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THE WELLBORE SIMULATOR SIMU2000

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ABSTRACT

This work presents a brief description of the architecture and scope of the wellbore simulator SIMU2000. Its prime application involves the representation of the different flow types and thermodynamic conditions found in geothermal wells. The simulator utilizes a homogeneous flow model that incorporates the fundamental theories of Fluid Mechanics. It allows the handling of two-phase three component mixtures (H_2O-NaCl-CO_2), which represent the main constituents appearing in the production of geothermal fluids.

SIMU2000 uses a new two-phase friction factor developed based on 64 production tests carried out on 45 different wells. More than 324 pressure drop data and 628 temperature measurements were recovered from wells. Mechanical log recorders (Kuster) were mainly used but some electronic logs (Hot Hole and Pruett) were also carried out. The friction factor is calculated using the Reynolds number, steam quality, and fluid pressure, therefore, it is independent of any flow pattern identification. Production data included specific enthalpies from 650 to 2780 kJ/kg, fluid pressures between 0.4 and 14 MPa, and fluid temperatures from 110 to 340 °C.

The computer code of SIMU2000 is written in Fortran 90 and generates an executable file a little bit greater than 1 Mb. This program is divided in four parts: the wellbore simulator; a graphical output to analyze the results on the screen; a separate subroutine to evaluate the mass flow rate of three component flows discharging to the atmosphere at the speed of sound; and a dialog box to calculate the thermodynamic state of a three component mixture for manual calculations. The code incorporated an efficient algorithm to solve the fluid transport phenomena, based on a numerical method of successive approaches. The simulator systematically uses the International System of Units, for data input and for output generation. Everything is realized into a friendly Windows 95 environment for the user.

Up to date, SIMU2000 has been applied on multiple wells covering a broad extent of thermal conditions. Results obtained through its use have been good enough from the engineering point of view. Nevertheless, updating of the simulator is not only a continuous task with the purpose of improving the simulator performance, but also looking for extending its application field.

1. INTRODUCTION

In this work the operational characteristics of the computer program named SIMU2000 are described. This program incorporates two fundamental parts: The uses of a wellbore simulator with the capacity of simulating a three component mixture; and the uses of an on-line graphical output that makes possible the analysis of the simulation results on a computer screen, without having to leave the program. The program also has a subroutine that allows the estimate of three component mass flow rates discharging to the atmosphere at the speed of sound.

The purpose of this project consisted of developing a simple simulator using a new model. This model can be apply to reproduce the thermodynamic conditions of the different flow thermodynamic conditions (it could be single-phase, bubble, slug, churn, or annular flow), which happen inside the wells. Also, the model must maintain the fundamental form of the equations of the fluid mechanics for single-phase flows so that the fluid can be considered as a homogeneous mixture. However, the model cannot be directly applied using the single-phase Colebrook-White friction factor in two-phase flows. This is because of the use of this correlation in two-phase flows generates lower pressure drops than those measured inside wells, mainly when the mass flow rate is low and the wells produce low enthalpy fluids.

The first target of this work consisted the development of a two-phase friction factor correlation to be used in the simulator. Thus, the available data of 64 production tests carried out on two-phase producing wells, were analyzed. Each production test included the following data: total mass flow rate, the gas/gas+steam mass ratio, total dissolved solids (TDS) in the liquid phase, enthalpy, well completion, formation temperature distribution (few wells), production period, and pressure and temperature logs run throughout the well. The information was processed in a computer using the momentum equation along with pressures, temperatures, enthalpies, and other auxiliary supports (steam tables, etc.), to estimate among others: the Reynolds number, average pressure and temperature, steam quality, dynamic viscosity, friction factor, and some specific dimensionless groups. In the beginning, most of the dimensionless groups were plotted as those used in the petroleum technology (Hagedorn and Brown, 1965). It was looking in these plots for a correlation that allowed to estimate the friction factor, however, that failed. Later, some correlation was noticed when a log-log plot using Reynolds number as abscissa and friction factor as ordinate was used. Finally, three relevant features were observed on this figures, these are: The Colebrook-White friction factor can be applied for cases where Reynolds numbers are greater than 3×10^6, regardless of steam quality (X). The friction factor for moderate-high enthalpy flows ($0.25<X<1$) is not pressure dependent; For flows with steam quality between $0<X\#0.25$, the friction factor is pressure dependent. With this new correlation the friction factor does not require the previous identification of the flow pattern.

