Proceedings Eighth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1982
SGP-TR-60

FLASHING FLOW IN FRACTURED GEOTHERMAL RESERVOIRS

A. J. Menzies*
J. S. Gudmundsson
R. N. Horne

Petroleum Engineering Department
Stanford University

ABSTRACT

Flashing two-phase flow can occur in fractured geothermal reservoirs when water flows toward the wellbore. The mass flow and enthalpy characteristics of wells with two-phase flow feedzones have been investigated by using a modified critical flow slip model. The model includes the effect of heat transfer from the reservoir rock to the two-phase flowing mixture. It was possible to estimate the effective fracture width of geothermal reservoir-well systems and to demonstrate under what conditions choking may occur in feedzone fractures.

INTRODUCTION

Flashing can occur when liquid water flows rapidly into a region where the pressure is below the saturation pressure corresponding to the liquid temperature. In geothermal energy production this situation arises in the transmission of two-phase mixtures up wellbores and along pipelines to steam-water separations. However flashing flow may also occur in the reservoir when liquid water flows toward the wellbore with a strong pressure gradient. In geothermal reservoirs this flow will more likely than not be along fractures.

The purpose of this paper is to report the use of a developed two-phase flow model to flashing steam-water flow in fractured reservoirs. The streamtube model of Wallis & Richter (1978) is applied to an idealized reservoir-well system where the steam-water mixture enters the well through a single fracture. It is an attempt to understand the complex flow of two-phase mixtures in geothermal fractures using a simple model. More details of this work are discussed by Menzies (1982).

FLOWING WELLS

Geothermal wells can be characterized by the massflow and enthalpy of the steam-water mixture produced at various wellhead pressures. Simultaneous massflow and enthalpy measurements are still rare worldwide but data on massflow against wellhead pressure are more readily available. The fluid entering a flowing well in a liquid dominated reservoir is commonly pressurized water or brine. The water flashes as it rises in the wellbore and for most practical purposes the enthalpy of the steam-water mixture is that of the pressurized water. The enthalpy is usually taken to be independent of wellhead pressure, although that need not be the case.

The fluid entering a flowing well in a liquid dominated reservoir is not always pressurized water. It can also be a two-phase mixture of steam and liquid water that results from flashing outside the wellbore. These two-phase feedzone wells are the subject of the current paper. The task at hand is to find a model that can describe the flashing process near the wellbore. Many assumptions have to be made about the reservoir-well system for this to be possible. The two main assumptions of concern to reservoir engineers are that the well has only one two-phase feedzone through a fracture and, the steam-water flashing occurs as it would in pipes and nozzles. The validity of these and other assumptions must then be gauged against the results.

As an example, the flowrate and enthalpy of the steam-water mixture produced by well 403 in Tongonan is shown in Fig. 1 at various wellhead pressures (P.N.O.C. 1981). The characteristic features of these data are the near constant flowrate (massflow) and the increasing enthalpy with decreasing pressure. The measurements show that the enthalpy of the fluid entering the well at low wellhead pressures is higher than at high pressures. There are at least two ways to explain this behavior. The well may have two or more feedzones (which produce different enthalpy fluids in proportions dependent on the wellhead pressure) or, the well may have a two-phase feedzone and flashing in the reservoir.

In addition to the flowrate and enthalpy measurements shown in Fig. 1, there are

* Now, KRTA, Auckland, New Zealand

available flowing temperature and pressure surveys for well 403. All these measurements were conducted between August 1980 and February 1981. Field analysis of the data shows that well 403 has a major feedzone at 2000-2200 m depth and a minor feedzone at a shallow depth which may contribute to the total flow at high wellhead pressures. The flowing surveys show that well 403 has two-phase flow in the wellbore at least down to the major feedzone at 2000-2200 m depth. This indicates that the fluid entering the well is two-phase and probably results from flashing in the reservoir. When liquid water flashes in fractures the fluid temperature decreases and causes a temperature difference between the rock and the two-phase mixture. This in turn can result in heat transfer from the reservoir rock to the flashing water such that the mixture enthalpy rises. It may be that the enthalpy increase measured in well 403 results from such reservoir heat transfer.

