MEASUREMENT OF STEAM-WATER FLOWS FOR THE TOTAL FLOW TURBINE

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Hot water geothermal fields discharge steam-water mixtures, which have proved difficult to measure compared with the dry steam from fields like The Geysers and Larderello.

With the development of the lip pressure method, however (James 1962), an accurate method was derived which could measure the flow when a geothermal well discharges to the atmosphere at sonic velocity. Fortunately most discharges from wells do in fact attain such velocities, and as long as the enthalpy of the mixture is known, the flow can be determined. Where the enthalpy is unknown some other measurement has also to be made in order to solve the two factors of flow and enthalpy. By discharging the whole mixture into a silencer, the water portion can be estimated by means of a weir, and this provides the second measurement (described in James 1966) required to solve both unknowns.

The relationship at the location of sonic flow has been empirically determined as follows:

$$\frac{G\ h_0^{1.102}}{P_c^{0.96}} = 11\ 400 \qquad (1)$$

where G is the mass-velocity in $lb/ft^2 s$
h_0 is enthalpy in Btu/lb
P_c is critical discharge pressure (lip pressure) in psia.

To convert units of G into units of W lb/h

$$W = G \left(\frac{\pi}{4}\right)\left(\frac{d}{12}\right)^2 60^2$$

where d is the inside diameter of the discharge pipe in inches.

The Total Flow Turbine

This approach entails the discharge of the whole unseparated steam-water mixture from the geothermal well through nozzles onto the wheel of a specially designed impulse turbine and thence into a separating condenser. A development program to solve the various problems involved is underway at the Lawrence Livermo: Laboratory, University of California. With the more conventional approach of separating the steam from the water and passing it into a steam turbine, flows can be measured by means of orfice plate meters as described by the ASME (1959), although there is some difficulty with the hot water flow as this is exactly at the boiling point and flash steam can appear in the line and falsify the flow estimate. Worse still, even a small quantity of carryover steam from the separator can wildly distort the readings and result in large errors (James 1975). Such steam carryover is by no means uncommon; in fact, there is some indication that effective separation depends to an extent on small steam loss into the water phase due to vortexing within the vessel. The measurement problem can be overcome by external cooling of the water line or increasing the pressure head by raising the level of the water within the separator.

How then can we measure the flow of a steam-water mixture to a total flow turbine? This can be accomplished by means of the nozzle which discharges onto the wheel, so long as the mixture enthalpy is known. As the LLL program is specifically directed to exploiting the large geothermal resources of the Salton Sea, the enthalpies of the wells there appear to be fairly stable and draw on hot water with temperatures of about 300°C (A.L. Austin and others 1977).

A convergent-divergent nozzle is the means by which the heat and pressure energy of the fluid is converted to kinetic energy for directing onto the turbine blades. Study of such nozzles for the flow of superheated and saturated steam has been well documented in the literature and in textbooks on fluid flow and thermodynamics (Streeter 1966).

Sonic velocity is attained at the throat of such nozzles and the ratio between the throat pressure and the up-stream manifold pressure has been experimentally determined for steam. For superheated steam, the ratio is about 0.55 and for saturated (moist) steam is about 0.58 (Potter 1958). Unpublished tests by the author on steam-water flows through steam nozzles gave the same ratio of 0.59 as for saturated steam. This is confirmed by the tests undertaken by LLL in their report on the program status (1977).

Hence, it is clear that so long as the mixture enthalpy is known, together with the nozzle throat pressure, then the formula for the lip pressure given as equation (1) may be employed to determine the flow, with P_c taken as the throat pressure and d being the throat diameter. However, it would be unnecessary to attach a pressure tapping directly to the throat of the nozzle, as the manifold pressure just up-stream of the throat would be rather precisely controlled by a turbine governor valve and using the ratio of 0.58, the pressure at the throat where critical flow occurs (sonic velocity) can be estimated.

Let suffix 0 represent up-stream stagnation conditions within the manifold and suffix t represent throat conditions where sonic flow occurs.