The simulator can consider simultaneously the three predominant components in a geothermal system, they are: water (H_2O), sodium chloride (NaCl), and carbon dioxide (CO_2). Geothermal fluids are known to contain dissolved solids and non-condensable gases. However, it is considered in the practice of reservoir and wellbore simulation that the total dissolved solids (TDS) presented in the liquid phase of a geothermal fluid (Cl, B, HCO_3, SiO_2, SO_4, Na,K, Li, Rb, Cs, Ca, As, etc.) can be represented by an equivalent sodium chloride. In the same manner, the different constituents of

the gaseous mixture (CO_2, H_2S, NH_3, He, H_2, Ar, N_2, CH_4, etc.) can be substituted by a carbon dioxide equivalent. The resulting mixture of these three components is internally treated by the simulator as a pseudo-homogeneous fluid. Note that it is assumed that the flow travels uniformly through any pipe section at an average velocity and there is no slip between phases. Based on these assumptions, those thermodynamic parameters of the mixture involved in the fluid transport are calculated, among them: enthalpy, specific volume, and dynamic viscosity.

The thermodynamic properties of each component of the mixture are calculated using published information (Battistelli et al. (1993), Haas (1976 a, b), Pritchett et al. (1981), Schmidt (1979), Sutton (1976), and others). This simulator mainly manages the information in a tabular form, however, some properties are quantified using high precision correlations (Pritchett et al.1981). The calculation of tabulated thermodynamic parameters (Haas 1976 a, b and Schmidt 1979) is carried out using lineal methods of interpolation and extrapolation. When the liquid and vapor CO_2 partitions have to be estimated, Henry's Equation (Battistelli et al. (1993)) and Dalton's Law or Sutton's Relation (Sutton (1972)) are used, along with, the mass and energy conservation equations. The iterative method of Newton-Raphson is applied for these last purposes. However, the main solution algorithm that SIMU2000 presents, is an efficient numerical method of successive approaches. Though, the convergence criteria take values about 1×10^{-12}, sometimes.

The simulator code can handle at a time one of three different thermodynamic processes throughout the well, according to its surrounding formation conditions, these are: adiabatic; isoenthalpic; and radial heat transfer under pseudo-transient state. All of them are applied considering a steady-state flow inside the whole well. The simulator can run either from wellhead to bottom hole and vice versa. It uses the pressure or the temperature as the prime thermodynamic variable. The specific enthalpy or the dry mass fraction as secondary variable (for subcooled liquid, pressure or temperature can be used as secondary variable). Furthermore, it must be defined the mass fractions of sodium chloride and carbon dioxide and both must be based on the total mass flow rate. In this way, the simulator needs four thermodynamic variables to initiate a run. Besides, the well completion (Figure 1) is introduced to instruct the simulator with respect to the different pipes throughout the fluid flows upwards to the surface. This information embraces the lengths, inclinations and diameters of the pipes. In addition, the depth at the liner was hanged, the depth at the well was left as discovered hole, and its diameters, too. Also, the simulator requires to know the values of some thermo-physical properties of the materials. Mainly those of the formation (thermal conductivity and diffusivity) and the cement (thermal conductivity). Those last are required to include the effects of heat transfer between the well and the formation. Additionally for this option, the diameters of the holes where the pipes were cemented have to be included. It is also needed to know the distribution of temperatures in the formation (stabilized temperatures). All these data can be incorporated to the simulator through the filling of an electronic format (template) which is incorporated to the main menus of the program.

The simulator code and the graphical output were developed in language Fortran 90. It generates an executable file lightly bigger than 1 Mb, after its compilation. Many subroutines were created and designed in a modular form. It was done to carry out multi-tasks without having to leave the application. This program has the support of Windows 95, allowing that any graphical result can be sent to the printer connected to the computer system. In this way, it is possible to save graphical results in files with bitmap format, too. Also, it is easy to copy information in the clipboard to paste it on documents created with a text processor, later. The program incorporates a series of dialog boxes. Those are used mainly to estimate the critical mass flow rates of three-component mixtures and defining the thermodynamic states of those same ternary systems, these last for manual calculations.

2. PREVIOUS WORKS

Up to date, diverse two-phase correlations have been published to predict the pressure losses in vertical, horizontal and inclined pipes. They were mainly developed to be applied in the oil industry, but they have also been used in Geothermics. Because the fluid mechanics of multi-phase flows is very complex , empirical correlations have often been used to fit measured data. Consequently, the validity of these depended on the quality and quantity of the production data. It has been reported in the literature that the use of those correlations provides satisfactory results inside the limits they were developed. However, outside these limits usually they fail. Recently mechanistic models, which have theoretical justification, have been increasingly used. Next, some wellbore simulators are briefly described because their principal characteristics are known.

