C00--2729-T1

MASTER

TWO-PHASE FLOW IN GEOTHERMAL ENERGY SOURCES

PROGRESS REPORT NO. 1: EIGHT MONTH PERIOD

OCT. 1, 1975--MAY 30, 1976

FOR

DENVER RESEARCH INSTITUTE

SUBCONTRACT TO ERDA CONTRACT NO. E(11-1)-2729

UNIVERSITY OF HOUSTON

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JUNE, 1976

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INTRODUCTION

The majority of geothermal deposits consist of pressurized, hence sub-cooled liquid (brine) rather than vapor. These deposits can be produced as a vapor-liquid mixture by geothermal wells operating at characteristic bottom hole pressure and temperature.

Under normal operating conditions the pressurized hot brine flows up the well and undergoes a pressure drop due to gravitational and frictional effects. At a certain well depth the local pressure attains its saturation value at the local liquid temperature, resulting in flash vaporization of the liquid. Flashing continues up the well due to further decrease of pressure and the vapor flow rate increases gradually. The two-phase mixture reaches the wellhead at a total mass flow rate determined by the total pressure drop along the well. The geothermal well therefore consists of two sections: the single phase region and the two-phase region.

The flow in the two-phase region, unlike the one in the single phase region, is rather complex. As vapor is constantly generated up the well its local volume fraction, or void fraction, increases, resulting in a variety of flow patterns that appear successively. In addition, the void fraction affects both the mixture density and viscosity and hence the local gravitational, frictional and, at high vapor flow rates, the accelerational pressure gradients.

It now becomes apparent that the total production rate at the wellhead and, in particular, the relative mass flow rates of liquid and vapor, or flow quality, are a function of a fairly large number of variables. These include: bottom hole flowing pressure and temperature, wellhead pressure, well diameter profile, well depth and heat losses to the surrounding formation.

The ability to predict the relationship between the vapor and liquid flow rates at the wellhead, operating conditions, and well characteristics is of prime importance for optimal design and reliable operation of geothermal production wells that contain both liquid and vapor.

To insure a trouble-free operation of the well it is also essential to be able to predict the conditions for critical flow (i.e., sonic velocity) of the two-phase mixture and the minimum vapor flow rate required to insure continuous removal of liquid from the well. Both problems are characteristic of high vapor volumetric flow rates, at which the vapor forms a continuous phase.

The overall purpose of the University of Houston components of the project is three-fold. First, to supply theoretical and calculational support for the geothermal well design manual with emphasis on the two-phase aspect of the problem. Second, to provide fundamental two-phase flow experimental data which are presently unavailable. Third, to provide correlations as models for the significant variable so that these variables important to the production of geothermal fluid can be predicted under anticipated conditions of an operating well.

The work reported here is part of a coordinated project under ERDA Contract No. E(11-1)-2729 to Denver Research Institute as prime contractor and involves the coordinated efforts of DRI, the University of Houston and Coury and Associates. The University of Houston subcontract was received and executed by the UH on October 25, 1975 and by DRI on November 4, 1975. Although contract authorization was specified as August 1, work effectively began on October 1, 1975.

METHOD OF APPROACH

The following lines of approach were formulated for the first stage of the investigation to be reported here. A detailed parametric study of the major variables that affect the pressure profile in the geothermal well, and hence its performance, was conducted in order to identify and define the pertinent problems that require further experimental and theoretical investigation.

The well and, in particular, its two-phase section were modeled on the basis of sound two-phase flow principles. A computer algorithm was developed for pressure profile calculations and simulation of well performance. The algorithm was written in a versatile form that allows incorporation of any desired pertinent correlation.

The algorithm was used to study the effects of total mass flow rate, heat losses to the surrounding formation and void fraction on the pressure profile and the vapor and liquid production rates. In addition, several existing void fraction and frictional pressure drop correlations were evaluated in order to determine their applicability to geothermal systems.

Existing models of two-phase critical flow will be evaluated in order to determine the effect of near-sonic flow on pressure drop calculations.

Finally, models for minimum vapor flow rate required to remove the liquid from deep well will be tested.