From equation (1),

$$\frac{G_t \; h_0^{1.102}}{P_t^{0.96}} = 11\ 400$$

and $P_t = 0.58\ P_0$

while $W = G_t \left(\frac{\pi}{4}\right)\left(\frac{d_t}{12}\right)^2 3600 = 19.6\ d_t^{\ 2}\ G_t$

$$\text{so } G_t = 11\ 400\ \frac{P_t^{\ 0.96}}{h_o^{\ 1.102}} = 11\ 400\ \frac{0.58^{0.96}\ P_o^{\ 0.96}}{h_o^{\ 1.102}}$$

$$= 6758\ \frac{P_o^{\ 0.96}}{h_o^{\ 1.102}}$$

$$W = 19.6\ d_t^{\ 2}\ \frac{6758\ P_o^{\ 0.96}}{h_o^{\ 1.102}} = 132\ 450\ \frac{d_t^{\ 2}\ P_o^{\ 0.96}}{h_o^{\ 1.102}} \qquad (2)$$

As it is more usual to give flow through nozzles in lb/s

$$w\ \text{lb/s} = 36.8\ \frac{d_t^{\ 2}\ P_o^{\ 0.96}}{h_o^{\ 1.102}} \qquad (3)$$

Illustrative Example

Taking the LLL report (1977) on a nozzle test from their Table 3-2, we have P_o = 367 psia, h_o - 526 Btu/lb

Nozzle throat diameter calculated from the throat area of $6.87\ (10)^{-4}\ ft^2$ · given on their Figure 3-16. d_t = 0.35 inches diameter.

From equation (3) above:

$$W = 36.8\ \frac{d_t^{\ 2}\ P_o^{\ 0.96}}{h_o^{\ 1.102}}$$

$$= 36.8\ \frac{(0.35)^2\ (367)^{0.96}}{526^{1.102}} = 1.31\ \text{lb/s}$$

This equals the flow-rate given for their test conditions, so agreement looks very good.

Saturated Water Flow Through Nozzles

In observing steam-water flow through nozzles we assume that there is steam present within the up-stream manifold with a volume exceeding that of the associated water. In the example above, for instance, the LLL test gave a manifold dryness fraction of 14% quality and such steam is necessary to give a ratio of 0.58 for $\frac{P_t}{P_o}$ and for sonic conditions to prevail at the throat.

Where an all-water state occurs in the manifold, even if it is exactly at the boiling point for the liquid pressure, the throat pressure has been found from tests at Wairakei to be greater than 0.9 P_o. It appears that the time duration is so short when the fluid passes from the manifold to the throat that none is available for bubble formation. Hence, only an all-water condition exists at the throat. This invalidates the conditions for sonic flow and thus the relationship of equation (3) does not hold. It is also difficult to sustain stable flow as the flash front within the nozzle constantly "hunts" from the throat to some distance downstream within the convergent part, leading to pulsations of pressure and presumably cyclic flow variation. This might create problems when applied to a turbine as resonance effects might follow.

Therefore it may be necessary to execute some degree of throttling upstream of the nozzle manifold in order to permit some steam to exist within this chamber and thereby stabilize the flow; perhaps this will allow sonic flow at the nozzle throat. If this proves correct, measurement of the discharge may again be possible as for genuine steam-water flow described above.

Field Test Conditions

This example was based on values taken from a laboratory test using clean water and negligible non-condensible gas. Future tests in the Salton Sea geothermal field will involve steam-water mixtures where the water contains up to 30% wt of dissolved solids, while the steam phase may contain substantial quantities of gas, mainly carbon dioxide (perhaps up to 10% wt). Correction factors will have to be estimated to allow for these significant departures from the steam-water employed in laboratory experiments. Grens (1975) has calculated the effect of intense brines on dryness fraction and enthalpies of such mixtures. Also the quantity of gas can be used to compute the partial gas pressure at the nozzle throat which, together with the vapor pressure of the steam, combines to give the total throat pressure.

Obviously some field tests will be required to ascertain the effectiveness of these "corrections" on true flow-rates.

CONCLUSIONS

With the hoped-for commercial success of the total energy turbine in the near future, it will be necessary to have a means of measuring the steam-water flow into the machine. As long as the enthalpy of the flowing fluid is known, there should be no intrinsic difficulty in obtaining this, as the nozzles themselves act as metering devices due to the phenomena of sonic velocity at the throat. High gas concentrations in the steam phase, together with high chemical content in the water phase, require the use of "corrections" which will have to be determined from field tests to confirm theory. Clean steam-water mixtures appear to present no difficulties.

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