Mapping the performance of centrifugal pumps under two-phase conditions

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Abstract. *Centrifugal pumps are known to show a "surging" behavior at certain conditions of free gas and liquid flow rate at the intake. In the "surging" region, the head generated by the pump increases with the liquid flow rate, and it is significantly lower than if the pump were handling a homogeneous mixture. Therefore, to be able to predict the performance of centrifugal pumps under two-phase conditions, one has to be able to "map" the conditions in which this "surging" behavior occurs. This paper reports on the results of experimental and theoretical work conducted with the objective of better predicting the gas-liquid performance of centrifugal pumps under all range of conditions, including those characterized by "surging". The focus was on small diameter centrifugal pumps used to produce oil wells. It was observed that, under gas-liquid conditions, two basic two-phase flow regimes may establish within the pump impeller. The first regime is characterized by small dispersed bubbles flowing throughout the whole impeller channel. The second regime is characterized by a large stationary gas bubble occupying part of the impeller channel. Under the first regime, there is little deterioration of the "normal" pump head. Under the second regime, the "surging" behavior is observed. A new criterion to determine the flow regime at the pump impeller, based on non-dimensional numbers, was developed. A new mechanistic two-fluid model to calculate the head generated by the pump, under both regimes, was also developed. The predictions of the model show good agreement with data collected for this study, and with data recently collected by other research organizations.*

Keywords: *centrifugal pump, two-phase, flow, regime, impeller, surging, mapping, performance*

1. Introduction

Centrifugal pumps are commonly used in oil wells, mostly to allow for higher production rates. In these down hole conditions, associated produced gas often exists, as a free gas phase, at the pump intake. Therefore, to properly select what type of equipment to use and how to operate it, it is important to understand the performance of these centrifugal pumps when handling two-phase (gas-liquid) mixtures.

Several investigators have studied, both experimentally and theoretically, the behavior of centrifugal pumps used in oil wells, and in other applications, when handling two-phase mixtures. The experimental work (Lea & Bearden, 1980, Cirilo, 1998, Romero, 1999 and Rodrigues 2001) has shown that these pumps can experience a phenomenon that has been called "surging". It is characterized by a rapid increase in the pump head with the liquid rate, and it usually occurs at relatively high (higher than 10%) gas void fractions. The two-phase models developed so far for the pump performance (Minemura & Murakami, 1974, 1980, Minemura et al, 1985, 1995, Zakem, 1980, Furuya, 1985, Sachdeva (1988), Gaard et al, 1991, Clarke & Issa, 1995, Noghrehkar at al, 1995, Minemura & Uchiyama, 1993) were usually based on the assumption of a relatively homogenous gas-liquid mixture (small bubbles dispersed in a continuous liquid phase) flowing through the impeller channels, and are unable to accurately predict the pump performance under "surging" conditions. This assumption is likely only valid for very small gas void fractions (lower than 5%). Other investigators (Minemura & Murakami, 1974, Patel & Runstadler, 1976, Sekoguchi, 1983), for instance, have observed the presence of elongated stationary bubbles at the entrance of the impeller channels for higher gas fractions, and this should certainly influence the performance of the pump under these conditions.

To the best knowledge of the authors, until the work reported in this paper, no reliable criteria had been developed to determine in which conditions the pump may exhibit or not the "surging" phenomenon. This paper reports on the results of experimental and theoretical work conducted with the objective of better predicting the gas-liquid performance of centrifugal pumps under all range of conditions, including those characterized by "surging". A new criterion to determine the flow regime at the pump impeller, based on non-dimensional numbers, was developed. A new mechanistic two-fluid model to calculate the head generated by the pump was also developed. The predictions of the model show good agreement with data collected for this study, and with data recently collected by other research organizations, in a wide range of flow conditions.

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2. Experimental Work

Initially, with the objective of visualizing the main two-phase phenomena occurring inside an impeller, an experimental apparatus was built in which the main component was a scaled up stage made of acrylic. Figures 1, 2 and 3 illustrate what was observed: under certain conditions, a relatively large stationary bubble is formed at the entrance of the impeller channel, and the liquid phase occupies only a small portion of the channel flow area. Downstream of the gas bubble, however, a relatively homogeneous flow develops, in which small gas bubbles are dispersed in the liquid phase, which occupies the whole channel flow area. What happens is that small dispersed bubbles coalesce into the large bubble at the rotor entrance but are again formed at its tail by the action of a liquid jet. This assures the steady-state of the two-phase flow.

