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CHOKED FLOW IN FRACTURED GEOTHERMAL RESERVOIRS

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ABSTRACT

Field data indicates that the output from some geothermal wells may be limited by choked flow in the reservoir. To investigate this possibility, a one dimensional thermodynamic model was developed to study flashing steam/water flow in a fracture. The model was based on the "streamtube" model of Wallis and Richter (1978), modified to include the effect of heat transfer from the rock to the field.

The results of the study indicate that:

- Choked flow is a possible explanation for certain characteristics noted in geothermal wells where flashing occurs in the formation.

- Choked flow is likely to occur when the water saturation is less than 0.6-0.7.

INTRODUCTION

Studies of the output characteristics of geothermal wells in liquid dominated reservoirs have largely been limited to the situation where flashing occurs in the wellbore (Nathenson, 1974 and Ryley, 1980). Under these conditions the discharge enthalpy is essentially constant over a range of wellhead pressures and the massflow from the well is generally limited by the well design, suggesting that the reservoir permeability is not a limiting factor in the exploitation of the resource. An example of the output characteristics for this type of well *(Type* I) are shown in Figures 1 and 2.

With exploitation of lower permeability resources, the point is reached where the reservoir permeability becomes a limiting factor. When this happens, the higher pressure drop required for flaw will generally cause flashing of the fluid in the reservoir. An example of output characteristics for this type of well *(Type* II) is included in Figures 1 and 2. The important points which set these wells apart are the constant massflow at low wellhead pressures and the increasing enthalpy.

The constant massflow behaviour indicates that the flow has become "choked". This choking does not appear to occur in the well as similar wells, where flashing occurs in the wellbore, have massflows at least four times greater; hence it is likely that the choking is occurring in the formation.

Two phase compressible flow has been studied in detail, particularly in nuclear reactor engineering, but very little of this research has been applied to geothermal systems. Choked or critical flow has formed an important part of this research, and although it forms the basis of the James (1962) method €or measurement of output parameters in geothermal wells, the idea that choked flow could occur in reservoir flow systems, thereby limiting the systems' output has not been widely discussed. It was therefore decided to study this concept by adapting a critical flow model from the nuclear reactor engineering literature for use in the geothermal situation.

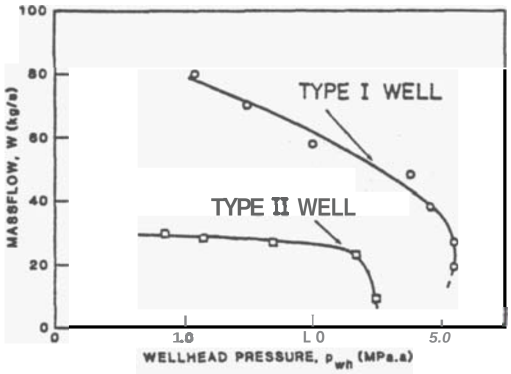

Figure 1: Massflow Characteristics

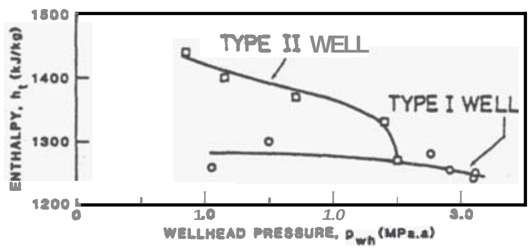

Figure 2: Enthalpy Characteristics

The increasing enthalpy is considered to be due to heat transfer from the rock to the fluid as flashing occurs and the fluid temperature falls below the rock temperature. The model would also have to take this into account.

MODEL

Selection of Model

In an attempt to better understand the processes involved in the two phase flow of steam and water in a fractured geothermal reservoir, a model of steam/water flow in a confined conduit was sought.

There are a number of existing one dimensional models for the study of two phase vapor liquid flow, normally classified as homogeneous, slip or separated flow models. The model found to be most appropriate was the "streamtube" model of Wallis and Richter (1978). This model overcomes the difficulties inherent in the usual slip flow theory by allowing the velocity and thermodynamic state to vary normal to the flow direction. It does this by considering the two phase flow field to be distributed between a number of discrete streamtubes, hence the name streamtube model. The streamtube model has been found to predict critical flow in nozzles more accurately than other slip models.

