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CALCULATION OF OUTPUT CHARACTERISTICS OF SHALLOW WELLS

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ABSTRACT

A well bore simulator is described and used to establish the output characteristics of two shallow geothermal wells. The influence of a number of the geoemtric and fluid variables on the characteristic is illustrated. The need for a reliable and well proven model that can account for changes in thermodynamic properties of the geofluid due to gas and solids in solution as well as the use of such simulators for field management decision making are emphasised.

1.0 INTRODUCTION

The calculation of flowing pressures and output of a geothermal fluid from a well bore has received attention in the literature recently. The early work of Gould (1974) and Upadhyay et al (1977) consisted of using Hagedorn & Brown type correlations for vertical flows to determine pressure and temperature profiles in geothermal wells. Since that time more work has resulted in further correlations and an extension of the results from profiles to predicting well output characteristics, Miller and Harrison (1985), Gudmundsson (1984).

Such simulators have a wide application in the development of geothermal resources. Some examples of their use are (1) to show the effect of well bore diameter on the flowrate including the effects of well bore scaling. (2) Given well head conditions, downhole pressures can be calculated or alternatively, if the reservoir conditions are known, the simulator can be used to determine the well head pressure as a function of flowrate, that is, the output curve. (3) A simulator may also be used to predict an output curve from a single output measurement, a technique which is useful if discharge of a well is restricted on environmental grounds, i.e. noise or waste water disposal, or if the economics of testing over the full range of output are not justified at the field investigation stage.

In all cases the accuracy of the simulation has to be justified by continually matching output with experimental data. In all the simulators that are available, correlations are used for void fraction, slip factor, etc, to close the one dimensional equations of motion. In addition to these fundamental equations, correlations of steam tables are required and have been developed with suitable provision for modifications of the fluid transport properties due to deviations from pure water. such as the addition of salts and carbon dioxide. However many of the simulators have had little exposure to a variety of actual well test data, consequently it has been found by the authors that whereas a simulator will give an adequate output for one well, its use in another well, even in the same reservoir, may not produce a satisfactory result. Efforts are being made to rectify this situation. This paper presents a study using one of the simulators, that due to Bilicki et al (1981) which we will call the Brown simulator. The effects of well depth on the output characteristic with a particular emphasis on the shallow (≈ 200 m) moderate temperature well are reported. This latter aspect is demonstrated for two particular fields - Yangbajing, Tibet, Peoples' Republic of China, and the Rotorua field in New Zealand.

2.0 THE WELL BORE SIMULATOR

A study of the published simulators shows that although they are all generated from the same basic equations of motion and generally use a stepwise integration technique up and down the well depending upon whether well head or downhole conditions are specified, there is a wide variation in the correlations used for the two phase parameters void fraction, slip velocity, etc, and the transport properties of the mixture. In addition some simulators include the effects of well bore heat flow whilst others have allowances for changes in friction factor due to roughness. Some use corrections for non-dissolved solids whilst others also include correlations for dissolved gases.

For this paper we use the Brown simulator which is fully described in Bilicki et al (1981). The model calculates flow parameters in a well based on conditions at bottomhole. A stepwise integration technique is used up the well bore. The model assumes a steady one dimensional flow of geofluid up the well. It also assumes a single feed point and single phase fluid (liquid) at the bottom of the well. As the fluid ascends to the surface it flashes to two phase water-steam as the saturation pressure is reached. Above the flashing level a sequence of flow regimes can occur depending on the criteria for their appearance. Four flow regimes are identified. In order of appearance these are bubbly, slug, froth and annular mist. The limits which delineate the four flow patterns from each other follow from definite criteria, a detailed statement of which is given in Bilicki Z and Kestin J (1980). For transitions from the bubble to slug and slug to froth regimes Prandtl's mixing length theory is followed. The criteria for transition from froth to annular was taken from the work of Pushkin and Sorokin (1962).

The one dimensional equations are then closed using Petrick's (1958) correlation for wall stress together with empirical correlations which determine the void fraction for each topological flow structure, Mendelson (19671, Dukler (1978). The therriophysical properties of water and steam of pressure and/or temperature are taken from analytic formulations based on the 1967 International Formulating Committee (IFC). The effect of the presence of dissolved solids on the thermodynamic properties is also accounted for in the model. The solids are represented by an equivalent NaCl content which is considered to be the major constituent and its effect on the density, viscosity, enthalpy and saturation temperature at a given pressure is accounted for by suitable correlations developed from the literature, Bilicki et al (1981).

