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SIMPLIFIED PREDICTION OF OUTPUT CURVES FOR STEAM WELLS

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ABSTRACT

A simplified method for the prediction of output curves for steam is presented. The method of Ramey (1981) is developed and an equivalent wellbore diameter used to represent changes in well profile. Results are compared with those from a homogeneous model wellbore simulator. Model validity is confirmed with a field test.

INTRODUCTION

Determining flow capacities for steam wells is difficult due to the lack of field data which arises partly from the fact that most steam wells are throttled by the formation and not by the flow capacity of the casing.

Theoretical steam flow assuming adiabatic wellbore conditions is described by Ramey (1981):

$$P_{wf}^2 + B = (P_{tf}^2 + B)e^{(ML/773Z_{av}T_{av})} \quad \ldots\ldots\ldots(1)$$

where

$$B = f(Z_{av}T_{av}W)^2/17.95MD^5 \quad \ldots\ldots\ldots(2)$$

Units are lbf, lbm, in, h, °R except "L" which is in ft.

Steam properties are evaluated at the average pressure and temperature conditions in the wellbore.

METHOD

Well Flow Capacity Correlation

Equation 1 can be simplified using the exponential series approximation:

$$e^x = 1 + x + x^2/2 + x^3/6 + \ldots + x^n/n! \quad \ldots(3)$$

For $x < 0.1$ Equation 3 can be approximated by the following expression to 1% accuracy

$$e^x \approx 1 + x \quad \ldots\ldots\ldots (4)$$

Therefore:

$$e^{(ML/773Z_{av}T_{av})} = 1 + ML/773Z_{av}T_{av} \quad \ldots\ldots\ldots(5)$$

Substituting Equation 5 in Equation 1 gives:

$$P_{wf}^2 + B = (P_{tf}^2 + B)(1 + ML/773Z_{av}T_{av}) \quad \ldots(6)$$

Solving for "B" in Equation 6:

$$B = [P_{wf}^2 - P_{tf}^2(1 + ML/773Z_{av}T_{av})] / (ML/773Z_{av}T_{av}) \quad \ldots(7)$$

For geothermal conditions:

$$ML/773Z_{av}T_{av} \ll 1$$

Therefore from Equation 7:

$$B \approx P_{wf}^2 - P_{tf}^2/(ML/773Z_{av}T_{av}) \quad \ldots\ldots\ldots(8)$$

Now solving for the mass flow "W" from Equations 1 and 8 gives:

$$W = [(P_{wf}^2 - P_{tf}^2)(773*17.95MD^5) / (LfZ_{av}T_{av})]^{0.5} \quad \ldots(9)$$

Assuming complete turbulence the friction factor can be expressed as:

$$f = 0.094(e/D)^{0.21} \quad \ldots\ldots\ldots(10)$$

Assume a casing roughness (e) for commercial steel of $4.5*10^{-5}$ m. Substituting Equation 10 into Equation 9 and converting to S.I. units (pressure MPa) gives:

$$W = 3.456*10^5[D^{5.21} / (LZ_{av}T_{av})(P_{wf}^2 - P_{tf}^2)]^{0.5} \quad \ldots(11)$$

Equivalent Diameter

Equation 11 necessitates the use of a single friction factor. Wellbore geometries of varying diameters can be represented by a single equivalent wellbore diameter. The parameters Z_{av}, T_{av} are assumed to remain constant at the average pressure in each wellbore step.

To compute the equivalent wellbore diameter consider the stepped well shown in Figure 1.

Consider section a-b and apply Equation 9:

$$W^2 = (P_b^2 - P_a^2)(C_1D_{ab}^5)/(L_{ab}f_{ab}) \quad \ldots\ldots\ldots(12)$$

where

$$C_1 = \text{constant} = f(M, Z_{av}, T_{av})$$

Consider section b-c:

$$W^2 = (P_c^2 - P_b^2)(C_1D_{bc}^5)/(L_{bc}f_{bc}) \quad \ldots\ldots\ldots(13)$$

Eliminating P_b from Equations 12 and 13 gives:

$$P_c^2 - P_a^2 = (W^2/C_1)(L_{ab}f_{ab}/D_{ab}^5 + L_{bc}f_{bc}/D_{bc}^5) \quad \ldots(14)$$

For a stepped well with equivalent uniform diameter, D_e, and friction factor, f_e, Equation 12 can be rearranged as:

$$P_c^2 - P_a^2 = (W^2/C_1)(L f_e/D_e^5) \quad ....(15)$$

Comparing Equations 14 and 15:

$$L f_e/D_e^5 = L_{ab} f_{ab}/D_{ab}^5 + L_{bc} f_{bc}/D_{bc}^5 \quad ...(16)$$

Rearranging gives:

$$D_e = [L f_e/(L_{ab} f_{ab}/D_{ab}^5 + L_{bc} f_{bc}/D_{bc}^5)]^{0.2} \quad ....(17)$$

The number of variables can be reduced by noting:

$$L = L_{ab} + L_{bc} \quad ....(18)$$

APPLICATION

The philosophy of applying the method is:

a) Calculate wellbore and fluid properties.

b) For a stepped well calculate the equivalent wellbore diameter.

c) Compute the downhole pressure from the mass flow and wellhead pressure using Equation 11.

d) If deliverability effects are important use the duration of discharge and known formation pressure to calculate the deliverability index.

e) Use the well geometry, fluid properties and formation deliverability to produce the well output curve using Equation 11 modified to include deliverability effects as required.