SUMMARY OF PROGRESS

1. A geothermal well, comprising of single and two-phase sections, was modeled based on sound two-phase flow principles and selected available correlations.
2. A computer algorithm was written in a versatile form, that can incorporate any desired void fraction correlation and frictional pressure drop correlation as subroutines. It can easily be adapted to field usage.
3. The algorithm was used to assess the effects of important parameters on the overall pressure profile in the well in order to identify the pertinent problems that require further experimental and theoretical investigation. In addition, it was used to evaluate the applicability of pertinent two-phase flow correlations to geothermal wells.
4. The results of the parametric study indicated the importance of heat losses, mass flow rate, and void fraction effects on pressure profile and well performance.
5. The analysis has identified the necessary components of field data that must be obtained from a test well in order to firm up a reliable design and performance code.
6. A preliminary study of the theoretical background of critical two-phase flow and minimum vapor velocity required for continuous removal of the liquid from the well was made in order to formulate methods of attack.

WELL MODELING

Simulation of the pressure profile in the entire well and the evaluation of the effects of the operating variables and well characteristics on its performance require consideration of both the single phase and the two-phase sections of the well casing.

A. Two-phase section

The two-phase flashing flow is modeled by considering a vapor-liquid mixture that flows through the section in steady one-dimensional diabatic flow, with unequal phase velocities, namely in slip flow. The phases are assumed to be in thermodynamic equilibrium.

The governing equations for evaluating the two-phase pressure drop were derived by numerical integration of the appropriate conservation equations for the two-phase mixture over a well segment i of length Δz_i . The length of the section is segmented since the flow rate of each phase varies along the well string.

The resulting momentum equation is given by

$$\Delta P_i = \frac{g}{g_c} \bar{\rho}_{TP_i} \Delta z_i + \left(\frac{dP_f}{dz} \right)_i \Delta z_i + \frac{G^2}{g_c} \Delta_i \left[\frac{(1-\alpha)^2 v_L}{1-\alpha} + \frac{\alpha^2 v_G}{\alpha} \right] \quad (1)$$

where subscript i represents the conditions over the increment.

Equation (1) relates the total pressure drop over the increment, ΔP_i , to the gravitational pressure drop, frictional pressure drop and the net rate of momentum efflux from the increment, or accelerational pressure drop. The mixture density, defined by

$$\rho_{TP} = \alpha \rho_G + (1-\alpha) \rho_L \quad (2)$$

and the friction pressure gradient, dP_f/dz , are averaged over the increment.

The integrated energy equation, given by

$$-\frac{\bar{q}_i}{W_T} = \Delta_i [h_L + Xh_{fg}] + \frac{g}{g_c} \frac{\Delta z_i}{J} + \frac{G^2}{2g_c J} \Delta_i \left[\frac{(1-X)^3 v_L^2}{(1-\alpha)^2} + \frac{X^3 v_G^2}{\alpha^2} \right] \quad (3)$$

relates the changes of enthalpy, potential energy and kinetic energy of the flowing mixture to the wellbore heat losses per unit mass.

The kinetic energy term is usually very small and may be neglected.

The average heat transfer rate to the surrounding formation was approximated by

$$\bar{q}_i = U_{TP} \pi D \Delta z_i (\bar{T}_i - \bar{T}_{R_i}) \quad (4)$$

where U_{TP} is the overall heat transfer coefficient and $\bar{T}_i$ and $\bar{T}_{R_i}$ are the average temperatures of the mixture and the formation, respectively.

In principle, Equation (1) may be solved for the pressure drop once the length increment is specified. The required entrance and exit flow qualities are obtained from Equation (3). However, since the exit flow quality depends upon the specific enthalpy of the phases, and hence, on the exit pressure, which is not known apriori, it is more advantageous to specify ΔP_i and compute the corresponding length of the increment.

It should be noted that Equation (3) cannot be solved independently for the increment exit quality since it requires knowledge of Δz_i and, hence, is coupled to Equation (1). Consequently, the pressure profile is obtained by a simultaneous iterative numerical solution of the two equations, recasted into the following form:

$$\Delta z_i = \frac{\Delta P_i - \frac{G^2}{g_c} \Delta_i \left[\frac{(1-X)^2 v_L}{1-\alpha} + \frac{X^2 v_G}{\alpha} \right]}{\frac{g}{g_c} \bar{\rho}_{TP_i} + \left(\frac{d\bar{P}}{dz} \right)_i} \quad (5)$$

$$x_i = \frac{1}{h_{fg_i}} [(h_{L_{i-1}} - h_{L_i}) + x_{i-1} h_{fg_{i-1}} - \frac{\bar{q}_i}{W_T} - \frac{g}{g_c} \frac{\Delta z_i}{J}] \quad (6)$$

where subscripts i-1 and i represent the inlet and outlet conditions.