2.1 Simulator Twophase. This simulator was implemented by Ortiz (1983) and it includes the use of the correlation of Orkiszewski. It has the capacity to simulate pure water and a unique method for the behavior of sodium chloride mixtures. It also includes, the mechanism of heat transfer between the well and the formation, under steady state.

2.2 Simulator Wellsim. This program incorporates the following five correlations of flow: Orkiszewski, Wellsim, Aziz, Duns and Rus, and Hagedorn and Brown. The simulator can handle the flow of three-component mixtures (H_2O-NaCl-CO_2), with or without the mechanism of heat transfer. Probst et al (1992) made a comparison of the operation of each of these models. They concluded that none of these correlations can be applied for all the cases.

2.3 Simulator Profili. This simulator was implemented by Battistelli et al. (1992) using the work of Barelli et al. It has the capacity to handle three-component mixtures (H_2O-NaCl-CO_2) in a liquid phase or in two-phases, considering a steady state flow. A numerical procedure is used to solve the conservation equations of mass, momentum, and energy. The procedure includes heat transfer mechanism between the well and the formation.

2.4 Simulator Simu1993. This simulator was developed by Sánchez (1995). It incorporates a homogeneous model able to simulate three-component fluids (H_2O-NaCl-CO_2), under steady-state conditions. This uses directly the correlation of Colebrook-White to calculate friction factor, so that the simulator can be used for the case of two phase flow only at high mass flow rates.

3. FUNDAMENTAL EQUATIONS

SIMU2000 solves simultaneously the three fundamental equations of Fluid Mechanics, assuming a steady-state flow. These and other auxiliary equations are presented below.

3.1 Momentum Conservation

The relation that results from combining the conservation equations of mass and momentum is

$$P_1 = P_2 + ISIG\left[\frac{f\dot{m}^2 L (v_1 + v_2)}{4 A^2 D_h} + \frac{2 g Cos(\phi) L}{v_1 + v_2} + \frac{\dot{m}^2 (v_2 - v_1)}{A^2}\right] \quad (1)$$

where:

P = fluid pressure
f = friction factor
$\dot{m}$ = mass flow rate of fluid
L = pipe length
v = specific volume of the fluid
g = acceleration of the gravity
A = area of the traverse section of the pipe
D_h = hydraulic diameter
Cos = cosine function
φ = angle of inclination from the vertical
ISIG = calculation direction (+1 from wellhead to bottom hole, -1 opposite direction)
1, 2 = pipe section number

3.2 Conservation of Energy

The relation that results from combining the conservation equations of mass and of the energy is

$$h_1 = h_2 + ISIG\left[\frac{\dot{m}^2 (v_2^2 - v_1^2)}{2 A^2} + g Cos(\varphi) L + \frac{q}{\dot{m}}\right] \quad (2)$$

where:

h = specific enthalpy of the fluid
q = heat transfer between the well and the formation

The heat transferred between the well and the formation is

$$q = U A_p (T_f - T_{hole}) = \frac{2\pi\kappa_{for} L (T_{hole} - T_{for})}{f(t)} \quad (3)$$

where:

U = global heat transfer coefficient
A_p = heat transfer area
T_f = fluid temperature
T_{hole} = temperature in the wall of the hole
κ_{For} = thermal conductivity of the formation
f (t) = function of time

The global heat transfer coefficient is quantified according to

$$U = \frac{1}{\frac{1}{h_i} + r_1(\delta + \gamma)}$$
$$\delta = \frac{1}{\kappa_a}\left(Ln\frac{r_2}{r_1} + Ln\frac{r_4}{r_3} + ... + Ln\frac{r_{n-1}}{r_{n-2}}\right) \quad (4)$$
$$\gamma = \frac{1}{\kappa_c}\left(Ln\frac{r_3}{r_2} + Ln\frac{r_5}{r_4} + ... + Ln\frac{r_n}{r_{n-1}}\right)$$

where:

h_i = convection heat-transfer coefficient
r_1 = internal radius of production pipe
κ_a = thermal conductivity of steel
κ_C = thermal conductivity of cement
r_n = internal radius of the hole (r_{hole})