This model does not include the effects of non-condensible gases or heat transfer to the surrounding formations, however both these effects and the reasons for not considering them are discussed in the original paper, Bilicki et al (1981). One further assumption used is that the pressure drawdown (reservoir pressure - well pressure) at the feed point is a linear function of well mass flow. This infers single phase Darcy-type flow and is applicable for low mass flow wells. At higher flow rates when a steam/water enters the well bore the relationship between mass flow rate and drawdown pressure will become non-linear, Gudmundsson and Marcou (1986).

In order to accommodate variations in well bore roughness the authors modified the friction factor in Petrick's equation from the smooth wall Blaisus expression to the analytic expression of Churchill (1977) so that production casing, slotted liners and open hole friction factors could be used where appropriate. The roughness values proposed by Gould (1974), namely 1.37×10^{-4} m for liner and 4.57×10^{-5} m for production casing were used for the case studies.

3.0 USING THE BROWN SIMULATOR

3.1 General

From a geofluid utilisation point of view, one of the most important performance characteristics of a geothermal well is the output curve, that is, the variation of total mass flow as a function of well head pressure (WHP). The shape of this curve is a function of many variables, well geometry, bottomhole conditions, fluid properties, gas and salt content, reservoir parameters, etc. For deep wells (≈1000 m) the characteristic curve is obtained by measuring the discharge over a range from maximum mass flow (minimum WHP) to maximum discharge pressure (MDP), Grant et al (1982). Very rarely is the return part of the curve, i.e. mass flows below (MDP) obtained. This region is of little interest as generally it is unstable and also the mass flow and hence the energy content of the flow is lower than the upper part of the curve. However two examples which are discussed below have appeared in the literature recently, both of which are for shallow moderate temperature wells.

Figure 1 illustrates some of the features of shallow and deep wells. The Brown simulator, is used with the data base as in Table 1. Two wells both with 9 5/8 in production casings, set to the bottom, one 200 m deep, the other 1000 m have been analysed with representative moderate and high bottom hole temperatures (170°C & 260°C).

A single feed point located at the bottom is assumed with a zero drawdown factor, i.e. (well pressure = reservoir pressure). We divided the well for analysis into 40 steps and assumed no salt or gas in the geofluid.

The 170°C and 260°C bottomhole curves with saturated pressure conditions at the bottom clearly indicate the influence of temperature in controlling MDP as discussed by James (1980). We have shown for comparison purposes only the lower part of the 260°C curve to illustrate the shape of a deep well output curve below MDP. Normally this type of well would be operated at mass flows above that corresponding to MDP and greater than 26 kg/s for this example.

For a low temperature deep well the characteristic is also a function of bottomhole pressure (BHP). For this case, 1000 m deep and 170°C. the variation in output is shown for a range of BHP from 86 bar to 40 bar that is compressed liquid. Of particular interest is the maximum mass flow achieved, i.e. the choke condition. The bottomhole pressure is a function of the drawdown in the well and hence the permeability. So an impermeable reservoir would be expected to have a high drawdown factor and consequently a low dynamic bottomhole pressure resulting in an output characteristic shape as shown in Figure 1.

These curves illustrate trends and are not specific. The case studies that follow indicate the type of matching that can be achieved with a simulator and its use in understanding and directing management type decisions.

3.2 Study 1: Rotorua (NZ)

The Rotorua geothermal field with over 400 production wells provides low enthalpy fluid for residential, comnercial and light industrial use. The wells are characterised by downhole temperatures in the range 120 - 200°C drilled to shallow depths of less than 200 m and lined with 102 mm (4 in) casing. A few of the wells produce artesian flow and aretermed high pressure, however the majority are low pressure which have to be stimulated to start the flow. Operation of these wells at low flow rates results in flow instability and final collapse. The deposition of calcite in these wells causes the output to decline with time.

Well 715 located on the eastern side of the field was selected. It is drilled to a total depth of 122 m, lined with a 4 in casing (BS 1387 heavy grade pipe) to 100 m and completed to the bottom with an open hole. It has a permeable zone near the bottom with a feed temperature of around 167°C. At present it is coupled to 9 domestic users with a nominal summer output of 0.4 kg/s. It is classed a typical low pressure well with a maximum well head pressure (WHP) of 4.5 bar abs. Maximum output mass flow was measured at 4.3 kg/s at an enthalpy of 720 kJ/kg and a WHP of 4 bar abs. Normal production flowrate varies between 0.4 and 1 kg/s depending upon the load.

