A NEW CORRELATION FOR PREDICTING NATURAL SEPARATION EFFICIENCY

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ABSTRACT
Based on the drift-flux model, a new mathematical formulation was developed to predict natural separation efficiency. The new model presented in this work considers the effect of the slip velocity in the radial direction, variable neglected in previous simplified models. In addition, a correlation for this effect was obtained by fitting the model to experimental data. Good agreement of this simplified model with the experimental data for not only lower but also for higher gas and liquid flow rates has shown the important effect that the slip velocity in the radial direction has in the prediction of natural separation.

INTRODUCTION

The amount of oil to be produced from a well depends on the bottomhole flowing pressure. Unfortunately for lower bottomhole flowing pressure below bubble point pressure, higher percentages of free gas will be present at the pump intake. As a result, the performance of the pumping system is significantly affected due to free gas. Quantifying the natural separation efficiency will allow not only predict how much free gas goes into the pump, but also will enable an optimum design of the lift system, increasing oil production and decreasing costs.

Since 1993, Tulsa University Artificial Lift Projects (TUALP) has been conducting important research in the area of natural separation. It has permitted gathering experimental data, using air and water, to develop, test, validate, and improve different correlations and models for estimating natural separation efficiency.

Based on the drift-flux model and assuming no slip velocity in the radial direction, in front of the pump intake, some simplified models have been developed at TUALP, such as Alhanati's (1993) and Serrano's (1999) models. Although these models have captured the physics involved in the problem, results have shown that they do not work very well for all operational conditions. On the other hand, simplified models do not consider the effect of important variables such as gas flow rate, pressure, geometric characteristics of the bottomhole and drag force in the radial direction, which have shown to have an strong effect on the natural separation process.

A new assumption has been considered in this work: the existence of the slip velocity in the radial direction. The new assumption allows obtaining a new mathematical formulation for the problem. Available experimental data was used to obtain a new correlation, which considers the drag effect not only in the vertical direction, but also in the radial direction. Results obtained for the new simplified model show the strong effect that the drag force has on the separation process. The new simplified model, with along the new correlation, represent an important change in the methodology used to predict natural separation efficiency.

LITERATURE REVIEW

Alhanati (1993) designed and conducted a vertical experimental facility to gather data on natural separation. The facility, shown in Fig. 1, presents an especial vertical casing section, which was designed and constructed to enable acquiring experimental data on natural separation efficiency. Gas and water are mixed in the lower part of that section. According to Alhanati, experiments showed that natural separation efficiency decreases with increasing liquid flow rate and pressure, and decreasing gas liquid ratio GLR.
Based on drift-flux approach, Alhanati developed the first simplified model for predicting natural separation efficiency in vertical flow. No slip velocity is considered in the radial direction. According to this model, natural separation depends on liquid flow rate and the terminal velocity of the bubbles in the vertical direction.

Serrano (1999) also conducted an experimental work for vertical and inclined flow by using the same experimental facility as Alhanati, shown in Fig. 1. However, a new casing section was designed and built to consider different inclination angles. Based on Alhanati's model, Serrano developed a new simplified model, which considers flow regime and inclination angle in the prediction of natural separation efficiency. No slip velocity in the radial direction was also assumed for this model.
Harun (2000) proposed a mechanistic model to predict natural separation efficiency in vertical pumped wells. The model

is based on the combined phase momentum equation and a general slip closured relationship. Experimental data was used to generate a correlation for drag coefficient and close the system of equations. Natural separation efficiency was obtained from the solution of the system of equations.

All models have been based on a single control volume situated in front of the pump intake port, where simple assumptions have allowed obtaining estimates of natural separation efficiency.

GENERAL FORMULATION OF THE NEW SIMPLIFIED MODEL

A single control volume situated in front of the pump intake will be considered in this approach. This single control volume is showed in Fig. 2. Three assumptions will be considered valid. The first assumption states that: the gas void fraction α_g is considered uniform across to the annulus domain and holds constant up to the pump intake port. The second assumption considers that the liquid column in the annulus in front and above the pump intake is not flowing in the vertical direction; it flows only in a radial direction towards the pump intake. The third assumption considers the existence of slip velocity between gas and liquid phases at the vertical and radial direction.
Assuming constant density, mass balance equation would allow establishing the following volumetric balance around the single control volume, as shown in Fig. 3.

$$Q_l^i = Q_l^p \qquad (1)$$

$$Qf = Q_{gv} + Q_{gp}^p \qquad (2)$$

Q_l^i and Q_l^p represent the liquid flow rate coming from the annulus and liquid flow rate going inside the pump, respectively. Similarly, Q_g^i , Q_{gp}^p and Q_{gv} are the gas flow rate coming from the annulus, gas flow rate going into the pump and the gas flow rate vented, respectively.

On the other hand, natural separation efficiency is defined as the ratio of the gas flow rate vented to the gas flow rate coming from the annulus, i.e.

$$E = \frac{Q_{gv}}{Qf} \qquad (3)$$

Combining Eqs. 2 and 3, the following equation for predicting natural separation efficiency E can be obtained

$$E = 1 - \frac{Q_{gp}^p}{Q_g^i} \qquad (4)$$

Gas flow rate can also be expressed as a function of superficial velocity and flow area, i.e.

$$\begin{aligned} Q_{gp}^p &= V_{rsg}^p \, A_p \\ Q_g^i &= V_{zsg}^i \, A_{Ann} \end{aligned} \qquad (5)$$

V_{rsg}^p and V_{zsg}^i represent the superficial gas velocity going into the pump and the superficial gas velocity coming from the annulus, respectively. A_p and A_{Ann} are the area of the port and the annulus, respectively. Combining Eqs. 4 and 5, natural separation efficiency would be given by

$$E = 1 - \frac{V_{rsg}^{p}}{V_{zsg}^{i}} \left(\frac{A_p}{A_{Ann}} \right) \qquad (6)$$

Based on a single control volume, as shown in Fig. 4, the following velocities field would be assumed valid in this work.

Gas Phase

$$V_{zg} = V_{zg}^{i} \;\; ; \;\; V_{rg} = V_{rg}^{p}$$

Liquid *Phase*

$$\overline{V}_{zl} = 0 \;\; ; \;\; \overline{V}_{rl} = V_{rl}^{p} \qquad (8)$$

The slip velocity V_s is defined as:

$$V_s = \overline{V}_g - \overline{V}_l \qquad (9)$$

Where $\overline{V}_g$ and $\overline{V}_l$ represent the average actual gas and liquid velocity, respectively.