Description of Model

The streamtube model of Wallis and Richter (1978) approximates the continuous flashing process by a series of discrete pressure steps. At each pressure step, a new streamtube is formed which the steam formed by the previous drop in pressure is assumed to flow. Once formed, the steam is assumed to expand isentropically during later pressure steps, resulting in some condensation. The amount of condensation is small and the homogeneous flaw model is used within each streamtube i.e. the steam and water velocities are assumed to be equal.

Other important points about the basic model are:

- there is no interaction between streamtubes
- each streamtube has a different velocity, resulting in a velocity profile normal to the flow direction.

The assumption of isentropic expansion appears to be valid for two-phase flow in pipes and nozzles where heat transfer is not an important consideration. In geothermal systems, where the flashing process promotes heat transfer from the rock to the fluid, this assumption is not valid. It is therefore necessary to modify the basic model to include the effects of heat transfer. To do this, the energy gain, Q, has been expressed by the basic thermodynamic relationship:

$$Q = c_p \, \Delta T \, (1-\eta_s) \qquad (1)$$

where c_p is the fluid heat capacity, AT the temperature difference between the reservoir rock and the flowing fluid and η_s, the effective isentropic efficiency. After each discrete pressure step in the model, this heat transfer step was added with the amount of heat transferred being controlled by the value of effective isentropic efficiency.

For example, if $\eta_s = 1$ the flashing process is said to be ideal and no heat transfer occurs. In a real system, however, some heat may transfer and $\eta_s < 1$.

The basic steps of the modified streamtube model are illustrated in Figure 3 which shows the enthalpy-entropy diagram of the process. In the modified model the velocity in each streamtube is assumed to remain constant during the added heat transfer step.

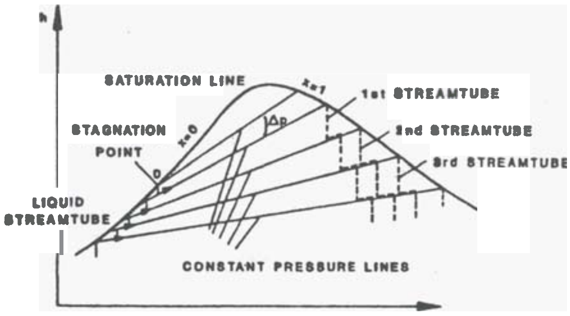

Figure 3: Enthalpy-entropy diagram for modified streamtube model.

Mathematical Formulation

The mathematical formulation presented here is based on the formation of the first two vapor streamtubes. As the pressure continues to decline further streamtubes are formed and expand in the same fashion. To simplify the computation, the model is normalized on the basis of unit massflow i.e.

$$Y_i + y_i = 1$$

If we consider the first isentropic expansion step we have a liquid massflow, Y_0, with enthalpy, h_0, entropy, s_0, and velocity v_0, calculated from:

$$v_0^2 - 2(p_0 - p_{sat})/\rho_f \qquad (2)$$

expanding to a liquid massflow, Y_1, with properties h_1', s_1', v_1 and a vapor massflow, y_1, with properties h_1'', s_1'' and v_1. Note that the liquid and vapor steamtubes are assumed to have the same velocity, when the vapor steamtube is first formed.

Applying the usual conservation equations,

mass:

$$Y_0 = Y_1 + y_1 \qquad (3)$$

and energy:

$$Y_0(h_0' + \frac{v_0^2}{2}) = Y_1(h_1' + \frac{v_1^2}{2}) + y_1(h_1'' + \frac{v_1^2}{2}) \qquad (4)$$

and the assumption of isentropic expansion:

$$Y_0 s_0' = Y_1 s_1' + y_1 s_1'' \qquad (5)$$

we get from (3) and (5):

$$y_1 = Y_0 \frac{s_0' - s_1'}{s_1'' - s_1'}, \qquad (6)$$

and from (3) and (4):

$$v_1^2 = v_0^2 + 2\{h_0' - h_1' - \frac{y_1}{Y_0}(h_1''-h_1')\} \qquad (7)$$

The liquid and vapor streamtubes now undergo heat transfer which increases both the liquid and vapor enthalpy and entropy.