The measured output for this well is shown at Figure 2. The maximum discharge pressure (MDP) was 4.5 bar abs at a flow rate of 3.2 kg/s. Maximum output to a 80 mm pipe was 4.3 kg/s at an enthalpy of 720 kJ/kg. The Brown program was used to calculate the well performance and a final match was achieved with data input as in Table 1. Note that the drawdown factor (K) was fixed at zero and the weight of dissolved solids at 0.07%. K = 0 is justified from the discussion below. Rotorua wells produce alkaline chloride water with chloride concentrations in the range 250 - 1000 ppm. A value of 0.07% total dissolved solids is therefore not unreasonable.

Having achieved a reasonable match the sensitivity of the output to small changes in some of the variables was investigated. Bottomhole temperature has the major effect on the output curve. Figure 3 shows the effect of changes in temperature and hence on the required accuracy of measured temperature as input to the program whilst the effect of drawdown factor is illustrated in Figure 4. Increase in drawdown factor K reduces the dynamic bottomhole pressure which results in a lowering of the flash point. For the small flows taken from this well large pressure is not expected, particularly since the reservoir is known to be highly permeable, so choosing K = 0 for the matching profile is justified.

Work by the Geothermal Task Force in Rotorua (1985) established that the mean draw-off for a domestic home on a low pressure bore was about 0.12 kg/s. Although well 715 serves 9 homes the demand shows that it has to be able to operate at low flow rates - however control of such wells is difficult. When operated at low output the wells operate in the slug flow regime with vigorous cycling of well head pressure which eventually leads, as flow rate is reduced, to well collapse, Figure 5. The normal operating range is illustrated in this figure. To avoid such problems users would tend to adopt usage at higher flow rates which leads to a wastage of energy. It is desirable therefore to be able to operate at higher flow rates above the mass flow given by MDP. i.e. the upper part of the output curve.

The Brown program was used to study the influence of reduced casing diameters on output. Production casings of 0.076 m (3 in) and 0.063 m (2 1/2 in) were used as input keeping the other parameters as used in the matching exercise constant. For flow rates less than 1.4 kg/s, the 0.076 m diameter casing gives a higher WHP for the same mass flow, Figure 6. It follows that a smaller diameter is more suitable for these lower flow rates since it allows the well to be operated on the stable part of the output characteristic whilst giving the desired mass flow.

3.3 Study 2: Yangbajing Tibet UNTCD

The Yangbajing field is located at an elevation of 4300 m some 90 km NW of Lhasa in Tibet. The identified geothermal field covers an area of about 15 km . 42 wells have been drilled with depths ranging from 43 to 603 m. One well was deepened to 1726 m for exploratory purposes. Excluding the exploratory wells, which are smaller in diameter, the wells are drilled with diameters ranging from 15 1/2 in to 8 1/2 with either a 9 5/8 or 7 in slotted liner at the producing horizon. Bottomhole temperatures are generally between 150 - 160°C, the maximum recorded is 172°C. The average enthalpy in the field is 650 kJ/kg corresponding to saturated water conditions. 10 MW of generating plant are installed using condensing turbines. The first unit (1 MW) was single flash, the latter units (3 x 3 MW) are all double flash.

Typical output characteristics of the wells are presented in Figure 7, Cappetti, Wu (1985). Two groups of wells are identified, low and high pressure. Calcite deposition and reinjection of fluid into production wells due to excessive pressure in the steam gathering system and to the different production characteristics of the wells are two major operating problems of the system.

ZK 327 was selected for study as the data available on this well was complete, Table 3. A match using the simulator with the output data was obtained, Figure 8, with a downhole temperature of 145°C, the measured temperature was 151°C. The difference in temperatures is greater than might be expected so the effect of some of the other input variables was investigated. Changes in total dissolved solids content are illustrated in Figure 9. The effect of 10% by weight total solids brings the two curves closer together but note that this has the effect of lowering the maximum mass flow and the MDP, both effects as the result of the elevation of the boiling temperature with an increase in percentage solids. The simulation treats the solids as if they were all sodium chloride. For the Yangbajing wells the total dissolved solids is estimated at 0.3% by weight of total fluid. (UNTCD 1985)

Diameter changes produce similar results to those discussed for the Rotorua case. Reduction in diameter reduces the MDP and reduces the maximum mass flow. This occurs because of increased two phase friction losses depressing the flashing level.