In the radial direction, the slip velocity definition given by Eq. 9, allows to obtain the following equation

$$V_{rs} = \overline{V}_{rg} - \overline{V}_{rl} = V_{rg}^{p} - V_{rl}^{p} \qquad (10)$$

V_{rg}^{p} and V_{rl}^{p} represent the actual gas and liquid velocity, respectively, going into the pump. Eq. 10 can also be rewritten as a function of superficial velocity and gas void fraction as:

$$\frac{V_{rsg}^{p} \qquad V_{rsl}^{p}}{(1-\alpha_g)} \qquad (11)$$

On the other hand, From Eq. 1 and assuming constant density, the following equation for V_{rsl}^{p} is valid,

$$V_{rsl}^{p} = V_{zsl}^{i} \left(\frac{A_{Ann}}{A_p} \right) \qquad (12)$$

Combining Eqs. 11 and 12, the following equation for V_{rsg}^{p} can be finally written

$$V_{rsg}^{p} = \left| V_{rs}\,(1-\alpha_g) + V_{zsl}^{i} \left(\frac{A_{Ann}}{A} \right) \right| \qquad (13)$$

Similarly, as in the radial direction, the slip velocity definition given by Eq. 9, can be used to obtain the following equation valid in the vertical direction.

$$V_{zs} = V_{zg}^{i} \qquad (14)$$

Eq. 14 can also be rewritten as a function of the superficial velocity and gas void fraction as:

$$V_{zs} = \frac{V_{zsg}^{i}}{\alpha_g} \qquad (15)$$

Therefore, one additional relationship for gas void fraction α_g can be obtained from Eq. 15. This equation is given by

$$\alpha_g = \frac{V_{zsg}^{i}}{V_{zs}} \qquad (16)$$

The solution of Eqs. 13 and 16 depends on two additional unknown variables, i.e. the slip velocity in the vertical and radial direction, V_{zs} and V_{rs}, respectively.

Using the drift-flux model approach proposed by Ishii (1975), the slip velocity V_s at any direction can be related to the terminal velocity of a particle V_∞. This relationship is given by

$$V_s = V_\infty\,(1-\alpha_g)^{n-1} \qquad (17)$$

n represents the effect due to the presence of others bubbles. Some authors have considered that under churn flow regime n may be negligible. Since most of the available experimental data is mainly under this flow regime, then n will be assumed equal to zero. Therefore, Eq. 17 will be given finally by

$$V_s = \frac{V_\infty}{(1-\alpha_g)} \qquad (18)$$

Using Eq. 18, superficial gas velocity going into the pump V_{rsg}^{p} and gas void fraction α_g, given by Eqs. 13 and 16, can be rewritten as a function of the terminal velocity, instead of the slip velocity, in the vertical and radial direction, $V_{z\infty}$ and $V_{r\infty}$, respectively.

$$V_{rsg}^{p} = \left| V_{r\infty} + V_{zsl}^{i} \left(\frac{A_{Ann}}{A} \right) \right| \qquad (19)$$

Combining Eqs. 19 and 20 and replacing into Eq. 6, natural separation efficiency would be finally given by

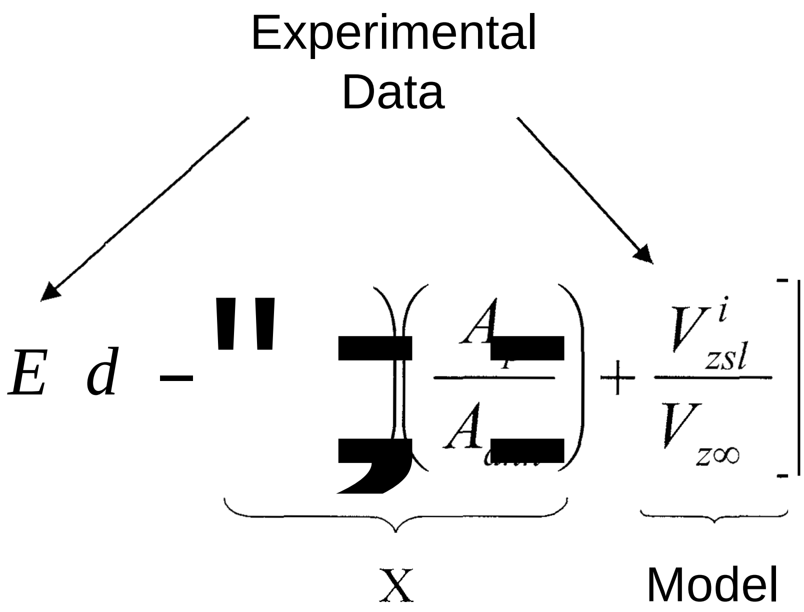
$$E = 1 - \left[\left(\frac{V_{r\infty}}{V_{z\infty}} \right) \left(\frac{A_p}{A_{Ann}} \right) + \frac{V^i_{zsl}}{V_{z\infty}} \right] \qquad (21)$$

Eq. 21 depends on superficial liquid velocity V^i_{zsl}, geometric configuration of the bottomhole $A_p \,/\, A_{Ann}$, and the terminal velocityratio $V_{rm} / V_{z\infty}$.

Terminal velocity at vertical direction $V_{z\infty}$ can be estimated from models such as Harmathy (1960), Wallis (1974), Ishii and Zuber (1979), among others. The geometric characteristics of the bottomhole can also be easily determined. The problem is how to estimate the terminal velocity in the radial direction V_{rm}. In this paper, a correlation will be showed as a solution for $V_{r\infty}$.

NEW CORRELATION

TUALP has been gathering experimental data on natural separation since 1993. Taking account this important aspect, the following analysis on Eq. 21 would show how the available experimental data could be used to obtain a correlation for the drag effect.



According to Eq. 21, natural separation efficiency E and superficial liquid velocity coming from the annulus V^i_{zsl} are two known variables from the available experimental data. Terminal Velocity at vertical direction $V_{z\infty}$ can be determined by using the Ishii's model. According to Ishii (1979), V_{zm} for bubbly and slug/churn flow regime is given by

$$V_{z\infty} = \sqrt{2}\left[\frac{\sigma\,(\rho_l - \rho_g)\,g}{\rho_l^2}\right]^{1/4} \qquad (22)$$

The only unknown variable is the parameter X

$$X = \frac{V_{r\infty}}{V_{z\infty}}\,\frac{A_p}{A_{Ann}}$$

Therefore, Eq. 21 can be rewritten as

$$X = 1 - \left[E + \frac{V_{zsl}^{i}}{V_{z\infty}}\right] \qquad (23)$$

All experimental data for natural separation efficiency used in this paper was compiled and summarized in a technical report presented by Marquez (2002). This experimental data allowed plotting a graph of X vs. $V_{zsl}^{i}/V_{z\infty}$, as shown in Fig. 5. According to Fig. 5, for low liquid flow rates the slip effect in the radial direction can be negligible. Therefore, the assumption of no slip velocity in the radial direction, considered by Alhanati, would result valid. However, for higher liquid flow rates this assumption cannot be considered anymore.