The thermal conductivity of steel with 0.5% of carbon is 48.44 W/m °C at T=200 °C. The thermal conductivity of cement is about 0.5 W/m °C (Willhite, 1967), for dry conditions. For a fully developed turbulent flow in a pipe the value of the film conductance (hi) is greater than 115 W/m² °C. Considering this, Equation (4) becomes

$$U = \frac{k_c}{r_1\left(Ln\frac{r_3}{r_2} + Ln\frac{r_5}{r_4} + ... + Ln\frac{r_n}{r_{n-1}}\right)} \quad (5)$$

and the function f(t) is calculated with

$$f(t) = E_1(\psi) = E_1\left(\frac{\rho_{for} c_{for} r_{hole}^2}{4\kappa_{for} t}\right) = E_1\left(\frac{r_{hole}^2}{4\alpha_{for} t}\right) \quad (6)$$

where :

$E_1(\psi)$ = exponential integral of ψ
ρ_{for} = formation density
c_{for} = specific heat of the formation
α_{for} = thermal diffusivity of the formation
r_{hole} = radius of the hole

Then the temperature in the wall of the hole (Willhite 1967) can be determined using

$$T_{hole} = \frac{T_f f(t) + \frac{2\kappa_{for}}{U r_1} T_{for}}{f(t) + \frac{2\kappa_{for}}{U r_1}} \quad (7)$$

3.3 Single-Phase Friction Factor

The friction factor for single-phase flows is calculated starting from the correlation of Colebrook-White. This is:

$$\frac{1}{\sqrt{f}} \& 0.8686\ Ln\left(\frac{1}{\frac{e}{D}}\right) \% 0.8686\ Ln\left(1\%\frac{9.28}{Re\ \frac{e}{D}\ \sqrt{f}}\right) ' 1.14 \quad \textbf{(8)}$$

where:

f = friction factor
Ln = natural logarithm
ε = absolute roughness of the pipe
Re = Reynolds number based on the pipe diameter

The Reynolds number based on the pipe diameter is:

$$Re ' \frac{4\ m}{\pi\ D\ \mu} \quad \textbf{(9)}$$

where:

μ = dynamic viscosity of the fluid

3.4 Two-Phase Friction Factor

It has been observed that applying the Colebrook-White single-phase friction factor to two-phase flow results in the prediction of lower pressure drops compared to measured. Thus, a new friction factor that works for two-phase flow was required to be included in SIMU2000. After studying and manipulating data from 64 production tests the set of equations presented in the Table 1 and represented in Figures 2 and 3 were obtained. The study also showed that the Colebrook-White single-phase friction factor can be applied to two-phase flow for Reynolds numbers greater than 3×10^6, regardless of the steam quality of the fluid.

4. EFFECTS OF NACL AND CO_2

The thermodynamic behavior of pure water under saturated conditions is altered according to the content of dissolved solids in the liquid phase. This effect can be clearly observed in a graph of temperature against pressure, showing the saturation line for pure water (Clapeyron's Diagram). The measured pressure and temperature must be incorporated to this graph. After that, it will be noted that the fluids inside the well under saturation conditions are located in the region of superheated steam, if the salt content is appreciable. In comparison to pure water, the pressure gradients inside the well are bigger. This is because the increase of the density and viscosity, and the reduction of the specific enthalpy of the fluid. The effect of CO_2 in pure water is more complicated than that of the NaCl. The two-phase pressure gradients of H_2O-CO_2 and H_2O- CO_2-NaCl mixtures are smaller than those observed in two-phase pure water flows. These effects can also be detected in a Clapeyron diagram because all these thermodynamic states lie on the subcooled liquid region. Thus the calculated flashing point inside the wellbore is sensible to the mass fractions of the constituents.

5. THE SIMULATOR'S PROBLEMS

The main problem during the development of the simulator arose when the thermodynamic condition of the three component mixture is close to the saturation state. It appeared in upwards or downwards simulations, when the flow tries to pass from the subcooled liquid region to two phases or vice versa, respectively. Apparently, there is a discontinuity in the thermodynamic tables developed for the simulator. The problem appeared when the subroutine in charge to calculate the partition of CO_2 in the liquid phase through a non-linear equation failed. This subroutine uses the Newton-Raphson method to obtain a solution but it sometimes did not converge. This problem was avoided by making an appropiate linearization of the equation. This last option is utilized when the probem occurs otherwise the original equation is employed.