The effects of gas have not been studied with this simulator. Generally we would expect the MDP to rise as a function of total percentage by weight of gas in the fluid. The Yangbajing wells have an average non-condensable gas content of 0.1% by weight in the total fluid. Utilising a simulator which is currently under development an increase of well head pressure for the same mass flow of the order of 20% is tentatively indicated. This effect needs further study.

4.0 FINAL COMMENTS

The studies have illustrated how well bore simulators can be used to investigate and prove well characteristics. For this work the Brown simulator has been used not because we have shown it is any better than any other, only that it performs satisfactorily for these shallow wells. This is probably because these shallow wells are generally operating with a bubble or slug flow predominantly in the upper part of the well as opposed to annular flow which is the regime normally experienced in the deep wells. There is still a need to have a more reliable model which has been validated in a wide range of operational geothermal fields. A detailed knowledge of the effects of gas and solids chemistry on the thermodynamic properties of the geothermal fluid is necessary as well as methods for accounting for multiple feed point wells. It may well be that a reappraisal of the technique using correlations for void fraction, etc is necessary. The problem is complex and a completely accurate simulator may not be possible. However the state of the art is that simulators are available which can be used as an aid for field management decision making with satisfactory accuracy.

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Table 1: General

	Shallow well	Deep well
Bottom Hole Temperature	170°C	170°C, 260°C
Well depth	200 m	1000 m
Casing inside diameter	0.2245 m	0.2245 m
Pipe roughness	4.57 x 10^{-5} m	4.57 x 10^{-5} m
Weight % dissolved solids	0	0
Drawdown factor	0	0
Calculation step	5 m	25 m

N.B. Bottom hole pressures are given in Figure 1.

Table 2: Rotorua Well 715

Bottom Hole Pressure	12.0 bar abs
Bottom Hole Temperature	167°C
Openhole Diameter	0.152 m (6")
Roughness	3.05 x 10^{-4} m
Casing inside diameter	0,1032 m (4.06")
Roughness	3.05 x 10^{-5} m
Depth to change of diameter	100 m
Weight % dissolved solids	0.07
Drawdown factor	0
Calculation step	2 m

Table 3: Yangbajing Well ZK 327

Static Bottom Hole Pressure	12.27 b abs
Bottom Hole Temperature	151°C
Well depth	110 m
from 110 m to 108 m open hole diameter	0.31123 m
from 108 m to 65 m slotted liner diameter	0.2245 m
from 65 m to 51 m blind liner diameter	0.2245 m
from 51 m to surface, diameter	0.3205 m
Weight % dissolved solids	0.3
Drawdown factor	12856 Pa/(kg/s)
Calculation step	5 m

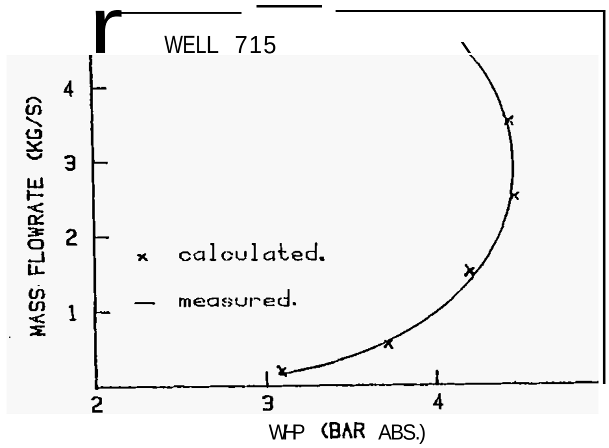
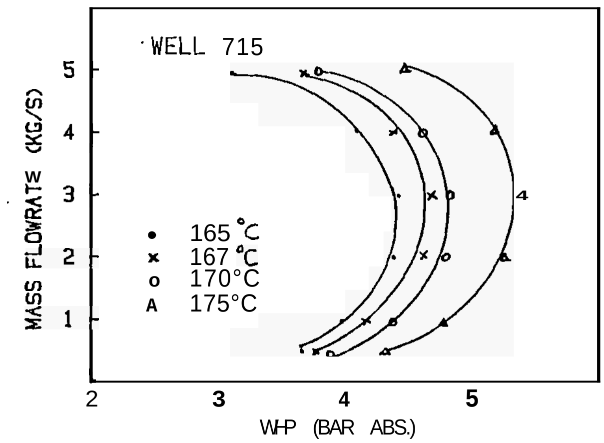