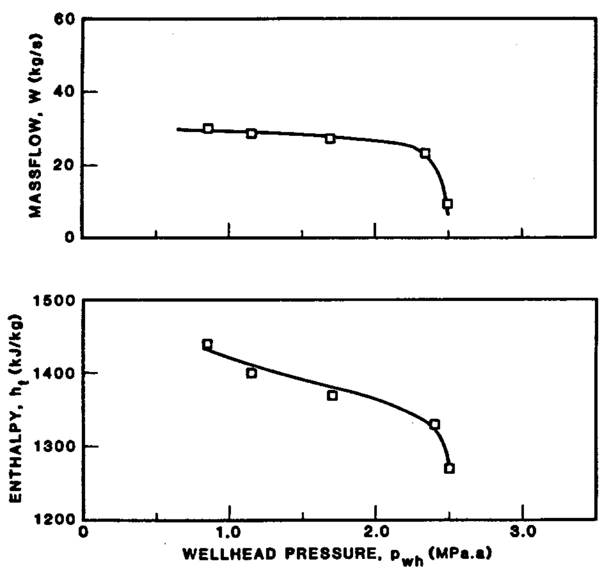

Fig. 1 Measured flowrate and enthalpy of well 403, Tongonan

The flowrate characteristic of well 403 in Tongonan is rather flat, except at high wellhead pressures. Fig. 1 shows that the flowrate does not increase much when the wellhead pressure decreases below about 2 MPa. This behavior indicates that the wellflow has reached some maximum value which depends on the nature of the reservoir-well system. The wellflow is choked because a lower receiver pressure (wellhead pressure) does not result in a larger massflow. The well has a similar casing design as other Tongonan wells which are capable of massflows 3-4 times greater than that of well 403. The choking is therefore likely to occur in or close to the major well feedzone at 2000-2200 m depth. Although the details of this two-phase choking are not well defined, it can be useful to analyze the situation by using a simple model. It is suggested here that the choking steam-water flow in well 403 can be analyzed by assuming two-phase flashing flow in a fracture.

STREAMTUBE MODEL

Various analytical approaches have been taken to two-phase critical flow (Wallis 1980). There are three main types of models that have been developed and these can be classified as homogeneous, slip and separated flow models. A two-phase slip model that predicts critical flow in nozzles, at least as accurately as any other model, is the streamtube model of Wallis & Richter (1978). This model is based on isentropic expansion of individual streamtubes that originate at the vapor-liquid interface as flashing progresses. The velocity field and thermodynamic state vary normal to the main flow direction. In this paper the streamtube model will not be derived and explained in detail. Interested readers are referred to Wallis & Richter (1978) and Menzies (1982). However, the model will be discussed briefly here to provide some background for its application in fractured geothermal systems.

In the streamtube model, discrete pressure steps are used to approximate the flashing process. At each pressure step a new streamtube is created in which initially only saturated steam flows. The steam in streamtubes that already exist is assumed to expand isentropically. A small amount of steam condenses during expansion and within each streamtube the homogeneous flow model applies. There is assumed to be no interaction between the streamtubes and thus no transfer of energy, mass and momentum occurs. Each streamtube has a different velocity, the first vapor streamtube the highest and the liquid streamtube the lowest. In the Wallis & Richter (1978) model only enthalpy and velocity changes were considered in the energy balance and the assumption of isentropic expansion requires the overall process to be reversible. The system is frictionless and an enthalpy decrease results in a velocity increase. These assumptions have been found to be valid in the study of two-phase flow in pipes and nozzles. The streamtube model provides an ideal reference process that can be useful in the study of real systems.

In geothermal reservoir systems, the transfer of heat from the formation rock to the flashing two-phase fluid can be important. This energy gain Q can be expressed by the basic thermodynamic relationship

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

where C_p is the fluid heat capacity, ΔT the temperature difference between the reservoir rock and the flowing fluid and η_s, the effective isentropic efficiency of the flashing process. The efficiency term η_s attempts to relate the ideal model and the real process. The above heat transfer step was added to the basic streamtube model of Wallis & Richter (1978) to make it more applicable to flashing in or near feedzones of geothermal wells. After each discrete pressure step in the model, a heat transfer step was added to allow the two-phase mixture to approach the rock temperature to a degree determined by the 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 Fig. 2 which shows the enthalpy-entropy diagram of the process. The energy gain Q is easily related to enthalpy and entropy. In the modified model the mixture velocity field is assumed to remain constant during the added heat transfer step.

