STUDY OF SONIC STEAM-WATER MIXTURES BY LASER BEAM, HOT-WIRE ANEMOMETER, PITOT TUBE AND DIGITAL THERMOMETER

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ABSTRACT

The purpose of this work is to determine the enthalpy and flow (and hence power) of geothermal steam-water mixtures discharging to the atmosphere from wells under test, using the simplest of portable equipment. Experimental apparatus consisted of a 10.8 mm inside diameter pipe discharging such mixtures at sonic velocity. The lip and jet efflux was explored by laser beam, hot-wire anemometer, pitot tube and probe of digital thermometer and correlations attempted with enthalpy for given values of lip pressure. The characteristic shape of the jet was also found related to enthalpy. Best results were from a single-tube heat exchanger crossing the jet as a hydraulic analog of the hot-wire anemometer, which estimated enthalpy to ±3%. Enthalpies synthesised were from 777 Kj/kg to that of dry steam at 2782 Kj/kg at lip pressures up to 3 bars, the limit of the equipment.

INTRODUCTION

Geothermal wells under test discharge to the atmosphere either vertically as in Figure 1 or horizontally. There is need of a method which can rapidly evaluate enthalpy within +3% without the expense of separating phases or employing huge calorimeters. The lip pressure would then be used to determine flow-rate, James (1980). A model well was used in which a 10.8 mm diameter pipe passed synthetic steam-water mixtures to the atmosphere from a manifold into which metered quantities of steam and hot water were transmitted from Ohaaki borehole number 22. Preliminary experiments were undertaken to rough-in the general picture and estimate which if any of a number of approaches showed promise. Procedure was simple in that mixtures of different enthalpies were discharged at a fixed lip pressure of 2 bars. At the lip pressure plane and down-stream of the outlet face, the jet was explored by (a) digital thermometer, (b) pitot tube, (c) hot-wire anemometer, and (d) laser beam. Also (e) the contour of the jet efflux was studied with a view to relating it to enthalpy. Angle theta of Figure 1 was also measured but found to be constant at 15° for all enthalpy values and hence rejected from the programme.

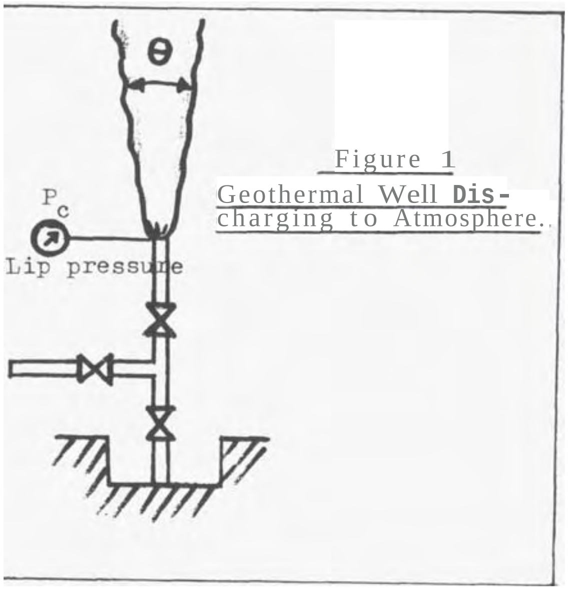

Figure 1
Geothermal Well Discharging to Atmosphere.

Steam-water mixtures travel at the speed of sound in the plane of the lip pressure and theory is complex due to variation across the jet of velocity, wetness ratio and 'slip' between the phases. Hence theory was not pursued in this work, where support calculations were based on the simplistic assumption of homogeneous and equilibrium conditions. However, part of the problem with theory is that little is known about the characteristic of sonic steam-water flow and results of the present work may assist in a greater understanding, independant of the main aim.

(a) Temperature of Jet Efflux

With lip pressure of 2 bars, enthalpies from very wet at 777 Kj/kg up to dry steam at 2782 Kj/kg were synthesised and discharged to the atmosphere with respective flows of 841 to 260 kg/h. Down-stream temperature measurements were made with a 'Comark' digital thermometer and are given in Figure 2 together with values at the lip pressure tapping, 1.6 mm upstream from the pipe outlet face. No significant temperature differences could be found in the free jet attributable to variation in discharge enthalpy and it is concluded that taking the temperature of the centre of the jet at various locations cannot define enthalpy. At the lip pressure, the temperature of mixtures agreed with the expected value from steam tables of about 120°C (saturated value at 2 bars). This confirms that temperature-pressure equilibrium exists for mixtures at the speed of sound. However, when passing dry steam, the lip pressure value of 113°C indicated that the rapid expansion near the pipe outlet in the absence of a water phase has lead to a metastable state with a depressed value. Another phenomenon noticed only with the dry steam discharge, was the presence of faint shock waves observed just down-stream of the outlet face indicating that sonic - and perhaps supersonic-flow was indeed taking place. Because of the opaqueness of the steam-water jets, they were not observable (if indeed they exist) under conditions of low-enthalpy mixtures. The steady decline in temperature along the free jet is probably due to diffusion of air into the fluid which may also explain the angle of expansion of about 15°. A test of this hypothesis would be to surround the jet by a cone to exclude air before measuring down-stream temperatures. Somewhat surprising is the fact that jet heat drops to around blood temperature in a mere 100 pipe diameters of free flow to the atmosphere - most people would expect it to be hotter much further.