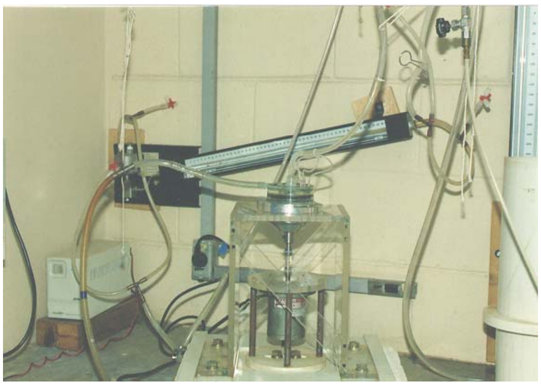

Figure 1. Scaled Up Transparent Stage

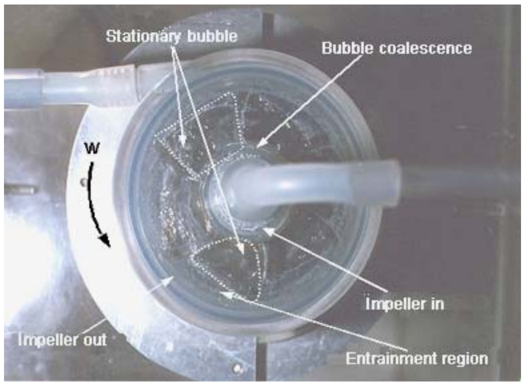

Figure 2. Stationary Bubble at the Entrance

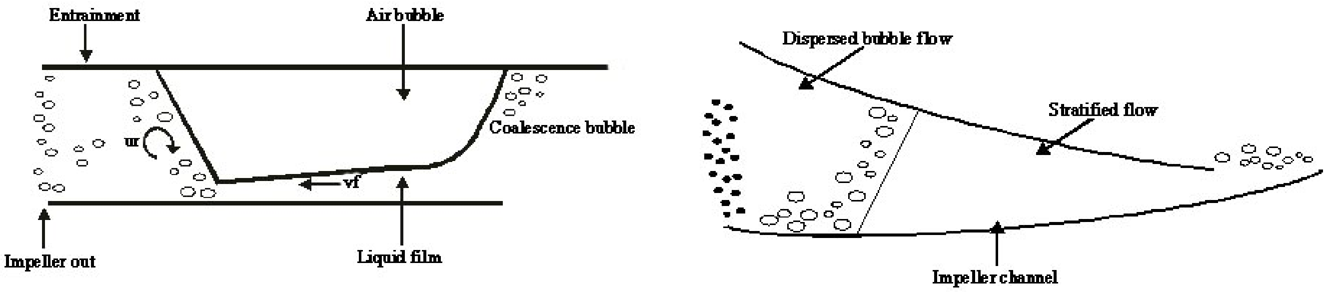

Figure 3. Graphical representation of the observed phenomena – vertical and horizontal cross sections

A second experimental apparatus was then built, to quantitatively measure the pump performance. This apparatus, shown in Figure 4, incorporated two stages of a commercial available pump. These stages were instrumented so that the pressure at the entrance and at the exit of each stage could be measured. A torque meter was included between the pump and the motor, to allow for the calculation of the pump efficiency. The gas fraction at the pump intake was also measured for each test performed, as well as the mean bubble diameter (d_{bm}) for the flow in the inlet pipe, for each test performed.

A similarity analysis can show that such pump, when operating at 800 RPM, has a similar behavior as a pump commonly used in the oil industry (Schlumberger-Reda DN-280), when operating at 3,500 RPM (normal operating speed for these pumps). Further details of the pump stage geometry are given by Estevam (2002).

Experiments were conducted at several levels of liquid flow rate (5-30m^3/day), gas fraction at intake (0-15%) and RPM (400-1000). Figure 5 illustrates some of the experimental results obtained. The figure shows non-dimensional head versus non-dimensional liquid flow rate for several levels of gas void fraction at intake. One can notice three distinguished regimes: (1) the pump behaves similarly to when handling single-phase liquid; (2) the "surging" phenomena is observed; and (3) the pump "gas locks" and practically no head is delivered.