The solution procedure requires knowledge of both the local void fraction and frictional pressure gradient. These may be obtained from numerous correlations available in the literature.

B. Single phase section

The pressure profile in this region is obtained by numerical integration of the mechanical energy balance and the energy balance over successive increments as the properties of the pressurized liquid vary along the flow path. The governing equations are

$$\Delta P_i = \left(\frac{g}{g_c} \bar{\rho}_{L_i} + \frac{2\bar{f}_i G^2}{g_c \bar{\rho}_{L_i} D} \right) \Delta z_i \quad (7)$$

$$T_i = T_{i-1} - \frac{1}{\bar{C}_{p_{L_i}}} \left[\frac{\bar{q}_i}{W_T} + \frac{g}{g_c} \frac{\Delta z_i}{J} \right] \quad (8)$$

$$\bar{q}_i = U_{SP} \pi D \Delta z_i (\bar{T}_i - \bar{T}_{R_i}) \quad (9)$$

COMPUTER PROGRAM

Simulation of a geothermal well and parametric study of its performance were carried out on a digital computer. For this specific purpose an algorithm was written to execute the numerical solution of the appropriate governing equations iteratively. The algorithm consists of two subprograms, one for the single phase region and one for the two-phase region of the well. The subprograms are coupled at the flash point depth. Since the wellhead flow quality X_{top} is not always available the calculations start at the bottom of the hole, where pressure and temperature are specified.

The single phase subprogram is straightforward. It uses the following input: bottom hole flow pressure and temperature, total mass flow rate, production casing I. D., relative pipe roughness, overall heat transfer coefficient and the formation temperature profile.

The pressure profile of the pressurized liquid is evaluated by step-wise calculations up the well using Equations (7)-(9). For a prescribed well length increment the subprogram computes the gravitational and frictional components of the pressure drop as well as the drop in temperature. An iterative procedure is used as the liquid exit temperature is not known at the outset. As both the temperature and pressure vary along the well the liquid density is evaluated at the local pressure and temperature, neglecting the brine salinity. The Fanning friction factor is computed using an expression proposed by Dukler [1].

As a final stage of the calculations in this region the program determines the position in the well where the subcooled liquid attains its saturation pressure, and thereby begins to flash, using the iterative Regula-Falsi method.

The subprogram output includes: pressure and temperature profiles, flash point pressure and temperature and length of the single phase region.

The two-phase subprogram is by far much more complex. It evaluates the pressure profile of the two-phase mixture, that flows under flashing and slip conditions, by a stepwise solution of Equations (4)-(6). The program can incorporate any desired void fraction correlation and frictional pressure drop correlation as subroutines. The required input is: wellhead pressure, total mass flow rate, casing I. D., well depth, pipe roughness, overall heat transfer coefficient and formation temperature profile.

The sub-program takes over at the flash point. It computes the length of successive well increments, corresponding to a specified ΔP_i step, by evaluating the average gravitational and frictional pressure gradients and the accelerational pressure drop, Equation (5). The frictional pressure gradient is determined from a selected correlation.

The pressure components depend upon the void fraction and the flow quality. However, only the latter needs to be considered directly as the α -X relationship is established by a void fraction correlation. As the flow quality varies along the increment due to continuous flashing both its entrance and exit values are required. The exit quality is computed from Equations (6) and (4). As the length of the increment is not known apriori an initial value of Δz_i is estimated from Equation (6) by neglecting the frictional and accelerational terms. Based on the computed exit quality a new Δz_i value is computed from Equation (5). A successive approximation procedure is used to affect convergence.

The manner in which the calculations are completed depends upon the available input data. In the case where the bottom hole pressure, P_{Bot} , is available the calculations are completed when the local pressure in the well equals the wellhead pressure. If, on the other hand, P_{Bot} is not known, its initial

value has to be assumed. New values are obtained using a Regula-Falsi procedure and the program terminates when the total sum of the Δz_i increments converges to the given well depth.

