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DISCHARGING THROUGH AN ORIFICE DETERMINES STEAM-WATER ENTHALPY

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ABSTRACT

A wide range of steam-water mixtures was discharged to the atmosphere through a 10.7 mm diameter orifice which was sharp-edged with a minuscule throat pressure tapping. The ratio of throat pressure to up-steam pressure was found sensitive to dryness fraction over the whole range studied from 0.03 to 1.0.

The technique (employing large orifices) has the potential of identifying the unknown enthalpy of geothermal wells discharging large flows.

Contrariwise, a nozzle (rounded entry orifice) was found remarkably insensitive over most of the dryness range and hence is useless for such determinations; however, it can be used to measure the flow-rate when enthalpy is known.

INTRODUCTION

What is the minimum wellhead equipment which will permit the evaluation of a steam-water discharge into its components of flow, enthalpy and (say) electric power potential? According to James (1970), an atmospheric separator is sufficient to accomplish this when lip pressure and reject water flow are measured. However, many wells - and especially isolated ones - are first discharged with no introduced equipment except the necessary discharge pipe vertically erected and bolted to the wellhead valve. Under this condition, it is still possible to estimate the power potential, James (1975), with an accuracy sufficiently good for most practical purposes. It is even possible to sometimes get an accurate figure for the enthalpy of flow from hot water reservoirs when the well is discharging under conditions of the highest possible wellhead pressure, James (1980a), and the lip pressure then employed to evaluate the other parameters.

The importance of enthalpy is such that it would be of considerable value if a technique could be developed to measure it directly from the discharge. An attempt to do just this was undertaken by James and others (1980b) who compared different approaches so as to find the most promising for further development. The methods tested included laser beam, hot-wire anemometer, pitot tube and digital thermometer.

The best tested proved to be a hydraulic analogue of the hot-wire anemometer, but had the disadvantage of interposing a small diameter pipe across the discharge near the sonic location which would result in its rapid erosion. It would be of advantage, therefore, to evolve an approach which avoided such interpositions especially when used on initial discharges which often eject rock fragments as well as steam-water mixtures at speeds up to 0.5 km/s.

To accomplish this, it was decided to study the effect of discharging steam-water mixtures through a nozzle in the expectation that the ratio of throat pressure to up-stream pressure would be related to the flowing enthalpy. (Up-stream pressure in this context is that of a vessel to which the nozzle is attached and whose dimensions are large compared with that of the nozzle's throat.) Experiments in the past have determined that this ratio is about 0.55 for superheated steam and 0.58 for moist steam, Potter (1959), hence it was thought likely that the ratio would increase further with steam wetness and provide a method of estimating the enthalpy of flow.

EXPERIMENTAL FACILITY

A geothermal well was used as the source of the steam and hot water which were individually piped to a small pressure vessel of 100 mm dia. The non-condensible gas content of the steam at the wellhead separator pressure of 10.75 bar was 2.5 wt% and steam and water enthalpies were 2781 and 777 kJ/kg respectively, at the same temperature of 183°C. By employing control and metering valves for the separate phases, any desired proportion of steam and water could be mixed in the vessel and then discharged through the nozzle whose throat diameter was 10.7 mm. Because of the pulsations inherent in the flow of steam-water mixtures, glycerine-damped pressure gauges were mandatory with needle valves between the gauges and the pressure locations; these were necessary to reduce the amplitude of the needle swing to readable values. The dimensions of the nozzle are shown on Figure 1 with P_m as the manifold vessel pressure, and P_c as a critical throat pressure, in consistent units. Critical flow is a term generally used about compressible fluids which have attained the speed of sound (Mach 1) and which for steam is about 500 m/s. Because of the large difference in cross sectional area of the manifold to the throat together with the former's higher pressure, the velocity within the manifold is only 3.3 m/s for critical flow of steam through the nozzle. Therefore, the pressure-drop along the manifold is negligible and the location of the manifold pressure tapping relatively unimportant.

In the case of steam-water mixtures, sonic velocity is significantly less than that of dry steam and the steam content of the manifold fluid much less than that at the throat being at a higher pressure and identical stagnation enthalpy, hence the velocity in the manifold is much less than that of the comparable steam flow. This confirms the relative unimportance of manifold pressure tapping location compared with the geometry of the throat pressure tapping which as seen on Figure 1 is given with some precision as it was suspected that its location would be critical in both senses of the word. The same argument applies to the orifice of later tests which is also shown on Figure 1.

NOZZLE TEST RESULTS

These are shown plotted on Figure 2 and within the limits of accuracy expected of field testing, agree well with the condition of dry steam flow giving a ratio at $x_m = 1.0$ of about 0.56 compared with published values of 0.58. There is not much change in this ratio even when the dryness has decreased to a half at $x_m = 0.5$ and even over most of the remaining dryness range the curve is fairly shallow and makes the nozzle an unexciting prospect for determining the dryness fraction within the manifold (and therefore the enthalpy of flow).