Serrano corroborated this fact later when extended Alhanati's model by gathering extra experimental data for higher liquid and gas flow rates. Alhanati's model failed to match the data taken by Serrano. Consequently, Serrano tried to obtain a better model by developing an empirical correlation to predicting the local gas void fraction for the region in front of the pump inlet ports, assuming no slip velocity in the radial direction.

The new model, proposed in this work, assumes the existence of the slip velocity in the radial direction and its effect could be considered by developing a correlation from Fig. 5.

Using a nonlinear regression model, the following correlation for Xparameter was found.

$$X = -\left[\frac{a\,b + c\,(\frac{V_{zsl}^{i}}{V_{z\infty}})^{d}}{b + (\frac{V_{zsl}^{i}}{V_{z\infty}})^{d}}\right] \qquad (24)$$

Where the coefficients a, b, c and d are given by

$$a = -0.046439$$
$$b = 71.381638$$
$$c = 48.017803$$
$$d = 1.2169696$$

On the other hand, the new correlation would be limited for the following boundaries

$$X1 = -\frac{V'_{zsl}}{} \leq X \leq X2 = 1 - \frac{V'_{zsl}}{}$$

Those two boundaries are shown in Fig. 6. According to this figure, for values of $V^{i}_{zsl} / V_{z\infty}$ between 0 and 10, good agreement of the new simplified model with the experimental by using the new correlation was found. However, for values of $V^{i}_{zsl} / V_{z\infty}$ higher than 10, the new model shows certain disagreement. In order to avoid this problem, the previous correlation given by Eq. 24 was corrected. This correction would allow to keeping this curve inside of the boundaries. Therefore, the new constrained correlation would given by

$$X = 1 - \left| \left| 1 + \frac{a\,b + c\,(\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}}{b + (\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}} \right|^{172} + \left\{ \frac{V^{i}_{zsl}}{V_{z\infty}} \right\}^{272} \right|^{1/272} \qquad (25)$$

The correlation given by Eq. 25 shows good agreement with the boundaries and experimental data. Finally, natural separation efficiency may be calculated by

$$E = 1 - \left| 1 - \left| \left| 1 + \frac{a\,b + c\,(\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}}{b + (\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}} \right\}^{272} + \left\{ \frac{V^{i}_{zsl}}{V_{z\infty}} \right\}^{272} \right|^{1272} + \left(\frac{V^{i}_{zsl}}{V_{z\infty}} \right) \right|$$

or simply,

$$E = \left(\left\{ 1 + \frac{a\,b + c\,(\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}}{b + (\frac{V^{i}_{zsl}}{V_{z\infty}})^{d}} \right\}^{272} + \left\{ \frac{V^{i}_{zsl}}{V_{z\infty}} \right\}^{272} \right|^{/272} - \left(\frac{V^{i}_{zsl}}{V_{z\infty}} \right) \qquad (26)$$

A graph of New Model Predicted Efficiency vs. Measured Efficiency from TUALP data bank is shown in Fig. 8. The effect of the slip velocity at the vertical and radial direction has been considered through a new, accuracy and reliable correlation. **A** graph of this model is also shown in Fig. 9.

RESULTS AND DISCUSSIONS

Model Comparisons

The evaluation of this study was based on statistical parameters given by average percentage error $E1$, absolute average percentage error $E2$ and the standard deviation $E3$.

$$E1 = \left(\frac{1}{N} \sum_{i=1}^{N} e_{ri} \right) 100 \qquad (27)$$

$$E2 = \left(\frac{1}{N} \sum_{i=1}^{N} \left| e_{ri} \right| \right) 100 \qquad (28)$$

$$E3 = \sqrt{\left(\frac{1}{N-1} \sum_{i=1}^{N} \left(e_{ri} - \frac{E1}{100} \right)^2 \right)} 100 \qquad (29)$$

Where N represents the number of data points. On the other hand, the error e_{ri} is given by

$$e_{ri} = \frac{E_{cal,i} - E_{meas,i}}{E_{meas,i}} \qquad (30)$$

The performance of the new simplified model proposed in this paper can be compared with others simplified models such as Alhanati and Serrano by using the percentage error equations shown previously. Results have been divided in two categories, low and high gas void fraction, as shown in Table 1 and 2.

For low gas void fraction, Table 1 shows a 14.41% of average error in the prediction of natural separation by using the new correlation. For high gas void fraction, the error is much more lower compared with the others simplified models. According to Table 2, the average error in the prediction of natural separation is 3.02 %. In both cases, Alhanati's model resulted to have the closer performance to the new simplified model. Therefore, a comparative analysis can be established between these two models.

Fig. 10 shows the predicted vs. measured natural separation efficiency obtained from Alhanati's model. According to this figure, the efficiency is under predicted. The new model proposed allows obtaining better results. The overall performance of Alhanati's model represents a 25.64% against of 17.43% of the new simplified model proposed.

Drag Effect

Drag effect in the vertical and radial direction has been considered in this new simplified model. This assumption was corroborated with the experimental results shown in Fig. 5. According to this figure, slip in the radial direction can be negligible for low liquid flow rates. However, this assumption cannot be considered anymore for high liquid flow rates. The new correlation takes in account that effect, so predictions on natural separation will able to be estimated with higher accuracy, as a shown in Fig. 8.

Effect of Viscosity

Assuming bubbles with spherical shape, Ishii (1979) considered a force balance analysis on a bubble in an infinite medium, where the bubble is moving through the liquid in the vertical direction, only. This force balance would allow writing the following equation

$$\vec{F}_d + \vec{F}_g + \vec{F}_b = 0 \qquad (31)$$

Where the forces due to drag F_d, weight F_g, and buoyancy F_b, are given, respectively, by

$$F_d = \frac{1}{2} C_d \ \rho_l \ V_{z\infty}^2 \ A_d \qquad (32)$$

$$F_g = B_d \ \rho_g \ g \qquad (33)$$

$$F_b = B_d \ \rho_l \ g \qquad (34)$$

A_d and B_d represent the area of a particle projected on a horizontal plane and the volume of a typical particle, respectively. C_d, $V_{z\infty}$, ρ and g represent the drag coefficient, the terminal velocity of the bubble in the vertical direction, density and gravity term, respectively.