The subprogram output includes: wellhead flow quality, pressure, temperature, quality and void fraction profiles, overall gravitational, frictional and accelerational pressure drops and the length of the two-phase section of the well.

The program uses steam table data for evaluation of specific enthalpy and specific volume of the phases. The required physical properties of the two phases as a function of temperature are entered as tables. Data interpolation is performed by appropriate function subprograms.

The present form of the program was evolved for a specific purpose, namely a parametric study of the important variables that affect the geothermal well performance and behavior. However, once the program is proven by reliable field data it can easily be adapted to field usage as well as for optimum design of new wells.

FIELD DATA

Two sets of field data were used in this investigation. Both sets came from U. S. Bureau of Reclamation test wells in California.

Holtville well

The parametric study of well behavior was conducted on the basis of the following preliminary data from a geothermal test well near Holtville, California, as supplied by Dr. Glen Coury:

Well depth: 6000 ft

Casing I. D.: 8 7/8"

Bottom hole temperature: 370°F

No-flow down hole pressure: 3000 psia

Wellhead pressures: corresponding to temperature range
of 240-270°F

Total flow rate: 200-300 gpm equivalent liquid

Brine salinity: 2%

The ranges of the wellhead pressure and total flow rate were narrowed down to the following data base:

$W_T = 150,000 \text{ lb/hr}$

$T_{\text{Top}} = 260^\circ\text{F}$, corresponding to a saturation pressure of 35.43 psia

It should be noted that although the data could be used as a preliminary basis for the proposed parametric study it was incomplete, and therefore insufficient for testing any desired geothermal well model since vital input data were unavailable, namely bottom hole flow pressure, wellhead vapor and liquid flow rates and the temperature profile of the formation.

The formation temperature profile was approximated by a linear temperature-depth relationship with the following end conditions:

$(T_R)_{\text{Bot}} = 370^\circ\text{F}$ @ Depth = 6000 ft.

$(T_R)_{\text{Top}} = 100^\circ\text{F}$ @ Ground surface

Mesa 6-1 well

For the purpose of testing the applicability of several existing void fraction correlations the more complete data from the Mesa 6-1 test well in Imperial Valley, California [2] were chosen, as follows:

Bottom hole depth: 7100 ft.

Casing I. D.: 8.625 in.

Total mass flow rate: 50,000lb/hr.

Bottom hole flow pressure: 1330 psia

Bottom hole temperature: 388°F

Wellhead pressure: 18 psia

The quasi-equilibrium formation temperature profile was taken from Figures 2 and 5 of the report [2] and approximated as two straight lines connecting at a depth of 2500 ft. The ground surface temperature was estimated at 110°F.

RESULTS AND DISCUSSION

The present investigation was conducted in two stages. The first part was devoted to a parametric study of the effect of several major variables on the well's pressure profile and performance. The second part was devoted to an assessment of the applicability of existing void fraction correlations to geothermal wells.

A. Parametric study

As the total number of variables affecting well performance is by no means small it was decided to analyse the effect of three important parameters, namely heat losses, total mass flow rate and void fraction. Frictional effects were also evaluated.

The void fraction of the flashing mixture was determined using the empirical correlations of Hugmark [3], Hughmark and Pressburg [4] and Hagedorn and Brown [5]. The two-phase frictional pressure drop was evaluated by the correlations of Dukler, et.al. (Case II) [6] and Wisman [7].

1. Heat Losses

The effect of heat losses was studied using the Holtville well data as a basis and assuming a formation temperature profile. The heat transfer rate from the bore to the surroundings was estimated by Equations (4) and (9) using a single overall heat transfer coefficient for the entire well. The heat transfer coefficient was varied in the range $0-10 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ at a constant total mass flow rate of 150,000 lb/hr and constant wellhead pressure of 35.43 psia. The variation of the pressure, flow quality and void

fraction profiles with heat transfer coefficient is summarized in Figures 1-4. The void fraction was evaluated by the Hughmark correlation and two-phase frictional pressure drop by the Dukler correlation.

Figures 1 and 2 indicate that at any constant U the single phase pressure gradient is practically constant while in the two-phase region it decreases rather sharply. The flash point location penetrates deeper into the well as the heat loss rate becomes smaller.