3. Theoretical Modeling Work

The modeling work was based on our understanding of the physical mechanisms involved in the flow of the two-phase mixture through the impeller channel. When the pump rotates at a high RPM, a strong centrifugal field is generated, which acts to hold back the small gas bubbles that are dispersed in the liquid phase. Note that, within the impeller channel, the pressure increases in the direction of the flow. Depending on the circumstances, the small bubbles can coalesce close to the entrance of the impeller, thus forming the elongated bubble. On the other hand, the liquid tends to drag the small bubbles in the direction of the flow. Therefore, the balance between centrifugal and drag forces acting on the bubbles is what likely determines the type of flow regime established in the flow channel. .

Thus, a Two-Fluid Model was developed for the flow inside the rotor of the pump, which takes into account the above mentioned force balance. The final momentum equations, for the gas and liquid phases respectively, are:

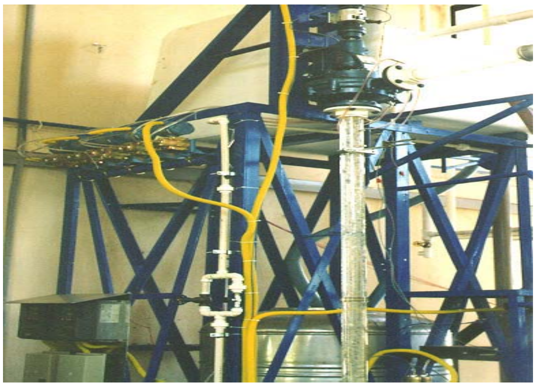

Figure 4. Experimental Setup

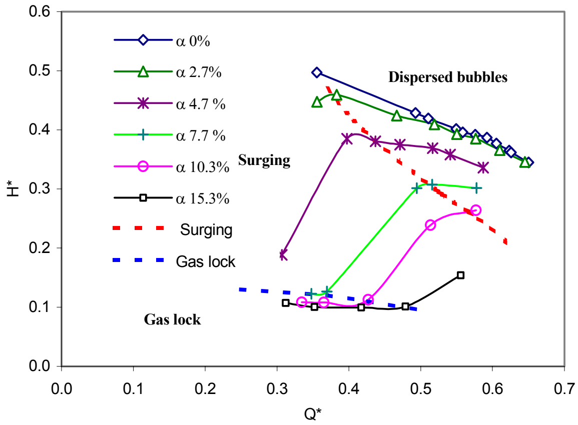

Figure 5. Experimental Results, 1000 RPM- 2º stage

$$\alpha\frac{dp}{ds}=\alpha(1-\alpha)\,\rho_L\omega^2 r\,Sin\beta+\frac{3}{4}\alpha C_D\frac{1}{d_{bm}}\rho_L V_{bs}\left|V_{bs}\right| \tag{1}$$

and

$$(1-\alpha)\frac{dp}{ds}=(1-\alpha)^2\rho_L\omega^2 r\,Sin\beta-(1-\alpha)\frac{2}{D_H}f_{\beta,\omega}\rho_L V_{LS}^2-\frac{3}{4}\alpha C_D\frac{1}{d_{bm}}\rho_L V_{bs}\left|V_{bs}\right| \tag{2}$$

Additional details are provided by Estevam (2002).

The effects of the centrifugal field and of the liquid drag can be clearly noticed in Equation (1). If this equation is integrated between the entrance and the exit of the impeller, the following equation results:

$$\frac{\Delta p}{\frac{1}{2}\rho_L\omega^2\left(r_2^2-r_1^2\right)}=(1-\alpha)+\frac{3}{2}\frac{1}{Sin\beta}\left[C_D\frac{(r_2+r_1)}{d_{bm}}\right]\left[\frac{V_{bs}\left|V_{bs}\right|}{\omega^2\left(r_2+r_1\right)^2}\right] \tag{3}$$

This equation can then be put in a non-dimensional form:

$$C_{PG}=(1-\alpha)+\frac{3}{4}\frac{1}{Sin\beta}I_S \tag{4}$$

where:

$$C_{PG}=\frac{\Delta p}{\frac{1}{2}\rho_L\omega^2\left(r_2^2-r_1^2\right)} \tag{5}$$

$$I_S=C_D\frac{\bar{r}}{d_{bm}}F_{r\omega} \tag{6}$$

$$\bar{r}=\frac{(r_1+r_2)}{2}; \tag{7}$$

$$F_{r\omega}=\left[\frac{V_{bs}\left|V_{bs}\right|}{(\omega\bar{r})^2}\right] \tag{8}$$