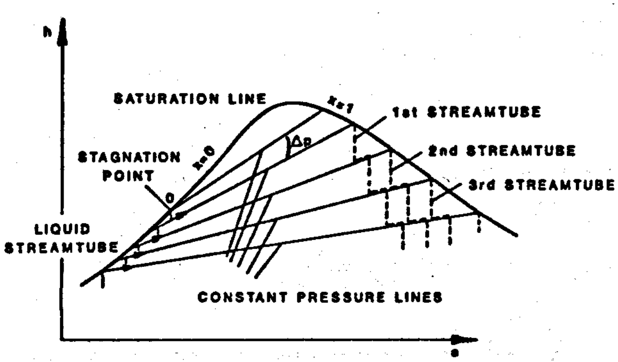

Fig. 2 Enthalpy-entropy diagram of the modified streamtube model

In the streamtube model the flashing two-phase massflux G can be calculated for each discrete pressure step. In the calculations reported here the pressure was decreased from the saturation pressure p_{sat} of the reservoir fluid in 50 kPa steps to the feedzone pressure of the well p_{wf} (downhole pressure, flowing well). The massflux was calculated for increasing $\Delta p = p_{sat} - p_{wf}$ values until two-phase critical flow was reached at:

$$\frac{dG}{dp} = 0$$

Typical results from the modified streamtube model are illustrated in Fig. 3. They show the two-phase massflux G increasing with increasing pressure drop Δp as more liquid flashes and the mixture velocity becomes greater. Fig. 3 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) there is no heat transfer from the formation rock to the flowing fluid. 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 no heat transfer situation.

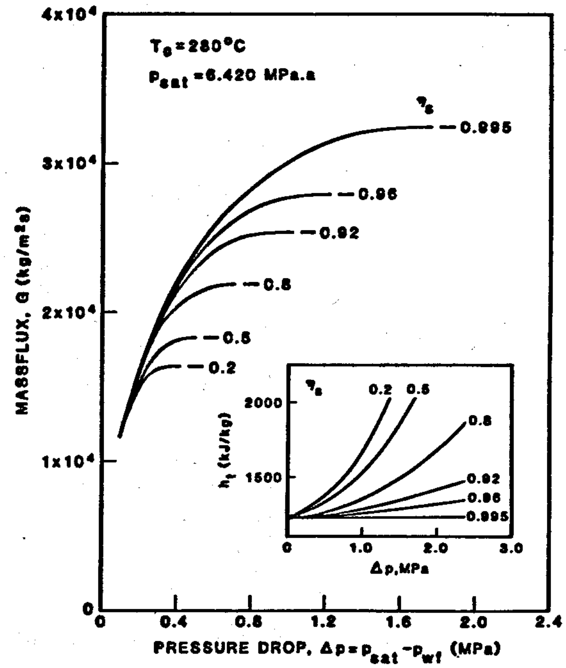

Fig. 3 Typical results from the modified streamtube model, reservoir temperature 280°C

MODEL TESTING

The modified streamtube model can be used to estimate the massflux and enthalpy of a two-phase flow mixture entering a geothermal well through a major fracture on feedzone. Field data can be used to test the model provided downhole pressure (and temperature) measurements are available in addition to wellhead massflow and enthalpy (and pressure) determinations. Such data are available for well 403 in the Tongonan geothermal field, the Philippines (P.N.O.C. 1981, Menzies 1982).

The massflow G entering a geothermal well through a major fracture needs to be related to the massflow W (flowrate) when model calculations and field data are compared. This calls for an assumption about the geometry of the fracture-feedzone where the two-phase mixture enters the well. A single horizontal fracture was assumed and is shown in Fig. 4. The two-phase flow was assumed to enter the wellbore uniformly around the circumference. The effective fracture width w_f was taken to be constant in the feedzone so the smallest flow area becomes $A = \pi d w_f$ where d is the wellbore diameter. The orientation of the fracture may affect the flow entering a well. This effect can be taken to be included in the effective isentropic efficiency η_s for the overall flashing process.