It is interesting to note that at a fixed wellhead pressure the flowing downhole pressure increases with heat loss rate. As a result larger pressure drops are required to deliver the geothermal fluid to the wellhead at the desired production rate. The reason becomes apparent from the following considerations. The pressure drop at the selected flow rate is due mainly to gravitation since the frictional pressure drop in this case constitutes only 0.7% of the total pressure drop. Consequently, as the flash point location approaches the wellhead the length of the all-liquid region becomes larger, resulting in higher pressure drops.

Figure 2 describes the pressure profile in the two-phase region. It illustrates the marked effect of the heat transfer coefficient on both the flash point depth and on the local pressure gradient. Based on the assumed temperature profile of the formation, which might not be too realistic, the model predicts that for $U > 10$ Btu/hr-ft²-°F the well will produce only liquid, which is obviously undesirable.

Figure 3 illustrates the pronounced effect of the heat loss on the flow quality profile in the well and, in particular, on the relative mass flow rates of vapor and liquid at the wellhead. The wellhead quality decreases markedly as the heat loss becomes significant since flashing takes place over progressively shorter sections of the well.

The predicted void fraction profiles are shown in Figure 4. Here too the effect of heat losses on the profile per se is marked, but unlike the quality, the wellhead void fraction varies over a relatively narrow range. Hughmark void fraction correlation indicates that at any given value of U the void fraction increases sharply from 0 up to about 0.5 over a very short length of the well. As the bubbly flow regime rarely extends over $\alpha=0.35$ it seems to be unimportant in geothermal wells, at least under the studied conditions. Various flow regime transition criteria indicate that in all cases the well fluids reach the wellhead in an annular-dispersed flow regime, except for $U=10 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ where the mixture is in churn flow.

The important conclusion from this phase of the study is that heat losses have a pronounced effect on the pressure drop over the well and, in particular, on the relative flow rates of the fluids at the wellhead, which is of prime importance from the practical point of view. Consequently, any model that is based on the assumption that the well operates under adiabatic conditions is totally unrealistic, unless substantiated by field data.

A practical corollary to the above conclusion is that in the case of significant heat losses the wellhead pressure would have to

be lowered in order to obtain reasonable values of X_{Top} . However, the trade-off of increased steam production could be rather dubious as the low pressure steam could be unsuitable for direct power production.

2. Mass flow rate

The Holtville data base was restricted to a single flow rate. This restraint was relaxed by varying the total mass flow rate in the range 25,000-450,000 lb/hr while keeping P_{Top} and U constant at 35.43 psia and 1 Btu/hr-ft²-°F, respectively. The Hughmark void fraction correlation and the Dukler frictional pressure drop correlation were retained.

Figure 5 displays a plot of the total mass flow rate vs. bottom hole flowing pressure, which is directly proportional to total pressure drop over the well. The curve demonstrates the interesting result that once the bottom hole and well pressures are fixed, two mass flow rates may satisfy the total pressure drop in the well.

In principle, the explanation lies in the two phase region and, in particular, in the interplay between the gravitational and frictional pressure drops. For the sake of simplicity consider the case where the liquid flow rate is fixed while the rate of the vapor is increased. At low vapor rates the gravitational pressure gradient decreases more than the accompanying increase of the frictional pressure gradient, with the net result that the total pressure gradient decreases as the total flow is increased. At high vapor rates, however, the frictional gradient begins to control and the total pressure gradient rises. Such a behavior was argued by Gould [8] in the case of a vapor dominated geothermal well

and demonstrated experimentally by Ros [9] in the case of gas-liquid flow in a pipe.

A detailed examination of the extensive computer output indicated that the average total pressure gradient does indeed exhibit a minimum with respect to W_T . However, the total two-phase pressure drop, which is a product of the pressure gradient and the length of the section, increased with the total flow rate whereas the total single pressure drop exhibited a minimum with respect to the total flow. Consequently, it is quite clear that the form of the curve in Figure 5 is dictated by the relative lengths of the two well sections rather than by the respective pressure gradients.

The length of the single phase region for $U=1$ Btu/hr-ft²-°F is plotted against W_T in Figure 6 and it can be seen that it exhibits a minimum at $W_T=175,000$ lb/hr, which corresponds to the minimum total pressure drop shown in Figure 5. Conversely, the length of the two-phase region reaches a maximum at this flow rate. The question still to be answered is why does the length of the two-phase region attain a maximum?