The basic equations are:

$$Q = C_p(T_0 - T_1)(1 - \eta_s) \qquad (8)$$

$$\Delta h = Q \qquad (9)$$

$$\Delta s = \frac{Q}{T_1} \qquad (10)$$

The actual change will depend on the effective isentropic efficiency and the specific heat of the fluid in each particular streamtube. It is also further assumed that the fluid velocities remain constant during the heat transfer step.

During the second isentropic expansion a new vapor streamtube is created. At the same time the first vapor streamtube expands and some of the vapor may condense resulting in a steam mass fraction of:

$$x_{1,2} = \frac{s_{1,1}{}^*-s_2'}{s_2''-s_2'} \qquad (11)$$

if: $x_{1,2} < 1$:

$$h_{1,2} = x_{1,2}h_2''+(1-x_{1,2})h_2' \qquad (12)$$

if: $x_{1,2} > 1$:

$$h_{1,2} = h_2''+ T_2(s_{1,1}{}^*-s_2'') \qquad (13)$$

The homogeneous mixture is assumed to have a uniform velocity and this is calculated from:

$$v_{1,2}{}^2 = 2(h_{1,1}{}^* - h_{1,2}) \quad v_{1,1}{}^2 \qquad (14)$$

The two vapor streamtubes and the liquid streamtube then undergo heat transfer, thereby increasing their respective enthalpies and entropies before the next isentropic expansion. This process is continued until the total pressure drop is reached, at which stage there will be n vapor streamtubes where n is the number of pressure steps.

Defining i as the streamtube number and n as the total number of pressure steps, the homogeneous density in the i^{th} streamtube is:

$$\rho i,n = \frac{1}{\frac{(1 - x_{i,n})}{\rho_n'} + \frac{x_{i,n}}{\rho_n''}} \qquad (15)$$

the total massflux can be calculated from:

$$G = \{\sum_{i=1}^{n} \frac{y_i}{\rho_{i,n}v_{i,n}} + \frac{Y_n}{\rho_n'v_n}\}^{-1} \qquad (16)$$

and the flowing enthalpy can be found from:

$$\bar{h}_t = \{\sum_{i=1}^{n} y_i h_{i,n}\} + Y_n h_n' \qquad (17)$$

RESULTS

A computer program, GEOFLOW, was written to solve the above equations at each pressure step. The massflux was calculated for increasing pressure drop (based on the saturation pressure) until the two phase critical flow condition was reached,

i.e. $\frac{dG}{dp} = 0.$

Typical results from the modified streamtube model are illustrated in Figure 4. They show the two-phase massflux G increasing with increasing pressure drop Δp as more liquid flashes and the mixture velocity becomes greater. Figure 4 shows the massflux for several values of the effective isentropic efficiency η_s for a reservoir temperature of 280°C. It also shows the total two-phase mixture enthalpy h_t. When the isentropic efficiency η_s is close to unity (=0.995 say), the mixture enthalpy remains constant as flashing progresses and the massflux attains a maximum value. However, when the efficiency η_s is lower (= 0.92 say) the enthalpy increases as the fluid flashes and the critical (choking) massflux is about 25% lower compared to the earlier situation. This situation was touched on by Reynolds and Perkins (1977). They state: "for a given flow-rate there is a maximum heat input for which the prescribed flow can be passed by the duct. Compressible flows therefore exhibit choking due to heating". The water saturation at which choking was found to occur was 0.6-0.7.