6. DISCUSSION

The new two-phase friction factor correlations presented here were developed assuming that the fluids of the 64 production tests were pure water. Also, it was assumed that the fluids followed an isoenthalpic process, and therefore, no heat transfer from the well to the formation took place. This friction factor depends on Reynolds number, steam quality, and pressure (sometimes). In the actual fluid case that includes dissolved solids and non-condensable gases, the Reynolds number is not the same as that of pure water. However, the results obtained after the simulation of many wells showed that the use of these friction factors generates reasonable results.

7. CONCLUSIONS

1. The results obtained from the application of the simulator SIMU2000 to multiple wells have been encouraging. This simulator has been applied to the following tasks: identification of feed zones; definition of optimal pipe completion for repair purposes; construction of output curves through the employment of a radial reservoir model; and estimation of reservoir parameters such as the hydraulic conductivity and average pressure and temperature. At present, the wellbore simulator is being implemented into a reservoir simulator in order to make the simulation of the whole reservoir-wellbore system. This is doing (Suárez, 2000) as a project to obtain the degree of doctor in engineering. Figure 4 shows matching the pressure profile of well Asal 3 (Battistelli et al., 1992). This well produced fluids with high salt content and low enthalpy.

2. SIMU2000 uses a unique homogeneous model that can be applied to any well at any thermodynamic conditions. This is because the new friction factor correlation does not depend on thermodynamic conditions or flow regimes. These new correlations can generate smaller values for friction factor than those calculated for single phase flows, specially for low pressure and low Reynolds number (see Figure 2). In these cases, the friction factor of Colebrook-White must be used.

8. ACKNOWLEDGMENTS

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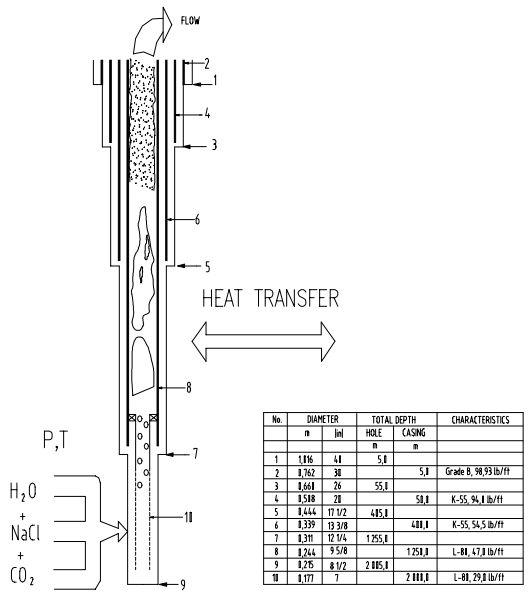
TABLE 1. TWO-PHASE FRICTION FACTOR

STEAM QUALITY	PRESSURE [MPa]	ENTHALPY [kJ/kg]	Re	EQUATION
0#X#1	$0.1	No	$Re>3x10^6$	Colebrook-White
0<X#0.25	>1.5, IF P>7.2, P=7.2	No	$8.5x10^5<Re<3x10^6$	$f = 10^{(3.2946-0.7925 \log (Re))}$ for P = 3.2 $f = 10^{(4.6226-0.7925 \log (Re))}$ for P = 7.2
	# 1.0	<700.0	$Re<1.0x10^5$	$f = 10^{(14.5-2.8614 \log (Re))}$ for P = 0.5 $f = 10^{(16.0-2.8614 \log (Re))}$ for P = 1.0
		<980.0	$1x10^5$#Re# $2x10^6$	$f = 10^{(15.0-2.8614 \log (Re))}$ for P = 0.5 $f = 10^{(16.0-2.8614 \log (Re))}$ for P = 1.0
		No	$1x10^5$#Re#$2x10^6$	$f = 10^{(14.5336-2.8614 \log (Re))}$ for P = 0.5 $f = 10^{(15.4980-2.8614 \log (Re))}$ for P = 1.0
	1.5	<980.0	$1x10^5$#Re#$2x10^6$	$f = 10^{(16.5-2.8614 \log (Re))}$
		No		$f = 10^{(15.9837-2.8614 \log (Re))}$
	2.0	<980.0	$1x10^5$#Re#$8.5x10^5$	$f = 10^{(17.0-2.8614 \log (Re))}$
		No		$f = 10^{(16.4694-2.8614 \log (Re))}$
	3.0	< 980.0	$1x10^5$#Re#$8.5x10^5$	$f = 10^{(18.0-2.8614 \log (Re))}$
		No		$f = 10^{(17.0436-2.8614 \log (Re))}$
	4.0, IF P>4.0, P=4.0	No	$1x10^5$#Re#$8.5x10^5$	$f = 10^{(17.2348-2.8614 \log (Re))}$
0.25<X<1	No	No	$3.5x10^5$#Re<$3x10^6$	$f = 10^{(2.743-0.699 \log (Re))}$