A possible suspect is the position of flash point in the well, that depends on the temperature profile in the single phase region and hence, on the flow rate. In order to clarify this point the program was run under adiabatic conditions. No significant change was observed, as seen from Figures 5 and 6.

As the length of the two-phase region depends upon the void fraction the effect of this parameter was investigated next.

3. Void Fraction

The effect of the void fraction--flow quality relationship was examined by checking and comparing the following void fraction correlations: Hughmark [3], Hughmark and Pressburg [4] and Hagedorn and Brown [5]. The α -X relationship of the homogeneous flow model was also included for the sake of comparison.

The Hughmark-Pressburg correlation was soon abandoned as it was restricted to flow rates up to 180,000 lb/hr.

Attention was focused on the two-phase region and adiabatic flow was assumed. This condition was most suitable for comparing the selected correlations since both the total pressure drop and the quality range were constant and thus independent of W_T . The inlet pressure corresponded to the adiabatic flash point pressure of 173.37 psia and the wellhead pressure was fixed at 35.43 psia.

Hughmark correlation. The results are shown in Figures 7-9. As seen from Figure 7 the length of the two-phase region reaches a maximum value at $W_T=125,000$ lb/hr, which corresponds to the minimum total pressure drop shown in Figure 5 for the adiabatic case. Figure 8 displays pressure profiles over a wide range of flow rates. The pressure at a given distance from the flash point does not vary with W_T in an orderly fashion since the length of the two-phase region exhibits a maximum. At high flow rates the pressure near the wellhead begins to level off. The relationship between the three pressure drop components and W_T is shown in Figure 9. At low flow rates the gravitational pressure drop dominates. As W_T increases frictional effects become significant so that the attendant contribution of the gravitational pressure drop diminishes.

The acceleration pressure drop becomes a factor only at high flow rates, as expected.

Hagedorn-Brown correlation. The dependence of the two-phase region length upon W_T is displayed in Figure 7. Unlike the case of the Hughmark correlation, the predicted length decreases monotonically as W_T increases, in complete analogy to single phase flow. The pressure profiles at various flow rates, shown in Figure 8, vary in a regular fashion. The predicted dependence of the pressure drop components on the total flow rate is shown in Figure 9. Frictional effects begin to be felt at low flow rates and the gravitational pressure drop decreases more pronouncedly. The contribution of the accelerational pressure drop is rather small over the entire flow rate range.

Homogeneous flow model. The trend of the results, shown in Figures 7 and 9, is similar to that of the Hagedorn-Brown correlation. In particular, the predicted length of the section decreases as the flow rate is increased. It should be noted that at $W_T=25,000$ lb/hr the predicted length exceeds the well depth of 6000 ft. Figure 9 indicates that the contribution of the frictional pressure drop is significant over most of the W_T range. It exhibits a maximum at $W_T=375,000$ lb/hr for reasons that are not yet understood. The accelerational pressure drop becomes important at high flow rates and at $W_T=450,000$ lb/hr its relative value is roughly 40% of the gravitational pressure drop and 50% of the frictional pressure drop.

Comparison of void fraction correlation. The comparison is summarized in Figures 7-12. Figure 7 indicates that the section length based on the homogeneous model void fraction and Hagedorn-Brown correlation decreases monotonically whereas the one computed on the basis of Hughmark correlation reaches a maximum as noted earlier. In the flow rate range of 25,000-150,000 lb/hr the predicted length varies significantly from one model to another, the Hughmark correlation predicting the lowest values. At high flow rates the differences diminish. These trends are reflected by the pressure profiles, as seen in Figures 11 and 12.

The most illuminating result of the comparison is shown in Figure 10, where the wellhead void fraction, α_{Top} , is plotted against the flow rate. The curves predicted by the Hughmark and Hagedorn-Brown correlations exhibit opposite trends with respect to W_T .