COMPARISON WITH FIELD DATA

In order to compare the results from GEOFLOW with field data it is necessary to have measurements of enthalpy and massflow over a range of wellhead pressures and, if possible, flowing pressure surveys. Unfortunately these measurements are not always taken and the number of field cases available for comparison is correspondingly small. The data presented here are from two geothermal wells; well 403, Tongonan Geothermal Field, Philippines (PNOC 1981, Menzies 1982) and well "Utah-State" 14-2, Roosevelt Hot Springs, Utah, USA (Butz and Plooster 1979).

To obtain the flow characteristics from GEOFLOW, a value for the flowing pressure opposite the production zone was used, corresponding to the highest value of massflow and hence, the probable choked massflow.

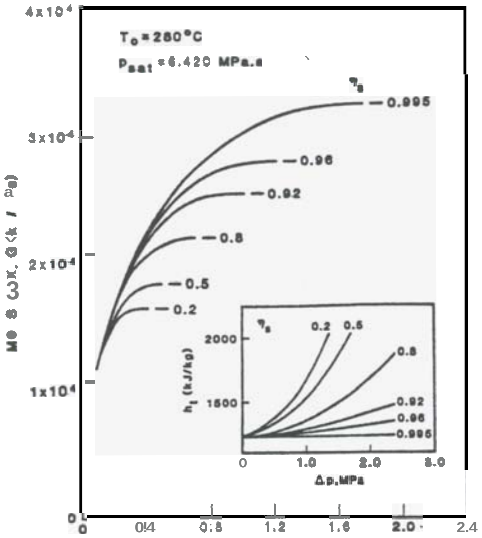

Figure 4: GEOFLOW results, T=280°C

GEOFLOW was run, using a trial and error technique, until the value of effective isentropic efficiency gave the required value of enthalpy at the measured flowing pressure. The flow area was then determined from the ratio of measured massflow to the corresponding calculated massflux. Using the calculated flow area, the massflux values were converted to massflows and plotted as a function of pressure, as were the calculated enthalpies. Both graphs and the crossplot of enthalpy and massflow could then be compared with the measured field data.

Well 403

Well 403 was drilled as a delineation well in the Tongonan Geothermal Field, Philippines to a depth of 2470m. It is known to produce from a 295°C resource at 2000 - 2200m but there also appears to be a minor inflow of cooler water at high wellhead pressures. Flowing pressure surveys indicate that at high wellhead pressures (2.5 MPa.a) flashing occurs in the wellbore but at lower wellhead pressures flashing occurs in the formation. The data from the flow tests and downhole surveys are summarised in Table 1.

Using the procedure described, it was found that an effective isentropic efficiency of 0.987 gave the best agreement between measured and calculated enthalpy. The flow area was found to be 8 x $10^{-4} m^2$ and a comparison of the field data with the calculated data is shown in Figures 5 - 7.

Choking was calculated to occur at a flowing pressure of 6.15 MPa.a; indicating that the total system massflow would be limited to approximately 28 kg/s.

TABLE 1: MEASURED FLOW DATA FROM WELL 403

Wellhead Preesure, P_{wh} (MPa.a)	Flowing Pressure, P_{wf} (MPa.a)	Massflow W (kg/s)	Enthalpy h_t (kJ/kg)
0.95		30.2	1440
1.26	3.73*	28.8	1400
1.80		26.6	1370
2.46	7.20	22.8	1330
2.58	11.33	9.0	1270

* estimated from flowing temperature survey

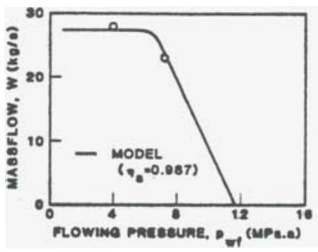

Figure 5: Mass flow vs flowing pressure - Well 403.