FIELD EXAMPLE

Wk232 was discharged vertically through a lip pressure pipe for 5 hours on 2 June 1987. The mass flow was estimated using the method of James (1970) at 18.3 *kg/s* for a wellhead pressure of 0.78 *MPa(abs)* and assumed enthalpy of 2750 *kJ/kg*. The discharge appeared to be dry steam.

Limitations due to deliverability were neglected as completion test data indicated the well had excellent permeability and the total well heat output was stable during vertical discharge.

Properties

Well parameters are (Figure 1):

top of liner--------------------------208 m
feed depth----------------------------375 m
production casing diameter---------0.199 m
slotted liner diameter-------------0.150 m
assumed casing roughness----------4.5e-5 m
assumed liner roughness-----------4.5e-5 m
feed temperature----------------------222 $^\circ C$
saturation pressure at feed----2.41 *MPa(abs)*

Steam properties are calculated at the average flowing pressure in the well.

$$P_{av} = (0.78+2.41)/2 = 1.60 \text{ MPa} \quad ....(19)$$

$$Z_{av} = 0.90$$

The saturation temperature at the wellhead is 169$^\circ C$. The average well temperature is:

$$T_{av} = (169+222)/2 = 195.5^\circ C = 468.5 \text{ K} \quad ....(20)$$

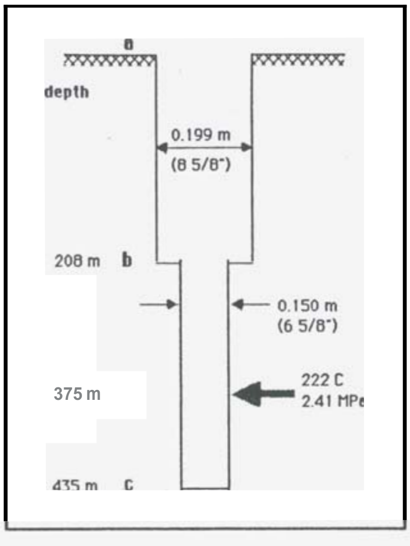

Fig 1: Notation and well profile for WK232.

Equivalent Diameter

Substitute in Equation 17 for the equivalent well diameter:

$$D_e = 0.1673 \text{ m}$$

The mass flow rate may now be calculated from Equation 11.

$$W = 3.456 \times 10^5 \{0.1673^{5.21}/[(375)(0.90)(469)] \ast (2.41^2 - .78^2)\}^{0.5} \quad ....(21)$$

= 18.8 *kg/s* (cf measured 18.3 *kg/s*).

The accuracy of the method is confirmed for this well which had excellent permeability and for which productivity is assumed to be infinite. Well flow is restricted only by the wellbore diameter.

Output Curve Prediction

The output curve for WK232 is best predicted by simplifying Equation 11 for the specific well conditions.

Substituting appropriate parameters gives:

$$W = 8.24(P_{wf}^2 - P_{tf}^2)^{0.5} \quad ....(22)$$

The output curve is shown in Figure 2

WELLBORE SIMULATOR

The sensitivity of the results was checked using a single phase homogeneous wellbore simulator. The results (Figure 2) confirm the accuracy of the simplified method.

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NOTATION

C_1 = constant
D = inside diameter
e = wellbore roughness
f = friction factor
M = molecular weight
L = well depth
P_{wf} = flowing bottomhole pressure
P_{tf} = flowing wellhead pressure
T = temperature
W = mass flow rate
z = gas law deviation factor

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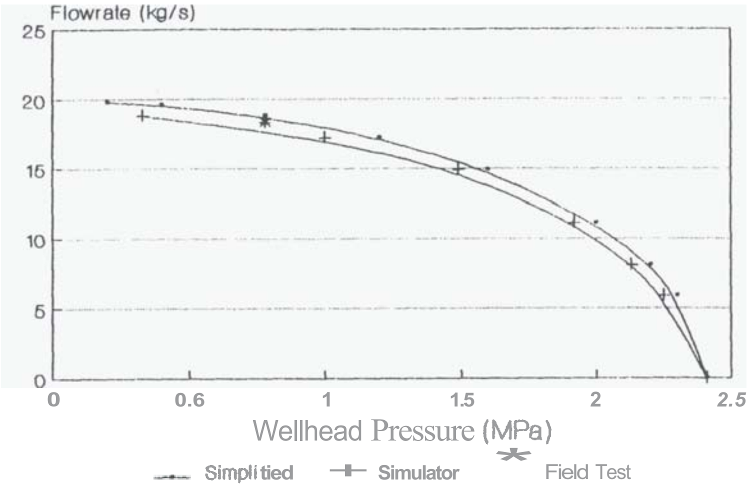

Fig 2: Comparison of output curve prediction using the "Simplified" method and the homogeneous wellbore simulator.