A cheerful aspect of these results however is that the nozzle can be used as a flow metering device if the dryness fraction at the manifold pressure is in fact known and it is wished to determine the flow-rate to the atmosphere or into a low-pressure vessel (pressure less than the nozzle throat pressure). In this case, the shallowness of the experimental curve is an advantage in estimating the value of P_c which can then be used in the formula given by James (1966) in the metric form and for a 1.0 mm tapping.

$$w = 1.6234 \frac{d_c^2 \; P_c^{0.96}}{h_o^{1.102}} \qquad (1)$$

w Flow of mixture, kg/s
d_c Nozzle diameter, mm
P_c Throat pressure, bar
h_o Specific stagnation enthalpy (enthalpy of steam or steam-water mixture in manifold at pressure P_m and dryness fraction x_m), kJ/kg.

This result should have widespread use in permitting calculation of the flow of steam-water mixtures through nozzles from vessels of known pressure and enthalpy (or dryness) in a similar manner to the classical method for dry or superheated steam, Potter (1959).

Although this was an unexpected bonus, it merely compensated for the failure to develop a method of directly determining enthalpy in which the nozzle had appeared the most promising candidate. At this point therefore, other devices had to be considered.

ORIFICE TEST RESULTS

Short tubes were tried and these appeared to have merit but only if very short. It was finally decided to take the shortest possible tube and hence the final design was in effect a sharp-edged orifice being a plate of 2 mm thickness with a pressure tapping hole of 1.0 mm diameter drilled within it as shown in Figure 1 where the orifice diameter was 10.7 mm as for the nozzle throat.

The experimental results are shown on Figure 2 together with that of the nozzle and it is clear that the pressure ratio is now much more sensitive to dryness fraction over the whole range tested, namely 0.03 to 1.0 and can be used to determine it with far greater precision.

Small wetnesses in steam are notoriously difficult to estimate, but the orifice appears to have the capability of evaluating these as easily as for higher wetnesses, as the curve is of constant slope over a dryness range of 0.1 to 1.0 (wetness 0.9 to zero).

Although as has been mentioned, the throat pressure of the nozzle can be used to calculate flows from vessels at known enthalpies and pressures, it does not appear that the orifice pressure P_c can be so employed as it is not at all certain if it functions under conditions of critical flow at Mach 1. At a given flow and enthalpy, it gives a much lower ratio; for dry steam the nozzle gives 0.56 whereas the orifice gives 0.16 for example. Perhaps the true critical pressure exists in the orifice a little upsteam of the pressure within the plate. The present test series has not studied these interesting aspects as they are perhaps irrelevant to the purposes of this investigation which was to discover the simplest promising technique (a strictly ad hoc approach or perhaps even a minimalist one).

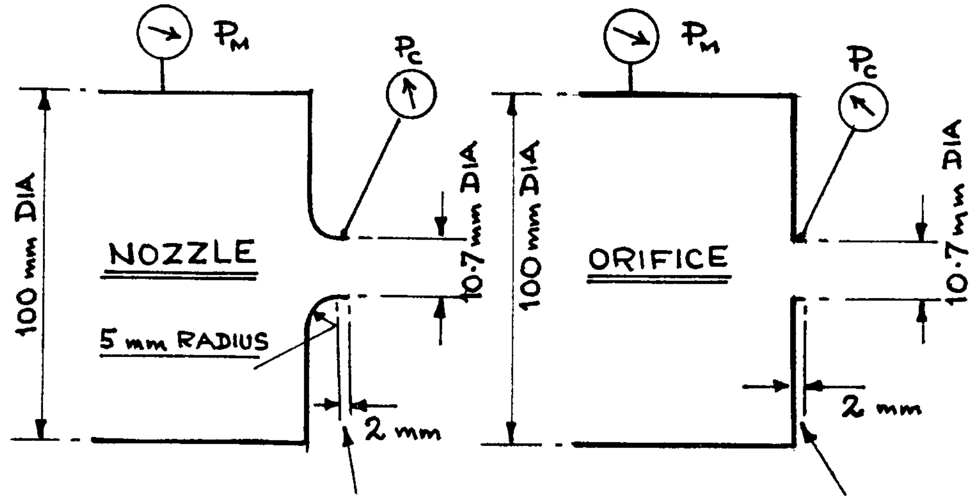
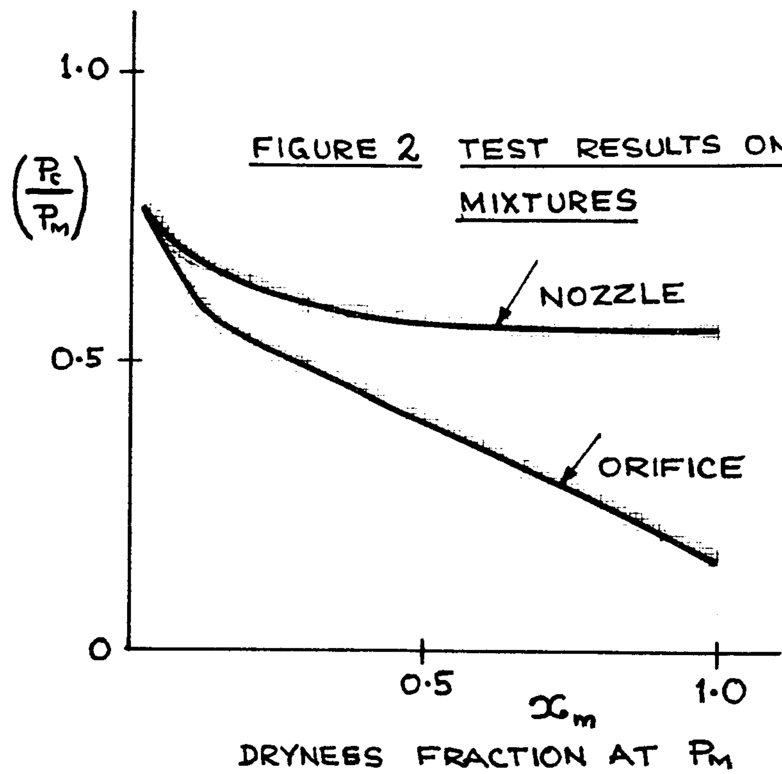