FIG.2 MATCHING OF OUTPUT CURVE



FIC.3 EFFECT OF BOTTOM HOLE TEMPERATURE

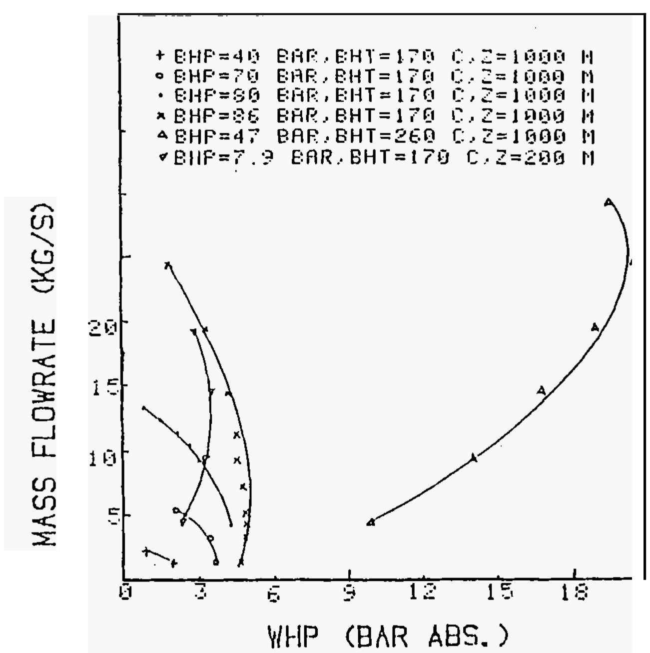
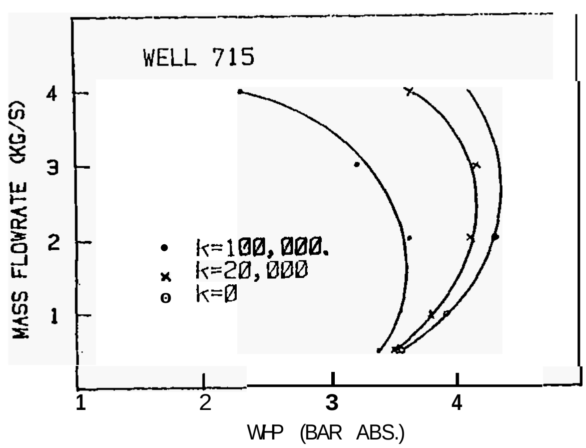


FIG.1 GENERAL CASE



FIC.4 EFFECT OF DRAWDOWN FACTOR

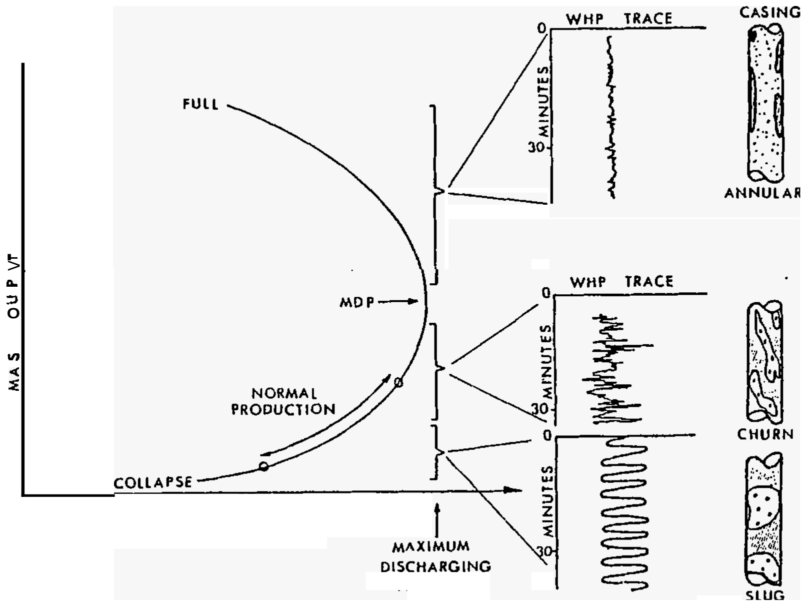
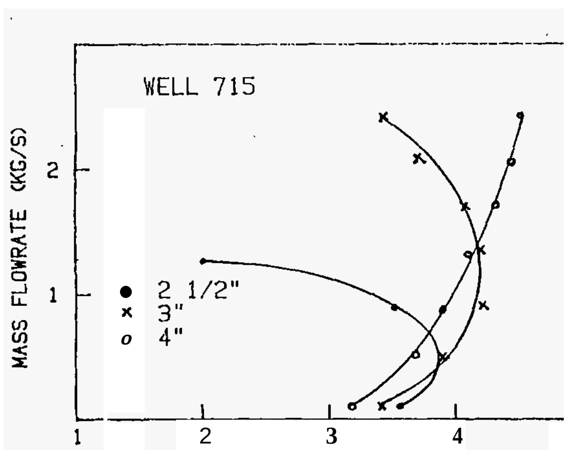