The reason why the Hughmark correlation predicts progressively larger void fractions becomes apparent upon examination of its structure:

$$\alpha = \frac{K(Z)}{1 - \frac{v_L}{v_G} (1 - \frac{1}{X})} \quad (10)$$

The void fraction depends upon the so-called Bankoff factor, that is correlated empirically with a Z factor which, in turn, is a function of the mixture Reynolds and Froude numbers and the input liquid volume fraction:

$$Z = \frac{Re^{1/6} Fr^{1/8}}{C_L^{1/4}} \quad (11)$$

As W_T increases so do the Reynolds and Froude numbers and hence the Z factor. Consequently, K increases with the flow rate. Under adiabatic flow conditions both X , v_G , and v_L at the wellhead are independent of W_T and hence are constant. It follows that α_{Top} should increase with the flow rate, as seen in Figure 10.

It should be noted that in the W_T range of 350,000-450,000 lb/hr, α_{Top} is constant. This stems from the fact that the Z values computed in this range exceeded the maximum value specified by Hughmark. As a result the computer program freezes its value at the maximum value and hence α_{Top} remains constant.

The Hagedorn-Brown correlation is derived on a different basis altogether. α is defined as an "effective" in situ average void fraction, which may not be the same as the "true" in situ average void fraction. In addition, the correlation is not based on experimentally measured values of α but rather on values computed from total pressure drop data obtained from a test oil well. As a result it is hard to find a rational for the α_{Top} - W_T relationship shown in Figure 10.

Figure 10 supplies all the necessary clues for interpreting the results of Figure 7. Consider first the homogeneous model. As there is no slip between the phases the void fraction at any given pressure and, hence, α_{Top} are constant, regardless of the flow rate. At the lowest value of W_T the gravitational pressure drop is dominating resulting in the highest value of the two-phase region length.

As the flow rate increases the frictional pressure drop rises sharply, Figure 9, resulting in a further decrease of the section length. At still higher values of W_T the accelerational pressure drop begins to pick up, causing a leveling off of the length.

The same line of reasoning holds for the case of the Hagedorn-Brown correlation all the more so since α_{Top} decreases as the flow rate is increased.

Lastly, consider the Hughmark correlation where α_{Top} increases monotonically with the flow rate. At low flow rates the gravitational pressure is dominating and hence the section length increases first. It reaches a maximum due to the interplay between ΔP_G and ΔP_f and then falls off as ΔP_f and ΔP_A become more and more effective.

The important conclusion from the foregoing is that the void fraction profile has a profound effect on the length of the two-phase region and on the pressure drop components. Consequently, since the selected void fraction correlations predict conflicting trends it is important to determine their reliability and applicability to geothermal wells by testing them with a more complete set of field data. This will be done in the next section.

4. Frictional pressure correlations. The predictions of Dukler [6] and Wisman [7] correlations were compared at $W_T=150,000$ lb/hr for the values of U shown in Figure 1. The differences between the two correlations were rather small. The Dukler correlation predicted slightly higher pressure drops, the maximum difference being 7%. Either one of the correlations could therefore be used.

B. Model testing

The data for the Mesa 6-1 test well were used in order to evaluate the applicability of the selected void fraction and frictional pressure drop correlations as they included well pressure and temperature profiles under flow conditions, flash point depth and formation temperature profile. The data did not include, however, the relative flow rates at the wellhead which, aside from its practical importance, is vital for testing any given model.

The predictions of the models, using the Dukler correlation and separate heat transfer coefficients for the sections of the well, are summarized and compared with the data in Table 1.

The predicted profiles are compared with the data in Figure 13. The model based on the Hagedorn-Brown correlation agrees very well with the field data. The total well length is predicted within 86 ft, the flash point depth within 20 ft, the flash point pressure within 6 psia and flash point temperature within 3°F. The model based on Hughmark correlation is totally unsatisfactory. It fails to predict the total well length even under adiabatic conditions. This results from the fact that at any given pressure in the two-phase section the correlation predicts a lower void fraction than that predicted by the Hagedorn-Brown correlation. Consequently, that length of the well increment corresponding to a ΔP step is shorter,

The predicted temperature profile agrees reasonably well with the measured profile, as may be seen from Figure 13. The transition to the two-phase section is sharper than the one indicated by the data. The predicted quality profile indicated that a slight condensation of the

TABLE 1

Comparison of Mesa 6-1 Data with Model Predictions

Parameter	Field Data	Predicted	
		Hagedorn-Brown	Hughmark
Well length, ft.*	7100	7186	5196
Distance from bottom hole to flash point, ft.**	2965	2986	
Flash pressure, psia**	190	196	
Flash temperature, °F**	377	380	
Exit quality	—	0.064	0.182
Exit void fraction	—	0.960	0.952

* Based on a chosen bottom hole reference depth

**Based on single phase flow calculations

steam phase as it approached the well exit. The predicted wellhead quality appears to be quite low,

The important conclusions of this phase of the study are two-fold. First, a complete set of field data is required to test any desired model. Second, it is of vital importance to develop a reliable and proven void fraction correlation that will be applicable to steam-water mixtures.