No. Without restrictions

FIGURE 1. VERTICAL WELL COMPLETION



No.	DIAMETER		TOTAL DEPTH		CHARACTERISTICS
	m	in	HOLE m	CASING m	
1	1,016	40	50		
2	0,762	30		50	Grade B, 98,93 lb/ft
3	0,661	26	550		
4	0,508	20		580	K-55, 94,0 lb/ft
5	0,444	17 1/2	4350		
6	0,339	13 3/8		4800	K-55, 54,5 lb/ft
7	0,311	12 1/4	12550		
8	0,244	9 5/8		12500	L-80, 47,0 lb/ft
9	0,215	8 1/2	21850		
10	0,177	7		21800	L-80, 29,0 lb/ft

FIGURE 2. TWO PHASE FRICTION FACTOR (UPWARDS FLOW VERTICAL PIPE)
$0 < X \leq 0.25$

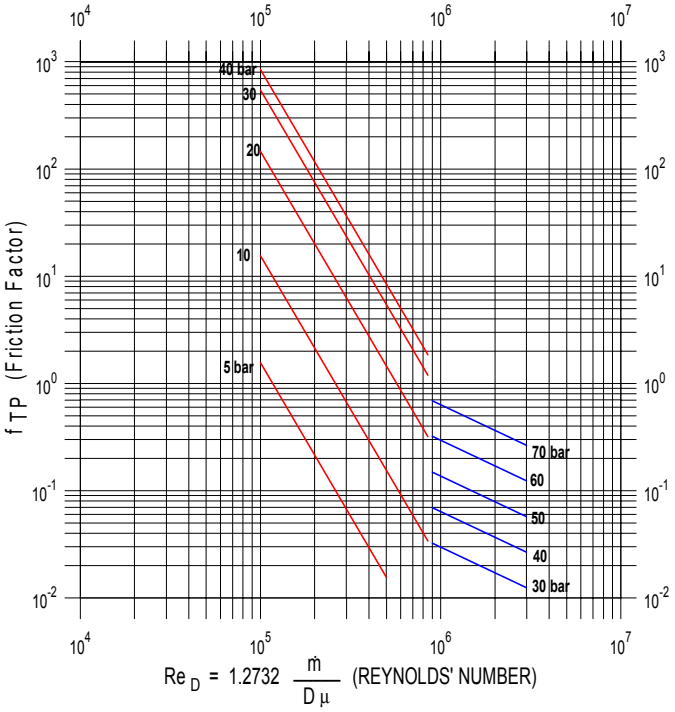


FIGURE 3. TWO PHASE FRICTION FACTOR (UPWARDS FLOW VERTICAL PIPE)
$0.25 < X < 1$

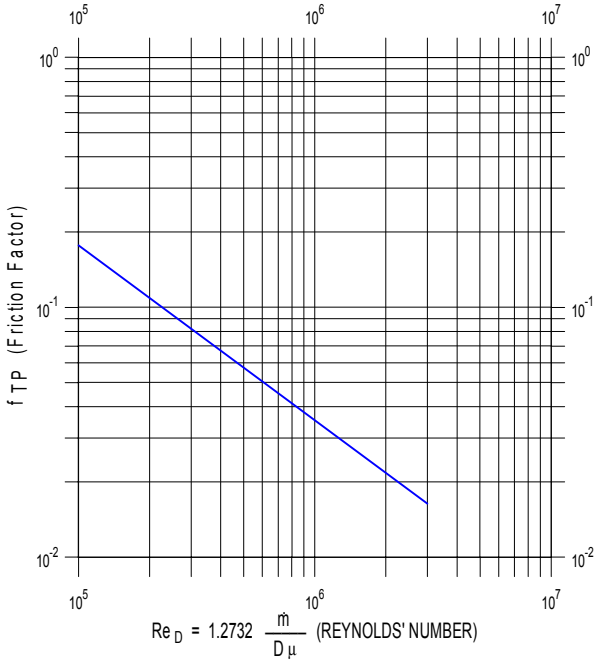


FIGURE 4. COMPARISON OF MEASURED AND CALCULATED PRESSURE
WELL ASAL 3, ASAL FIELD, REPUBLIC OF DJIBOUTI, EAST AFRICA