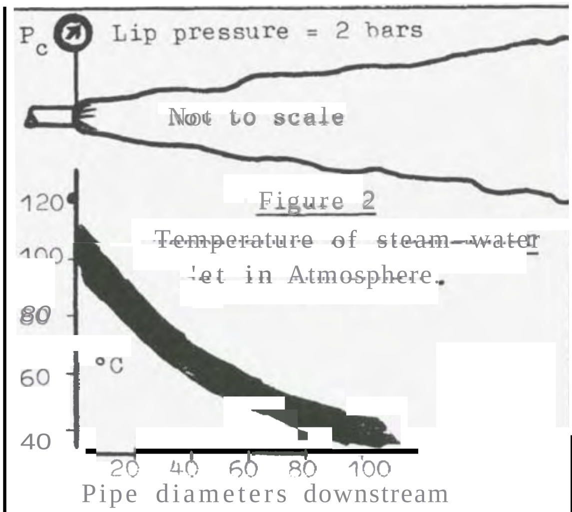

Figure 2
Temperature of steam-water Jet in Atmosphere.

(b) Pitot Tube Impact

A small stainless steel sharp-edged pitot tube of inside diameter 1.6 mm was centrally located in the jet efflux just within the test pipe so that its face was at the lip pressure plane. The other end of the tube was connected to a pressure gauge so that its reading could be taken while mixtures of steam-water discharge with sonic velocity at a lip pressure of 2 bars. Results are shown on Figure 3 where it is evident that very little change occurs over the range of enthalpies up to dry steam. This confirms unpublished experiments conducted by one of the authors (James) at Wairakei some years ago in which a spring-loaded plate was inserted in similar flows at fixed lip pressure, and little variation in impact observed. Evidently, this technique is not useful for determining enthalpy of jets especially as particular interest lies between 1000 and 1400 Kj/kg (most productive geothermal wells derive their flow from reservoir water at associated temperatures of 232° to 310°C). The results are of interest however, in showing that discharging steam-water mixtures (at a given nozzle throat pressure) onto turbine blades, should generate roughly the same power whatever the fluid enthalpy; this is of importance to designers of the total flow turbine.

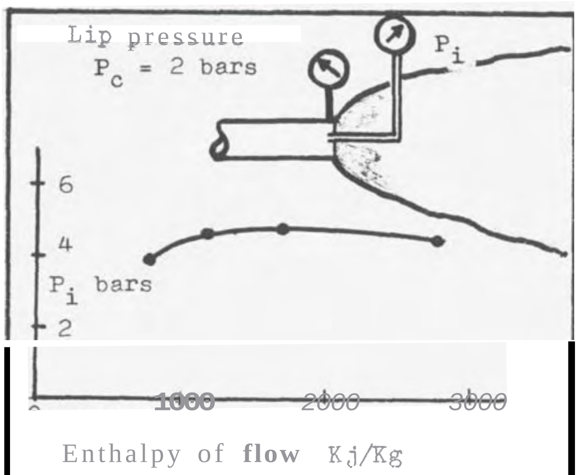

Figure 3 Impact pressure on Pitot at Lip pressure plane

(c) Hot-wire Anemometer (H.W.A.)

Before proceeding with a true H.W.A., tests were conducted on a hydraulic analog. This consisted of a stainless steel tube (3.2 mm o.d., 1.6 mm i.d.) which was inserted vertically across the jet downstream of the test pipe outlet face and at a distance of 1 diameter (10.8 mm). Distilled water at 26°C and at 0.55 ml/s flowed into the tube at the top and out at the bottom, becoming heated in transit by the flowing steam-water mixture. The outlet temperature is plotted on Figure 4 where it is seen to be dependant on the enthalpy of discharge which was varied at a constant lip pressure of 2 bars. Clearly, this simple initial result already demonstrates that enthalpy can be determined to the target accuracy of +3% and with easily understood apparatus which is widely available. When we attempted to improve on this model by employing a true H.W.A. we ran into many difficulties with passing high currents of 20 amps through tungsten filament wire (0.1 mm diameter) placed in the high speed jets. This wire crossed the flow at the plane of lip pressure and had an electric resistance of only 0.1 ohm over its length of 10.8 mm which presented problems in the contact resistances at the wire ends. Results obtained with the limited power that could be delivered to the wire show that the H.W.A. was unable to evaluate the enthalpy of flow, and hence was abandoned as a practical proposition.