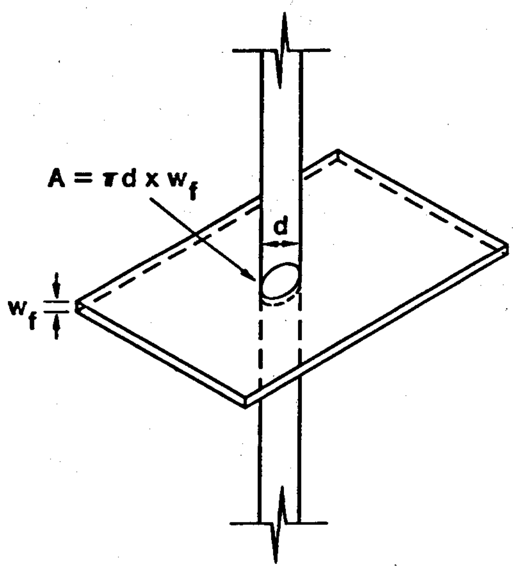

Fig. 4 Geometry of fracture feedzone of well

Well 403 in Tongonan is 2470 m deep and has a major feedzone at 2000-2200 m depth. The wellbore diameter at depth is 8 5/8" or 0.22 m. The reservoir temperature near the feedzone has been estimated at 295°C, which corresponds to a water saturation pressure of 8 MPa. The reservoir pressure near the feedzone has been measured at 12 MPa. The measured flow characteristics of well 403 in Fig. 1, illustrate the massflow W and enthalpy h_t against wellhead pressure p_{wh}. These data and three flowing survey feedzone pressures p_{wf} are shown in Table 1.

In the streamtube model the massflux G and enthalpy h_t are calculated in discrete steps from the liquid saturation pressure p_{sat} to the measured feedzone flowing pressure p_{wf}. This can be done for several effective isentropic efficiencies η_s until the calculated and measured enthalpy are the same. The isentropic efficiency found by this trial-and-error method can then be used to calculate the corresponding massflux and also the effective fracture width w_f. Using the relevant data for well 403 it was determined that $\eta_s = 0.987$ gave a reasonable match between model calculations and field data. Table 2 shows the results. The effective fracture width w_f was found to be about the same for the two data sets, 1.1 mm and 1.2 mm. Using the average effective fracture width of $w_f = 1.15$ mm, the flow characteristics (massflow and enthalpy) of well 403 were calculated at various feedzone pressures p_{wf}, and are shown as solid lines in Fig. 5 along with the two data sets. The effective isentropic efficiency $\eta_s = 0.987$ was used in the model calculations. Choking was estimated to occur when the feedzone pressure becomes less than 6.15 MPa, indicating that the maximum reservoir-well system massflow would be limited to 28 kg/s.

Table 1. Measured Flow Characteristics of Well 403, Tongonan (P.N.O.C. 1981)

Wellhead Pressure p_{wh} (MPa.a)	Feedzone 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.

Table 2. Modified Streamtube Model Calculations for Well 403

Feedzone Pressure p_{wf} (MPa.a)	Flowrate W (kg/s)	Massflux G (kg/m²s)	Area A (m²)	Fracture Width w_f (mm)
3.73	28.8	34,088	0.00084	1.2
7.20	22.8	29,063	0.00078	1.1

Model calculations have also been compared to field data from Roosevelt Hot Springs in Utah (Butz & Plooster 1979) and Krafla in Iceland (Stefansson & Steingrimsson 1980). For well 12 in Krafla, which has a choking flowrate of 6.7 kg/s, the effective fracture width was estimated at 0.3 mm when using an effective isentropic efficiency of 0.950. The reservoir-well system was estimated to be choked below a feedzone pressure of about 10 MPa. Well 14-2 in Roosevelt Hot Springs was calculated to become choked below a feedzone pressure of 3.44 MPa at a production rate of 75 kg/s. The effective fracture width was estimated at 3.8 mm and 4.1 mm for two data sets. The effective isentropic efficiency used in the calculations was 0.995. At high wellhead pressures well 14-2 flashes in the wellbore. Bodvarsson (1981) has derived an expression that relates pressure drop and massflow in fractures under conditions of liquid flow. When this expression is applied to well 14-2 the effective fracture width is estimated as 4.1 mm and 4.5 mm for the two data sets which are available for when flashing occurs in the wellbore. The agreement with the two-phase flow estimates is more than reasonable.