The "surging indicator" parameter I_S represents the ratio between the liquid drag and the centrifugal forces acting on the gas bubbles. Note that it is a function of the mean bubble diameter (d_{bm}). The smaller the bubble, the easier it can be dragged by the liquid against the centrifugal field, as the centrifugal force depends on the third power of the bubble diameter and the drag force depends on the second power. The pump stages therefore work as a "bubble filter" in which only bubbles smaller than a certain diameter are able to proceed to the next stage.

4. Mapping the flow regimes inside the impeller

Given Equation (4), an investigation was conducted to see if there could be a relationship between the flow regimes developed inside the impeller and the non-dimensional parameters I_S and $(1\text{-}\alpha)$.

Based on the experimental data collected points (i.e., values of liquid rate, gas void fraction, RPM and flow pictures of the inlet pipe) were identified that corresponded to the transition from a "normal" behavior (i.e., decrease in head with increase in flow rate) to a "surging" behavior (i.e., increase in head with increase in flow rate). When values for I_S and $(1\text{-}\alpha)$ were plotted for those conditions, a strong correlation was found (Figure 6).

The process was then repeated for the on set of "gas-lock". This "gas-lock" condition was arbitrarily selected based on a total head of 20% of the expected value under single-phase liquid flow conditions. Values for I_S were calculated assuming that 80% of the channel was occupied by the stationary gas bubble and only 20% was actually contributing to generating head (i.e., assuming that $r_1 = r_b$). Again, when values for I_S and $(1\text{-}\alpha)$ were plotted for those conditions, a strong correlation was found (Figure 6).

This suggested that a mapping of the flow regime inside the impeller, based on the non-dimensional parameters I_S and $(1\text{-}\alpha)$. and $(1\text{-}\alpha)$ was possible, as illustrated in Figure 7. As expected, for a certain value of the gas void fraction, the higher the value for the non-dimensional parameter I_S ,the higher the liquid drag force as compared to the centrifugal force, and the higher the chance for the pump to exhibit a "normal" behavior.

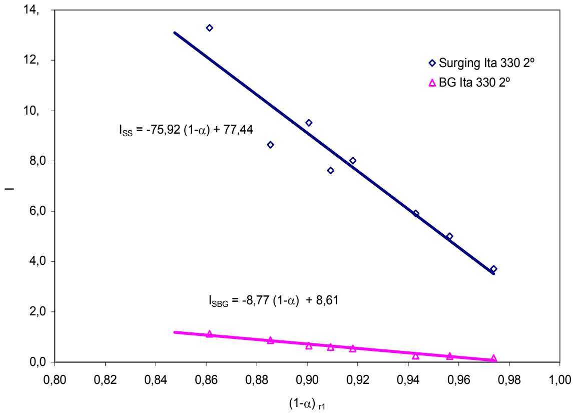

Figure 6. Onset of surging and gas-lock conditions

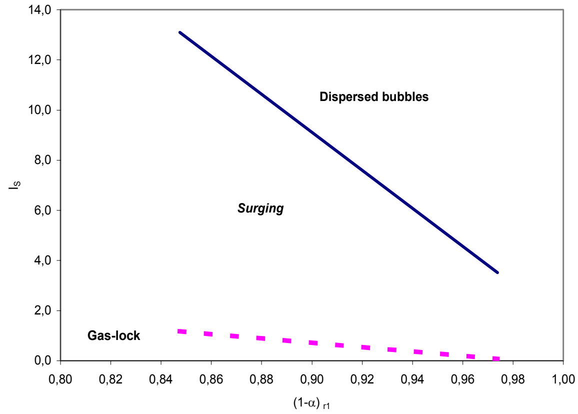

Figure 7. Mapping of the flow regime inside the impeller

To verify if the correlations found for the pump used in this experimental work would also apply to other pump models, the experimental results obtained by Rodrigues (2001) with a different pump (Baker-Hughes Centrilift GC 6,100) were used. Figure 8 shows calculated values for I_S and $(1\text{-}\alpha)$ for a number of these experiments, and the flow regimes they correspond to. Figure 9 shows values corresponding to the onset of "surging" conditions for this different pump, along with the correlation found based on the pump used in this experimental work. As it can be seen from these figures, apparently, the correlations found in this study apply to other models of pumps as well.