Assuming spherical shapes, the solution of Eq. 31, along with Eqs. 32, 33 and 34, permits one to obtain the following expression for the terminal velocity in the vertical direction $V_{z\infty}$.

$$V_{z\infty}^2 = \frac{8}{3} \frac{r_d}{C_d} \frac{(\rho_l - \rho_g) \ g}{\rho_l} \qquad (35)$$

The solution of Eq. 35 depends on variables r_d and C_d. According to Harmathy (1960), the drag force coefficient C_d is given by

$$C_d = \frac{4}{3} r_d \sqrt{\frac{(\rho_l - \rho_g) \ g}{\sigma}} \qquad (36)$$

Therefore, the terminal velocity in the vertical direction would be finally given by

$$V_{z\infty} = \sqrt{2} \left[\frac{\sigma \ (\rho_l - \rho_g) \ g}{\rho_l^2} \right]^{1/4}$$

According to Ishii, the model would be only valid for bubble and churn/slug flow regime. This model for $V_{z\infty}$ was used to predict the new correlation proposed in this paper.

Unfortunately, the model proposed for $V_{z\infty}$ does not allow considering the bubble size and viscosity effect. However, this particular case would change, if other formulations for C_d were used instead of recommended by Harmathy.

Drew and Lahey (1979) proposed the following correlation for drag coefficient C_d, assuming one-dimensional particle flow.

$$C_d = \frac{24}{\mathrm{Re}_p} (1 + 0.15 \ \mathrm{Re}_p^{0.687}) \qquad (37)$$

Where, the particle Reynolds number Re_p is defined as

$$\mathrm{Re}_p = \frac{2\, r_d\, |\vec{V}_s|\, \rho_l}{\mu} \qquad (38)$$

A special case would be the Stokes flow condition. In this case, the drag coefficient C_d is given by

$$C_d = \frac{24}{\mathrm{Re}_p} \qquad (39)$$

Considering Stokes flow, the terminal velocity in the vertical direction $V_{z\infty}$ would be given by

$$V_{z\infty} = \frac{2}{9}\frac{r_d^2}{\mu}(\rho_l - \rho_g)\, g \qquad (40)$$

One advantage of Eq. 40 would be that the viscosity and the bubble size could be considered in the prediction of natural separation efficiency. However, one additional closure relationship for the drag radius r_d would be required in this case. Since no reliable modeling or correlation is available for r_d, Ishii's model given by Eq. 22, instead of Eq. 40, was considered in this work. In short, the simplified model proposed in this work can also be modified in the future to consider viscosity effects.

Effect of Geometry

The new simplified model, given by Eq. 26, considers the effect of geometric characteristics of the bottomhole through A_{Ann}. As reported by Ghauri (1979), casing size is an important factor in submersible pump performance. The larger is annulus area; the better is natural separation efficiency.

The model was used to predict natural separation efficiency for a 4 in. outside pump diameter inside 5, 7 and 10 in. casings. According to Fig. 11, natural separation efficiency increases as the annulus area increases. This behavior is consistent with observed by Ghauri.

However, prediction about the port size effect will not able to be considered this time, even the simplified model suggests this variable. The new correlation only considers the annulus size. Therefore, the model suggests the possibility of develop a new mechanistic model instead of the correlation in order to quantify the effect of this important variable.

Effect of Gas

Lea and Bearden (1980) conducted tests with 500 series equipment inside a 7" casing, with air and water as experimental fluids at low pressures (25 to 30 Psig). According to their results, natural separation efficiency increases as the in-sib-free gas increases. Alhanati and Sambangi also reported the same observation. Unfortunately, the new correlation is not sensible to the gas flow rate. It does not appear to have any effect in the prediction of natural separation. Although the new simplified model performs satisfactorily, the mathematical solution based on a single control volume is not enough to capture all the variables involved in the natural separation process.

Effect of Pressure

Pressure is another important variable to be considers in the prediction on natural separation. Experiments have captured the effect of that variable in the separation process. However, the new simplified model, with along the new correlation, does not incorporate the effect of that variable in the prediction of natural separation. The only possible effect is through the fluid physical property calculation given by Eq. 22. The new simplified model developed should be improved to better incorporate the pressure effects observed in the experimental data.

CONCLUSIONS AND RECOMMENDATIONS

Some very important conclusions can be summarized, as follows:

1. A new simplified model to predict natural separation efficiency has been proposed in this paper. Based on the drift-flux model, mass and slip closure definition are solved into a single control volume situated in front of the pump intake.
2. This new model considers the effect of slip velocity in the radial direction, a variable neglected in previous simplified models. In addition, this variable is considered through a new and reliable correlation obtained from available experimental data at TUALP.
3. Results obtained in this work show the strong effect that slip velocity has in the prediction of natural separation efficiency, not only in the vertical direction, but also in the radial direction, especially for high liquid flow rates.
4. The new model presented in this work need to be improved. Variables such as gas void fraction and gas flow rate must be considered in the prediction of natural separation, because experimental results have shown have theirs effect on the separation process. Moreover, the dependence on pressure is weak. The only possible dependence occurs through the fluids' physical properties, present in the bubble rise terminal velocity.
5. Geometric configuration of the bottomhole is considered in the simplified model. The new approach (correlation) used in the solution of this model takes into account the annulus size effect.
6. Additional real experimental data is required to further verify the results obtained by using this new correlation. In addition, the viscosity effect could be considered and analyzed.

NOMENCLATURE

A	= Area, in.
D	= Diameter, in.
E	= Natural Separation Efficiency
Q	= Flow Rate, BD
V	= Velocity, ft/sec

GREEK LETTERS

ρ	= Density, lbm/ft^3
σ	= Surface Tension, lb/ft
g	= Gravity, ft/sec
α	= Void Fraction
∞	= Terminal

SUBSCRIPTS

Ann	= Annulus
c	= Casing
g	= Gas
i	= Inlet
l	= Liquid
P	= Port, Pump
t	= Tubing
s	= Slip, Superficial
r, z	= Direction

REFERENCES

1. Alhanati, F.J.S.: "Bottomhole Gas Separation Efficiency in Electrical Submersible Pump Installation", Dissertation. The University of Tulsa, 1993.
2. Ghauri, W.K.: "Production Technology Experience in a Large Carbonate Water-Flood, Denver Unit, Wasson San