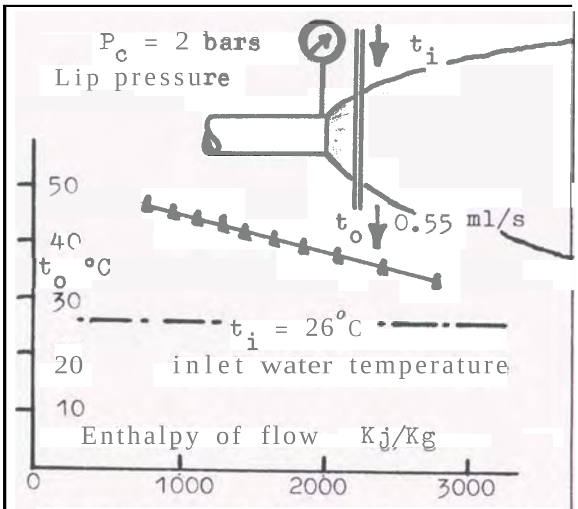

Figure 4 Hydraulic analog of H.W.A.

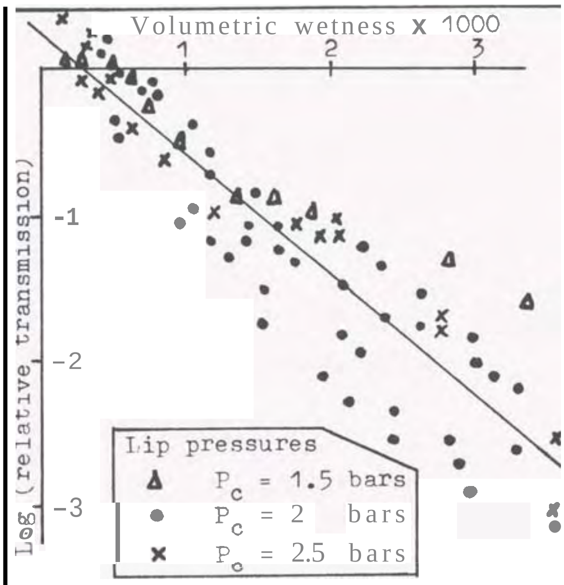

Figure 5 Ream transmission versus Steam-Water volumetric wetness.

(d) Laser Beam Method

The original idea was to pass an ordinary light beam through the jet to a photo-electric cell and measure the intensity penetrating various wetnesses; this is similar to the well-known method for metering the density of smoke in factory chimneys for pollution control.

Advantages of the laser included a more powerful beam with little variation of its diameter with distance, and so the initial tests were conducted with a 35 MW He Ne instrument as described by Barnes (1982) in more detail. Improvement in correlation was found in the free jet when closer to the outlet face of the test pipe with the best results when the beam crossed the flow at the plane of the lip pressure. To effect this, small glass windows were set in the pipe wall through which the beam passed to give the plotted values of Figure 5. It is clear from the spread of results that an accuracy no better than about ±10% can be obtained for enthalpy from detector values of relative transmission (light transmission through mixture relative to that through dry steam). As an alternative to enthalpy, values are also given of volumetric 'wetness' which has the advantage that it is apparently independant of lip pressure according to recent tests conducted at 1.5 and 2.5 bars. This is certainly an advantage, but whether the scatter of points can be reduced has yet to be determined.

(e) Shape of Discharge Jet

During the various tests, it was found that the 'tulip' shape of the jet gave a rough guide to enthalpy at a fixed lip pressure. Figure 6 is a sketch from photographs taken at a set distance of sonic steam-water flows discharging from the test pipe; enthalpy can probably be estimated by eye with an accuracy equal to that of the laser.

CONCLUSIONS

The most promising technique was found to be the single-tube heat exchanger (hydraulic analog of the H.W.A.) which evaluated enthalpy accurate to within ±3% as indicated on Figure 4. Obviously, further development is required on larger test pipes and at higher lip pressures to approach realistic borefield conditions.

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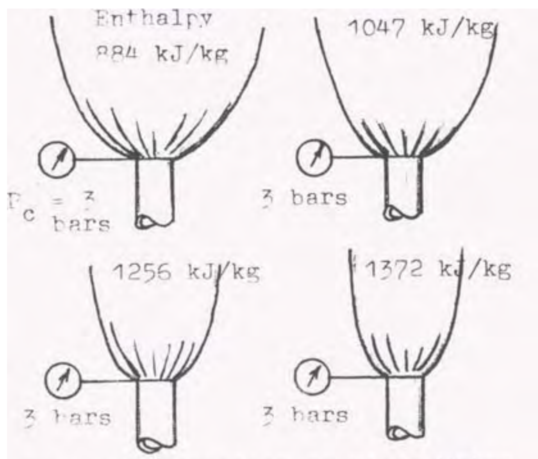

Figure 6 Variation of Steam-Water Jet with Enthalpy at fixed Lip pres.