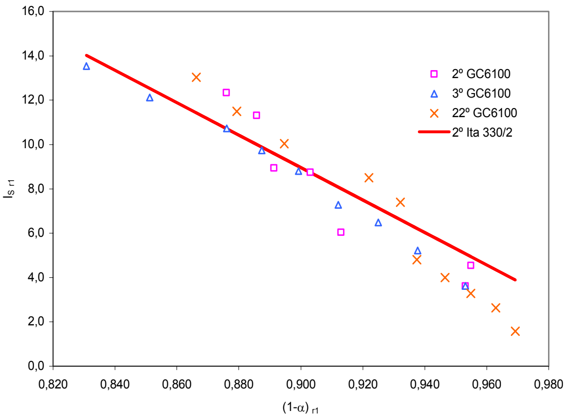

Figure 8. Onset of Surging (Rodrigues, 2001)

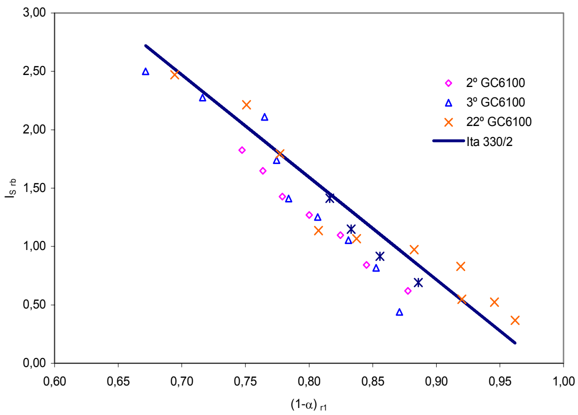

Figure 9. Onset of Gas Lock (Rodrigues, 2001)

5. Calculating the head generated by the pump

It is speculated that the pump exhibits a "normal" behavior if all the bubbles are small enough that they can be dragged by the liquid against the centrifugal field. When a stationary bubble starts forming at the entrance of the impeller channel, because a few larger bubbles cannot be dragged by the liquid anymore, the "surging" behavior is experienced. Under these conditions, only part of the impeller channel contributes to generate head. The bigger the stationary bubble, the less head is generated. At a certain point, the pump is not able to generate any significant head anymore, and it "gas-locks"

Calculating the head under the dispersed bubble, regime is relatively straightforward, because the pump exhibits a normal behavior, and equations developed for single-phase flow can be used (with the appropriate corrections). The same equations can be adapted to be used for the "surging" regime. The main difference is that one must only take into account the portion of the impeller channel, which is effectively contributing to generating head (i.e. the portion which is not occupied by the stationary gas bubble at the entrance). Thus, the experimental data was used again, to develop relatively simple correlations that allow for the determination of the active part of the rotor, given a set of conditions. Further details are provided by Estevam (2002). Figures 10 and 11 show the good agreement between the predictions of the model, using this approach, and the experimental results obtained by Rodrigues (2001), under both regimes.