Andres Field, West Texas", paper SPE 8406 presented at the 1979 SPE Annual Technical Conference and Exhibition, Las Vegas, NV, Sep. 23-26.
3. Harmathy, T.Z.: Velocity of Large Drops and Bubbles in Media of Infinite or Restricted Extent, AIChE, 6, 281(1960).
4. Harun, A.F., Prado, M.G., Serrano, J.C. and Doty, D.R.: "A Simple Model to Predict Natural Gas Separation Efficiency in Pumped Wells", paper SPE 63045 presented at the 2000 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 1-4 October 2000.
5. Ishii, M.: "Thermo Fluid Dynamic Theory of Two Phase Flow", Eyrolles, Paris, 1975.
6. Ishii, M. and Zuber, N.: "Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Fluids", AIChE Journal (September 1979) 25, No. 5, 843-855.
7. Lea, J.F. "Effect of Gaseous Fluids on Submersible Pump Performance", paper SPE 9218 presented at the 1980 SPE Annual Technique Conference and Exhibition, Dallas, TX. (Sep. 21-24).
8. Marquez, R., "Classification of the experimental natural separation data according to flow pattern regime". Technical Report. The University of Tulsa, Tulsa, Ok. (2002).
9. Serrano, J.C.: "Natural Separa Ishii, M.: "Thermo Fluid Dynamic Theory of Two Phase Flow", Eyrolles, Paris, 1975.tion Efficiency in Electric Submersible Pump Systems", Dissertation. The University of Tulsa, 1999.
10. Wallis, G.B.: "The Terminal Speed of Single Drops or Bubbles in an Infinite Medium", International Journal of Multiphase Flow (1974) 1, 491-511.
11. Zuber, N.: "On the Dispersed Two-Phase Flow in the Laminar Flow Regime", Chem. Eng. Sci., 19, 897 (1964).

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TABLE 1
MODEL COMPARISONS

LOW GAS VOID FRACTION (α<0.2)

SIMPLIFIED MODEL	AVERAGE ERROR %	ABS. AVERAGE ERROR %	STANDAR DESVIATION %
SERRANO	-18.58	19.41	1.727
ALHANATI	-16.51	17.33	1.750
NEW CORRELATION	7.48	14.41	1.912

TABLE 2
MODEL COMPARISONS

HIGH GAS VOID FRACTION (α>0.2)

SIMPLIFIED MODELS	AVERAGE ERROR %	ABS. AVERAGE ERROR %	STANDAR DESVIATION %
ALHANATI	-8.02	8.31	1.210
SERRANO	4.46	6.22	1.105
NEW CORRELATION	1.42	3.02	6.900