OUTLINE OF FUTURE WORK

A. The parametric study has demonstrated the central role of the liquid fraction holdup in the relationship between flow rate and pressure drop of a geothermal well. It has also shown that various existing correlations give widely divergent results. Approaches to resolving the problem will be

1. Analyze existing instrumental methods for measuring instantaneous void fractions in an upflow system.
2. Either adopt one such system or develop a new one to suit these needs.
3. Purchase, assemble and test such a system.
4. Develop new models for area average void fractions based on flow regime analysis recently completed in these laboratories for upflow systems.
5. Test these models on the existing upflow loop.
6. Modify the models as needed to conform with the new experimental results and new insights developed.

B. Models are now available for minimum gas flow rates necessary to lift the liquid. Test these models with newly designed experiments.

C. Continue analytical development of models for choking velocity in pipe flow.

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NOMENCLATURE

C_L	Input liquid volume fraction
C_p	Heat capacity, Btu/lb-°F
D	Casing inside diamters, ft.
f	Fanning friction factor
Fr	Froude number
G	Mass flux, lb/ft ² -sec.
g	Gravitational acceleration, ft/sec ²
g_c	Conversion factor, 32.2 lb _m -ft/lb _f -sec ²
h	Specific enthalpy, Btu/lb.
h_{fg}	Latent heat of vaporization, Btu/lb.
J	Mechanical equivalent of heat, 778 ft-lb _f /Btu
K	Bankoff factor, Equation (10).
P	Local pressure, psia
q	Heat transfer rate, Btu/hr.
Re	Reynolds number
T	Temperature, °F
U	Overall heat transfer coefficient, Btu/hr-ft ² -°F
v	Specific volume, ft ³ /lb.
W	Mass flow rate, lb/hr.
X	Flow quality = W_G/W_T
z	Vertical coordiante
Z	Correlating factor, Equation (11).
α	In situ void fraction = volume fraction of gas
Δ	Change over well increment
ρ	Density, lb/ft ³

Subscripts

A	Due to acceleration
Bot	At bottom hole
f	Due to friction
G	Gas, due to gravity
i-1	Entering well increment i
i	Leaving well increment i, pertaining to increment i
L	Liquid
R	Rock formation
SP	Single phase
T	Total
TP	Two-phase
Top	At wellhead

Superscript

— Average

Figure 1. Effect of heat losses on pressure profile in the entire well.

Figure 2. Effect of heat losses on pressure profile in the two-phase region, based on Hughmark void fraction correlation.

Figure 3. Effect of heat losses on quality profile.

Figure 4. Effect of heat losses on void fraction profile. Void fraction predicted by Hughmark correlation.

Figure 5. Variation of total mass flow rate with bottomhole pressure, based on Hughmark void fraction correlation.

Figure 6. Variation of length of the single-phase region with flow rate. Hughmark void fraction correlation.

Figure 7. Predicted length of two-phase region, based on void fraction test correlations, as a function of flow rate. Adiabatic flow.

Figure 8. Predicted pressure profiles in the two-phase region for adiabatic flow, based on Hughmark and Hagedorn-Brown correlations.

Figure 9. Predicted two-phase pressure drop components for adiabatic flow, based on void fraction test correlations.

Figure 10. Void fraction at wellhead as predicted by test correlations for adiabatic flow.

Figure 11. Predicted pressure profile in the two-phase region for mass flow rate=150,000 lb/hr. Adiabatic flow.

Figure 12. Predicted pressure profile in the two-phase region for mass flow rate=450,000 lb/hr. Adiabatic flow.

Figure 13. Pressure and temperature profiles in Mesa 6-1 test well. Model based on Hagedorn-Brown correlation.