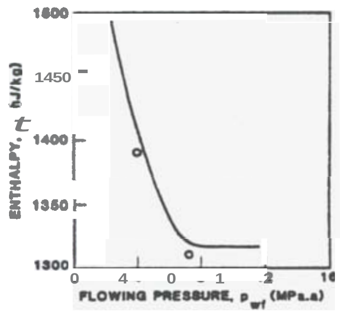

Figure 6: Enthalpy vs flowing pressure . Well 403

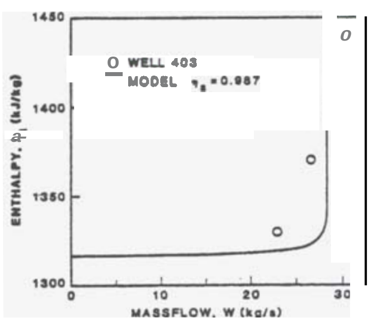

Figure 7: Enthalpy/massflow crossplot - Well 403

Well "Utah-State" 14-2

Well 14-2 was drilled to a total depth of 1860m and produces from a 260°C resource at 884-915m.

Two flow tests have been reported on this well; the first in May 1978 and the second in May 1979. Flowing pressure surveys were conducted at a number of massflows, but problems with the flow measuring equipment precluded the measurement of the total fluid enthalpy. The measured flow data is presented in Table 2.

TABLE 2: MEASURED FLOW DATA WELL 14-2

Date	Flowing Pressure P_{wf} (MPa.a)	Massflow W (kg/s)
May 1978	4.79	57.2
	(5.99)	45.0
	6.08	46.5
	(6.72)	32.1
May 1979	2.59	73.1
	3.52	55.8
	(4.22)	63.6
	6.41	40.9
	6.90	35.8

( )= estimated pressure

Without enthalpy data it was difficult to do a proper comparison between the data from GEOFLOW and the field data. However, it was found that an isentropic efficiency of 0.995 was necessary for choking to occur near the lower measured pressure of 2.59 MPa.a.

There were two flowrates at which flashing occurred in the reservoir and this data was used with the output of GEOFLOW to calculate the flow area, which was found to be 2.7 x $10^{-3}m^2$.

Using the average flow area from GEOFLOW the mass-flow/flowing pressure curve was calculated and is compared with the field data in Figure 8. The data has been extrapolated into the single phase region by assuming that the massflow is zero when the flowing pressure is equal to the reservoir pressure (when P_{wf} = 9.845 MPa.a).

GEOFLOW predicted that choking would occur when the flowing pressure was less then 3.44 MPa.a, suggesting that the maximum flowrate available from "Utah-State" 14-2 would be approximately 75 kg/s. This is somewhat ironical as the characteristics from this well have been used to study the effect of increased casing size on well output. If the flow is in fact choked in the reservoir, increasing the casing size will have no effect on well output.

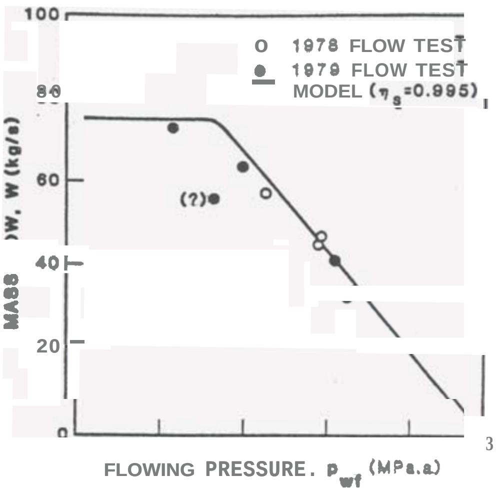

Figure 8: Massflow vs flowing pressure Well 14-2.

CONCLUSIONS

From this study, the following conclusions can be made:

(a) the modified streamtube model is useful for describing the thermodynamic behaviour of two-phase steam/water flow in the reservoir.

(b) the concept of choked flow is a possible explanation for the constant massflow and increasing enthalpy noted in the output characteristics of some geothermal wells.

(c) choked flow appears to occur when the inplace water saturation falls below 0.6-0.7. It is therefore possible that the output from geo-thermal wells producing from a two-phase resource may be independent of wellhead pressure.

(d) from comparisons with field data it was generally found that an isentropic efficiency of 0.95-0.99 was necessary to match the data. This indicates that only limited heat transfer is occurring from the rock to the fluid; possibly due to limited contact area between the rock and flowing fluid.

ACKNOWLEDGEMENTS

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