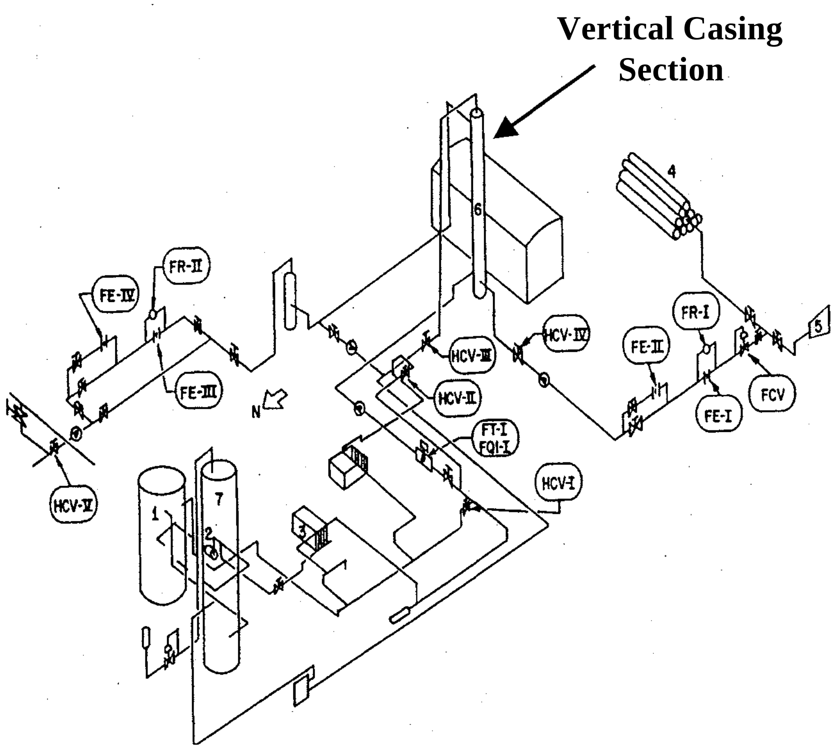

Figure 1- Experimental Facility. Alhanati's Work

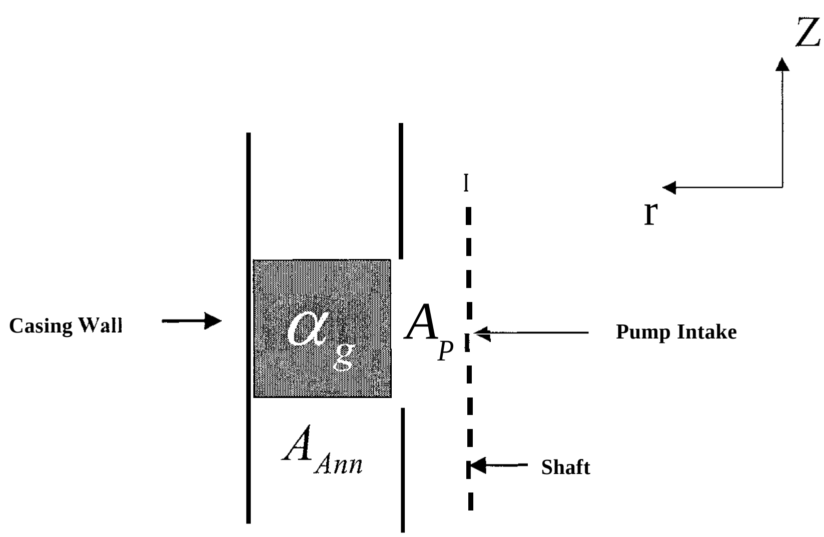

Figure 2 - Single Cell Domain

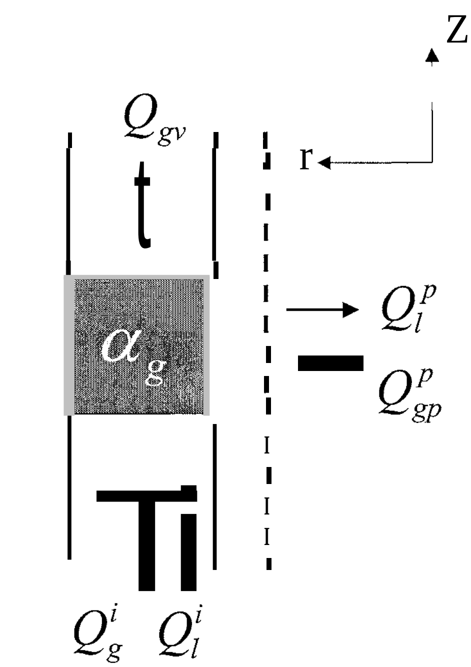

Figure 3 - Flow Rates Distribution Around the Control Volume

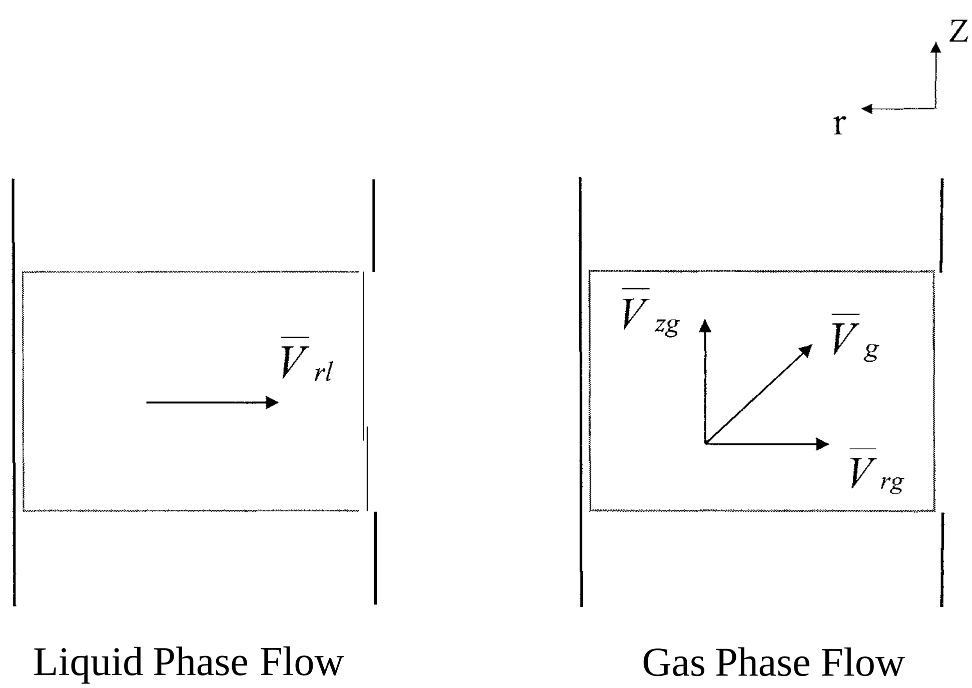

Figure 4 - Velocities Field into the Control Volume. Gas and Liquid Phase Flow