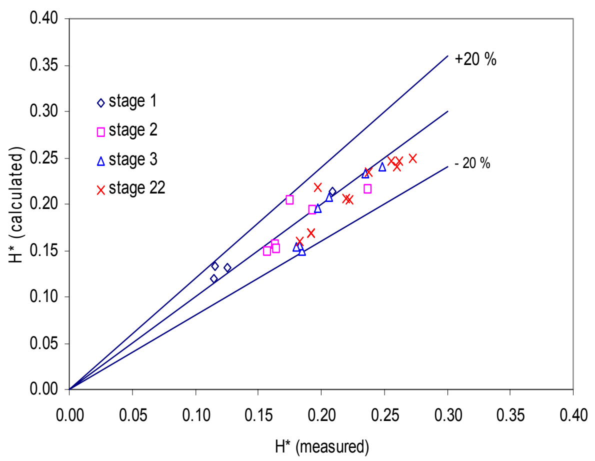

Figure 10. Model Predictions x Experimental Results

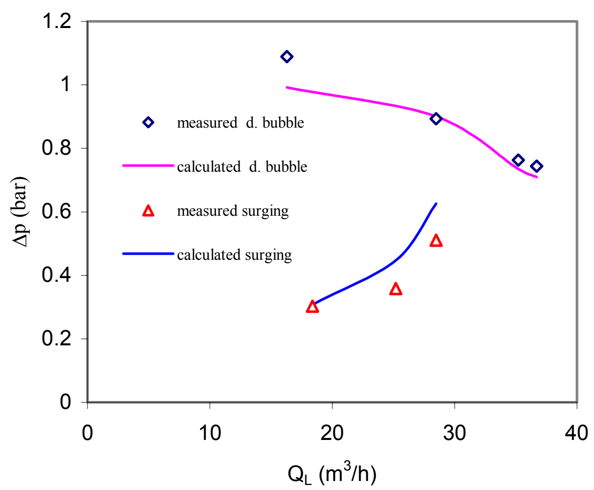

Figure 11. Model Predictions x Experimental Results

6. Conclusions

An experimental apparatus built to visualize the two-phase flow inside the pump revealed that under certain conditions, a relatively large stationary bubble is formed at the entrance of the impeller channel, and the liquid phase occupies only a small portion of the channel flow area. Downstream of the gas bubble, however, a relatively homogeneous flow develops, in which small gas bubbles are dispersed in the liquid phase, which occupies the whole channel flow area. When the pump rotates at a high RPM, a strong centrifugal field is generated, which acts to hold back the small gas bubbles that are dispersed in the liquid phase.

Depending on the operational conditions, the small bubbles can coalesce close to the entrance of the impeller, thus forming the elongated bubble. On the other hand, the liquid tends to drag the small bubbles in the direction of the flow. The balance between centrifugal and drag forces acting on the gas bubbles likely determines the type of flow regime established in the impeller channel. The smaller the bubble, the easier it can be dragged by the liquid against the centrifugal field. The pump stages therefore act as a "bubble filter" in which only bubbles smaller than a certain diameter are able to proceed to the next stage.

A theoretical two-fluid model has been developed, giving rise to a non-dimensional parameter, named the "surging indicator (I_S)". The parameter is a representation of the ratio between the liquid drag and the centrifugal forces acting on the gas bubbles, and it is a function of the mean bubble diameter. The analysis of the experimental data collected disclosed that there exists a strong correlation between the "surging indicator" parameter and the gas void fraction at the intake for the conditions representing the onset of the "surging" and the "gas-lock" phenomena.

A map for the flow regime inside the impeller was proposed, based on the non-dimensional "surging indicator" parameter I_S and the liquid fraction at the impeller intake (1-α). Apparently, the correlations found in this study apply to other models of pump as well.

7. Nomenclature

C_D drag coefficient
d_{bm} mean bubble diameter
D_H hydraulic diameter (impeller channel)
$Fr\omega$ centrifugal Froude number
$f_{\beta\omega}$ friction factor corrected for bent and rotation
H* non-dimensional Head
I_S non-dimensional parameter - surging indicator
Q* non-dimensional flow rate
r radial length of the rotor
s length
V_{bs} bubble relative velocity (S direction)
V_{Ls} liquid velocity (S direction)
α gas void fraction
β flow angle
ρ density
ω angular velocity
Δp pressure

Subscripts

G gas phase
L liquid phase
b tail of the stationary bubble
1 channel entrance
2 channel exit

8. References

Cirilo, R., 1998, "Air-Water Flow Through Electrical Submersible Pumps", M.S. Thesis, The University of Tulsa

Clarke, A. P. and Issa, R. I., 1995, "Numerical Prediction of Bubble Flow in a Centrifugal Pump", International Conference on Two-Phase Flow 95 – Kyoto, P8, pp 37-43

Estevam, Valdir, 2002, "Análise Fenomenológica da Operação de Bomba Centrífuga com Escoamento Bifásico". Tese de Doutorado – Fem - Unicamp

França, Fernando de Almeida, 1997, "EM-712 Sistemas Fluidomecânicos", Fem/Unicamp – Apostilas

Furuya O., 1985, "An Analytical Model for Prediction of Two-Phase (Non-Condensable) Flow Pump Performance," Journal of Fluids Engineering, Vol. 107, pp 139-147