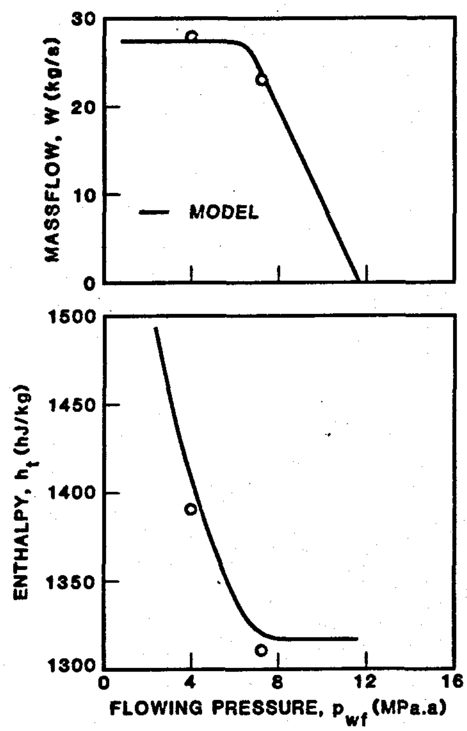

Fig. 5 Calculated massflow and enthalpy of well 403, Tongonan

CLOSURE

In this paper a new approach to two-phase flow in geothermal reservoir-well systems is reported. The approach concerns the gross assumptions that are made about the nature of flashing flow in fractures and how two-phase mixtures can enter a well. The work is based on a critical two-phase flow model which was developed for pipes and nozzles. By using the modified streamtube model it is possible to study flashing flow processes and make comparisons with field data. When this was done for wells with two-phase feedzones the results were found to be encouraging.

The notion that flashing in two-phase feedzone wells may in general occur close to the wellbore seems to be supported by the results of this study: the streamtube model appears to apply and; the flashing mixture approaches the reservoir rock temperature only to a limited extent.

It seems that critical two-phase flow can occur in fractures in geothermal reservoir-well systems. The choking behavior of some two-phase feedzone wells may be due to critical flow in fractures near the wellbore. Heat transfer from reservoir rock to a flowing two-phase mixture will lower the maximum flowrate a fracture can feed into a well.

The fracture width in geothermal reservoirs seems to be a few mm or less when estimated for two-feedzone wells. The streamtube model assumes frictionless two-phase flow which may not be true in narrow fractures. Although heat transfer from the rock formation to the flashing fluid would tend to counteract frictional effects, the effective fracture width would be larger if friction was indicated in the modified streamtube model.

ACKNOWLEDGEMENT

This work was in part supported by the Geothermal and Hydropower Technologies Division of the U.S. Department of Energy through contract DE-AT03-80SF11459.

REFERENCES

Bodvarsson, G. (1981): "Interstitial Fluid Pressure Signal Propagation Along Fracture Ladders," Proceedings, Seventh Workshop on Reservoir Engineering, Stanford University, SGP-TR-55, 139-141.

Butz, J. and Plooster, M. (1979): "Subsurface Investigations at the Roosevelt KGRA, Utah," Denver Research Institute, University of Denver, Report DOE/ET 28389-1.

Menzies, A. J. (1982): "Flow Characteristics and Relative Permeability Functions for Two-Phase Geothermal Reservoirs From A One Dimensional Thermodynamic Model," Stanford Geothermal Program, Stanford University, Report SGP-TR-59.

Philippine National Oil Company (1981): Unpublished data.

Stefansson, V. and Steingrimsson, B. (1980): "Production Characteristics of Wells Tapping Two-Phase Reservoirs at Krafla and Namafjall," Proceedings, Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-50, 49-59.

Wallis, G. B. (1980): "Critical Two-Phase Flow," Int. J. Multiphase Flow, 6, 97-112.

Wallis, G. B. and Richter, H. J. (1978): "An Isentropic Streamtube Model for Flashing Two-Phase Vapor-Liquid Flow," J. Heat Transfer, 100, 595-600.