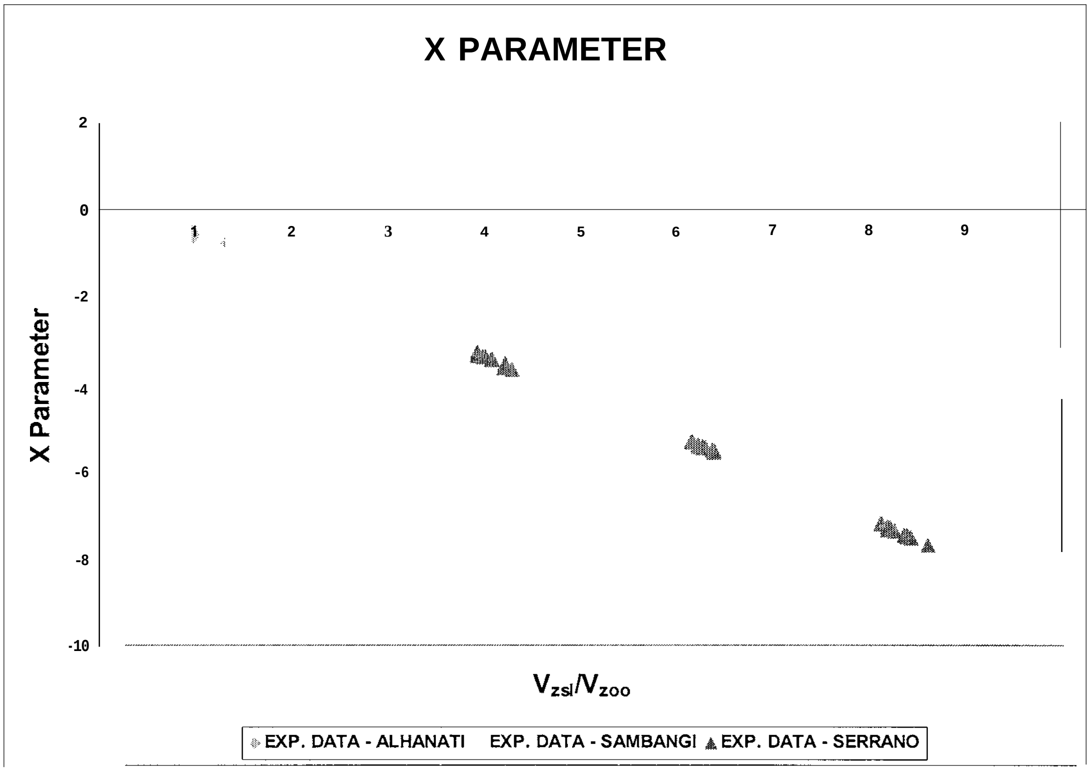

Figure 5 - χ Parameter

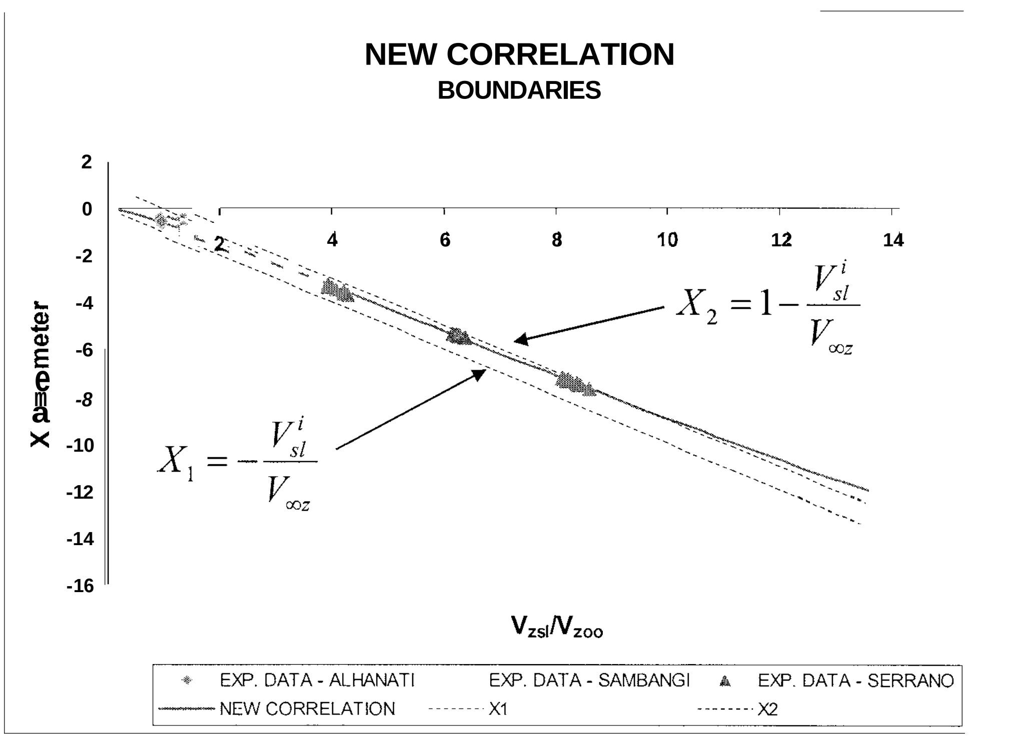

Figure *6* - Boundaries

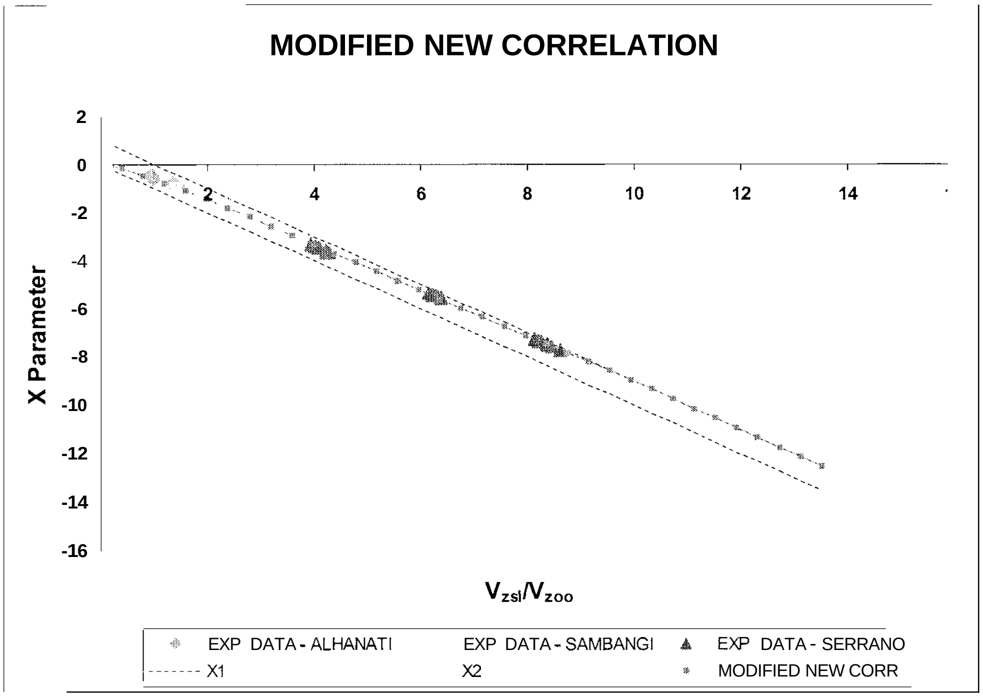

Figure 7- Modified New Correlation

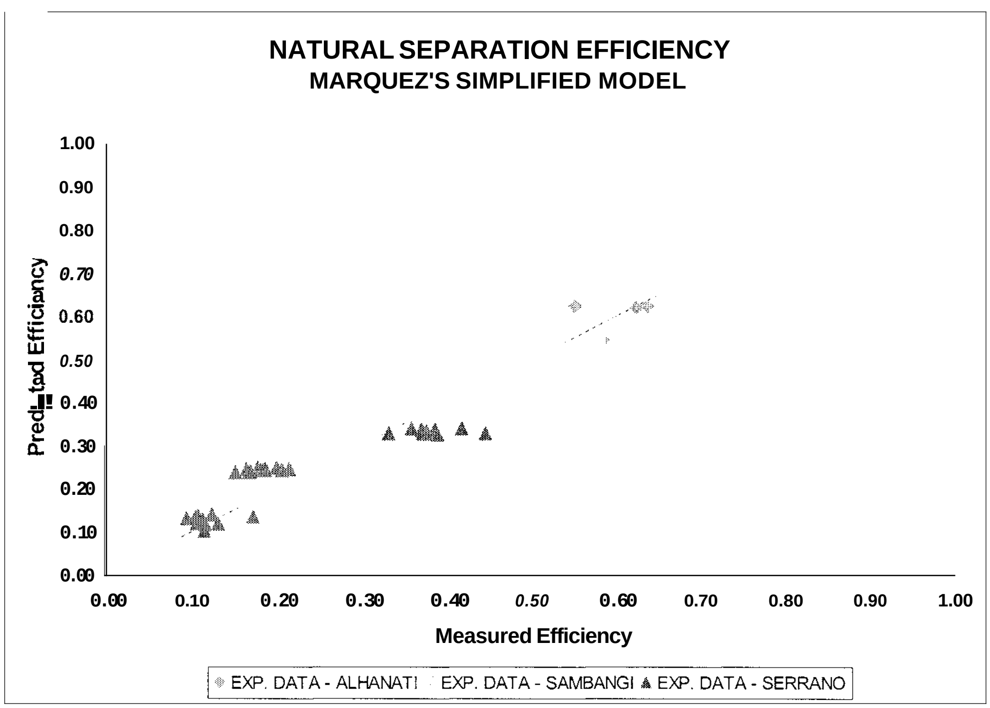

Figure 8 - Predicted vs. Measured Natural Separation Efficiency. New Correlation