FIG.5 OUTPUT CURVE ROTORUA



FIC.5 EFFECTS OF DIFFERENT DIAMETER

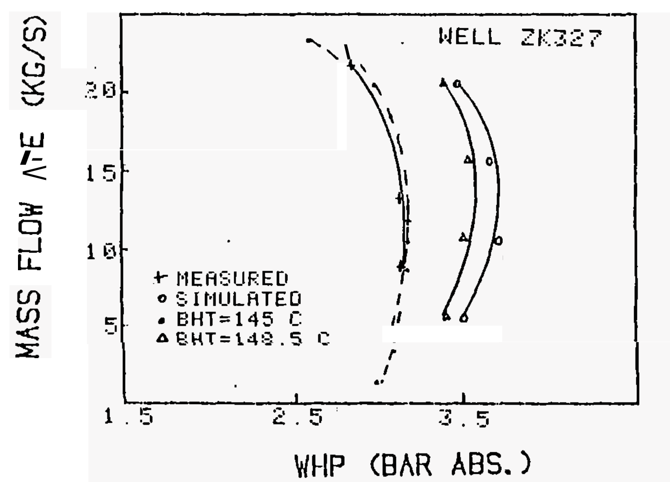
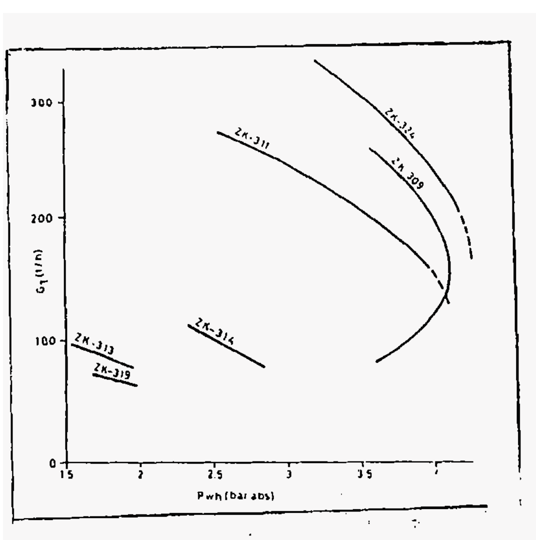


FIG.8 MATCHING OF OUTPUT CURVE



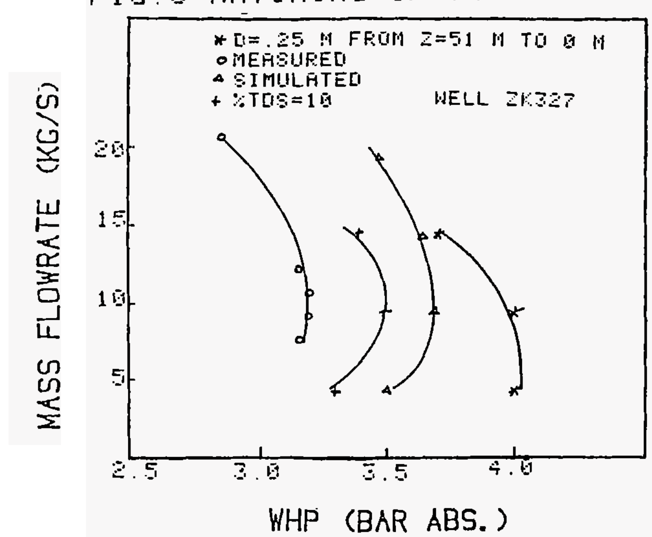


FIG.9 EFFECTS OF % SOLIDS AND DIAMETER