Gaard, S., Billdal, J. T. and Christiansen, B., 1991, "Two-Fluid Modelling of Bubble Flow in a Mixed-Flow Pump-Impeller," SINTEF Fluid Machinery, Trondheim, Norway, pp 156-167

Ishii, M., Zuber, N., 1979, "Drag Coefficient and Relative Velocity in Bubbly, droplet or Particulate Flows". AIChe Journal v. 25, n. 5, pp 843-855

Ito H., 1959, "Friction factors for turbulent flow in curved pipes", Journal of Basic Engineering, Trans. ASME

Ito, H., and Nanbu, K., 1971, "Flow in rotating straight pipes of circular cross section ", Journal of Basic Engineering, Trans. ASME

Lea J. F. and Bearden J. L., 1980, "Effects of Gaseous Fluids on Submersible Pump Performance," SPE 9218

Minemura K. and Murakami M., 1980, "A Theoretical Study on Air Bubble Motion in a Centrifugal Pump Impeller," Journal of Fluids Engineering, Vol. 102, pp 446-455

Minemura K., Murakami M. and Katagiri H., 1985, "Characteristics of Centrifugal Pumps Handling Air-Water Mixtures and Size of Air Bubbles in Pump Impellers," Bulletin of JSME, Vol. 28, Nº. 244, pp 2310-2318

Minemura, K. and Uchiyama, T., 1993, "Three-Dimensional Calculation of Air-Water Two-Phase Flow in Centrifugal Pump Impeller Based on a Bubbly Flow Model," Journal of Fluids Engineering, Vol. 115, pp 766-771

Minemura, K., Kinoshita, K., Ihara, M., Furukawa, H., Egashira, K., 1995, "Effects of Outlet Blade Angle of Centrifugal Pump On The Pump Performance Under Air-Water Two-Phase Flow Conditions," ASME, PD-Vol. 69, Pipeline Engineering, pp 113-117

Murakami, M. and Minemura, K., 1974, "Effects of Entrained Air on the Performance of a Centrifugal Pump, First Report - Performance and Flow Conditions," Bulletin of JSME, Vol. 17, Nº. 110, pp 1047-1055

Murakami, M. and Minemura, K., 1974, "Effects of Entrained Air on the Performance of a Centrifugal Pump, Second Report - Effect of Number of Blades," Bulletin of JSME, Vol. 17, Nº. 112, pp 1286-1295

Noghrehkar, G.R., Kawaji, M., Chan, A. M. C., Nakamura, H. and KuKita, Y., 1995, "Investigation of Centrifugal Pump Performance Under Two-Phase Flow Conditions," Journal of Fluids Engineering Vol. 117, pp 129-137

Patel, B. R. and Runstadler, P. W., 1978, "Investigations Into the Two-Phase Behavior of Centrifugal Pumps," ASME Symposium on Poliphase Flow in Turbomachinery - San Francisco USA

Pessoa, Rui; Machado Miguel; Robles, Jorge; Escalante, Sharon and Henry Joe, 1999, "Tapered Pump Experimental Tests with Light and Heavy Oil in PDVSA Intevep Field Laboratory", SPE 1999, ESP Workshop

Rodrigues, Rui Francisco Pessoa, 2001, “Experimental Investigation of Two-Phase Flow Performance of Electrical Submersible Pump Stages” – M.S. Thesis – The University of Tulsa, USA

Romero, M., 1999, “An Evaluation of an Electrical Submersible Pumping System for High GOR Wells”, M. S. Thesis, The University of Tulsa, USA

Sachdeva, R., 1988, “Two-Phase Flow Through Electric Submersible Pumps”, Ph.D. dissertation, Univ. of Tulsa, USA

Secoguchi N., Takada S. and Kanemori Y., 1984, “Study of Air-Water Two-Phase Centrifugal Pump by Means of Electric Resistivity Probe Technique for Void Fraction Measurement - First Report - Measurement of Void Fraction Distribution in a Radial Flow Impeller,” Bulletin of JSME, Vol. 27, Nº. 227, pp 931-939

Zakem, S., 1980, “Analysis of Gas Accumulation and Slip Velocity in a Rotating Impeller,” ASME Cavitation and Polyphase Forum, pp 32-34

Zakem, S., 1981, “Determination of Gas Accumulation and Two-Phase Slip Velocity in a Rotating Impeller,” ASME Cavitation and Polyphase Forum, pp 167-173.