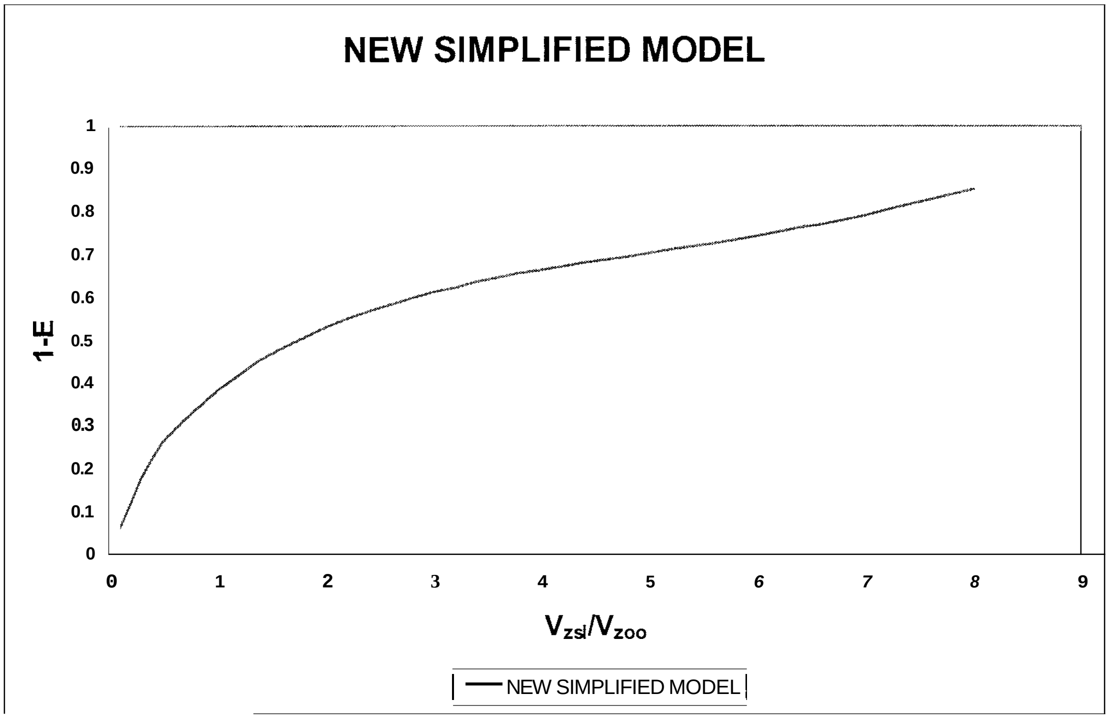

Figure 9 - New Simplified Model to Predict Natural Separation Efficiency

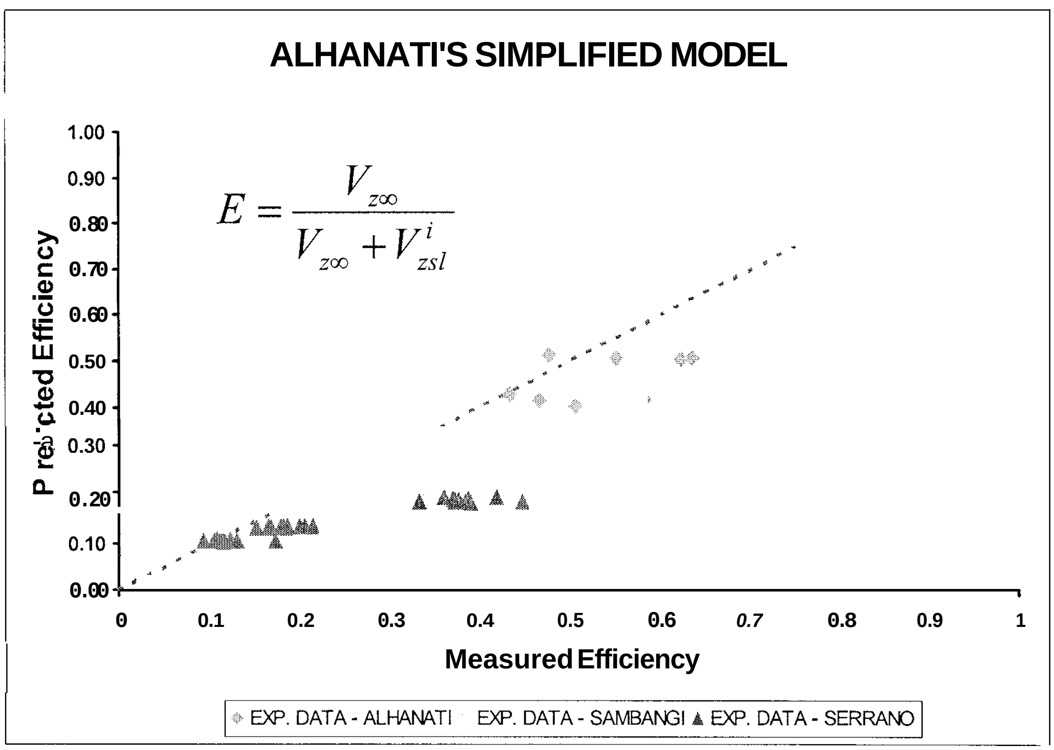

Figure 10 - Predicted vs. Measured Natural Separation Efficiency.Alhanati's Simplified Model

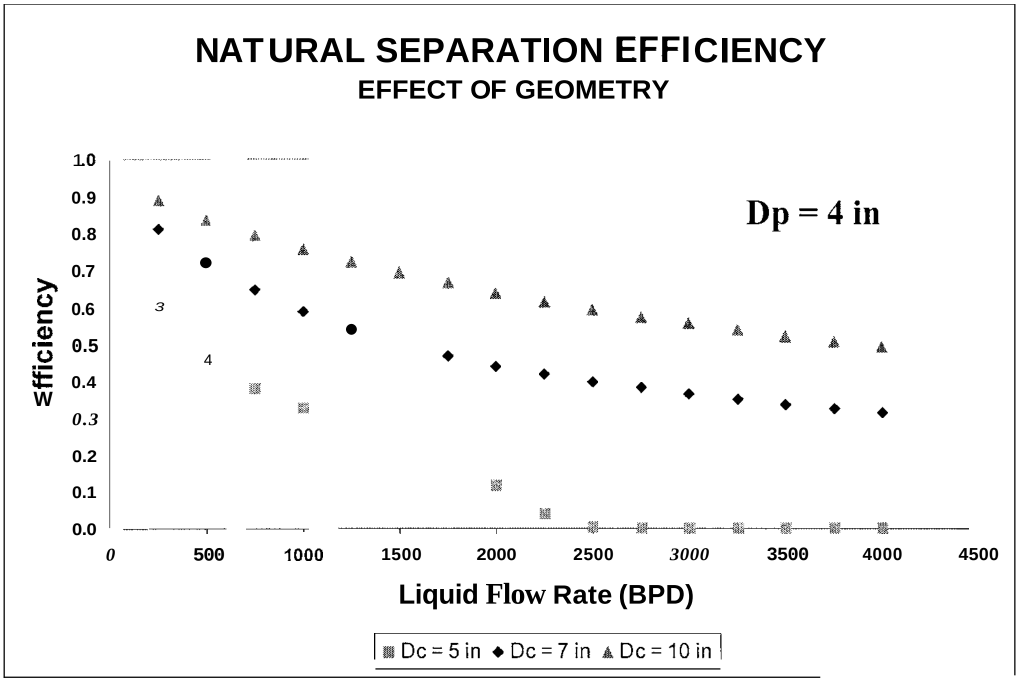

Figure 11 - Effect of Geometry on Natural Separation Efficiency