FIGURE 1 GEOMETRIC SHAPE OF NOZZLE AND ORIFICE

FIGURE 2 TEST RESULTS ON STEAM-WATER MIXTURES



From the viewpoint of geothermal wells, the orifice approach is not an ideal solution to the problem posed, as even for a relatively small output well, an orifice of 100 mm diameter would be required discharging from a manifold vessel of 1.0 m diameter and at least 1.0 m long; for powerful wells these dimensions would have to be doubled giving a vessel of not inconsiderable weight to be bolted to the wellhead. In practice, the orifice plate would have to be of stainless steel as although erosion could not be detected over weeks of testing, it is anticipated that standby corrosion would deteriorate the thin plate and its pressure tapping geometry. (Erosion is severe, however of objects which penetrate the flow for a significant period of time.)

If tests on large sized orifices confirm these results, then the example following may be typical of values obtained on actual wells which discharge steam-water mixtures of high enthalpy.

ILLUSTRATIVE EXAMPLE

Discharge through a 1.0 m diameter manifold and 100 mm diameter orifice gives a manifold pressure of 15 bar and orifice throat pressure of 6 bar. Estimate the enthalpy of discharge, and flow-rate.

$$\frac{P_c}{P_m} = \frac{6}{15} = 0.4$$

From Figure 2 for the orifice, $x_m = 0.485$

$$\text{Enthalpy } h_o = h_f + x_m h_{fg} \qquad (2)$$

$$h_o = 844.89 + (0.485)\ 1947.3 = 1789.3 \text{ kJ/kg}$$

where 844.89 and 1947.3 are the sensible and latent heats of steam at 15 bar from steam tables, Keenan and others (1969).

For a nozzle of throat diameter 100 mm and identical manifold pressure and dryness fraction of $x_m = 0.485$,

$$\frac{P_c}{P_m} = \frac{P_c}{15} = 0.57$$

Hence nozzle $P_c = 15\ (0.57) = 8.55$ bar
From equation (1)

$$w = 1.6234 \frac{(100)^2\ (8.55)^{0.96}}{(1789.3)^{1.102}} = \begin{matrix} 33.16 \text{ kg/s} \\ (119.38 \text{ t/h}) \end{matrix}$$

A good high-enthalpy well of standard casing can possibly discharge up to 400 tonnes/hour, hence an orifice of 200 mm diameter would be required to cover a full range of outputs.

CONCLUSIONS

For discharging mixtures at known enthalpy to the atmosphere, the nozzle appears to be a useful instrument to determine flow-rate but is relatively insensitive to enthalpy. However, the orifice has reverse characteristics in that it is sensitive to enthalpy and can be used to evaluate this important parameter while incapable of estimating flow-rate. The overall accuracy of the orifice as a geothermal field device can probably only be evaluated in the last analysis by field tests on fully sized diameters of 100 and 200 mm. However, the results on even the small instrument reported here show no inherent problems are anticipated.

The orifice may also have wide application in its ability to determine small wetnesses carried by nearly dry steam in conventional steam engineering.

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