaves the heat exchanger at or near the saturated vapor condition where the outlet temperature and enthalpy are fixed by the phase-change.

The flat curves in Fig. 10 represent compressed liquid outlet conditions. The sharp rise in the 12-1/4 gal/min curve near 2000 lb/in.² is the result of entering the two-phase flow region with wet vapor leaving the reactor. Sonic velocity is reached in the two-phase region at 20 gal/min flow rate before any appreciable power increase occurs.

Figure 11 shows the dependence of outlet temperature and pressure drop on the coolant flow rate for a reactor solution temperature of 850°F with various inlet pressures. As shown in this figure the pressure drop increases rapidly with increasing flow rate. The outlet temperature starts to drop rapidly after a certain flow rate is exceeded. The temperature drop is greatest for 3000 lb/in.² inlet pressure at all flow rates.

Figures 12 and 13 show the dependence of outlet temperature, outlet pressure and power on reactor solution temperature with various coolant inlet pressures at 12-1/4 and 20 gal/min coolant flow rate, respectively. As shown in these figures reactor power increases rapidly with increasing solution temperature in the region of 700-750°F solution temperature. The figures also show the coolant outlet temperature to decrease rapidly with decreasing inlet pressure and increasing flow rate in the wet vapor region.

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5. CONCLUSION

The performance charts of Figs. 3-13 show an estimate of the LAPRE power and flow characteristics. Uncertainties in the physical properties of the reactor solution may cause the results presented to be quantitatively in error. It is believed, however, that the general trends and order of magnitude of the effects are realistic. The charts show that it is desirable to operate the LAPRE at or above 750°F reactor solution temperature in order to obtain 2 Mw of heat output from the heat exchanger and that the probable maximum output is 3.5 Mw at the coolant pump capacity of 24 gal/min with 850°F solution temperature. It also appears to be desirable to operate with coolant inlet pressures in excess of 2000 lb/in.² at the design flow rate of 12 gal/min to avoid excessive pressure drop in the heat exchanger coolant flow for 2 Mw output.

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Fig. 1. Speed of sound in two-phase region.

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Fig. 2. Speed of sound in superheat region.

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Fig. 3. Results of typical solution for supercritical operation.

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Fig. 4. Results of typical solution for subcritical operation.

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Fig. 5. Outlet pressure vs inlet pressure for 850°F solution temperature.

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Fig. 6. Outlet pressure vs inlet pressure for 750°F solution temperature.

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Fig. 7. Outlet pressure vs inlet pressure for 650°F solution temperature.

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Fig. 8. Power vs inlet pressure for 850°F solution temperature.

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Fig. 9. Power vs inlet pressure for 750°F solution temperature.

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Fig. 10. Power vs inlet pressure for 650°F solution temperature.

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Fig. 11. Outlet pressure and temperature vs coolant flow rate, 850°F solution temperature.

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Fig. 12. Power and steam outlet conditions vs solution temperature, 12 $\frac{1}{4}$ gal/min flow rate.

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Fig. 13. Power and steam outlet conditions vs solution temperature, 20 gal/min flow rate.

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