Experimental analysis of air bubble inside a centrifugal pump

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Abstract

Many industrial processes show, in some particular cases, two phase flows. The two phase flow takes place when thermal and physical conditions like heat exchange, pressure drop, viscous stresses, etc., have uncontrolled changes. In other cases the process requires a two phase flow motion like in pipelines for water-cool mixtures. In all these cases literature [1][2][3] shows the flow observed inside the impeller is not properly described by classical Euler's equations. It is still possible to approximately reformulate the Euler's equations [2], when considering the interaction between gas and liquid phase. This analytical approach, even tough incisive, has some important restrictions. It must take into consideration the absence of thermal fluxes between the two phases, the absence of viscous stresses, and that the flow field is one-dimensional. In this way it is possible to see the global behaviour of the two phase flow, but not what the real distribution of the gas phase inside the mobile ducts is and how the flow field changes relating with the gas phase distribution.

This paper intends to be an experimental approach in order to individualize the two phase flow field inside the impeller, to understand the interaction between the gas and liquid phases and a correlation between their behaviours and the energy dissipation phenomena in a centrifugal pump.

1 Introduction

The two phase flow inside a duct can have many shapes due to the interaction between the gas and the liquid phases like, for example, little bubbles or big bubbles.

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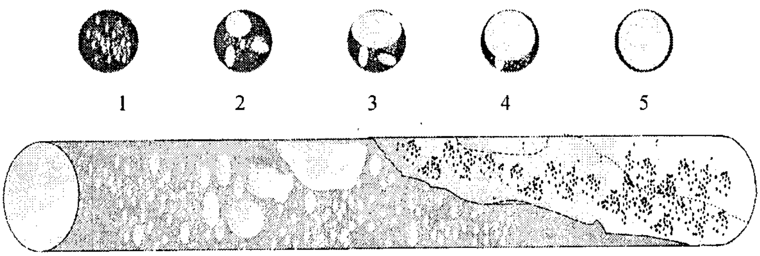

Figure 1: 1)Bubbly ;2)Plug ;3)Stratified ;4)Slug ;5) Anular -

Each of these geometrical shapes depends on particular conditions thermal flow dynamics conditions. Such shapes are not always precisely defined and this makes it difficult to give a single theoretical model able to describe all the possible two phase down flow.

It is accepted in literature, that laminar flow are described completely by Navier- Stokes equations and turbulent flow are explained by the statistics method given by the Reynolds equations with suitable limit conditions.

The study of a two phase flow needs a particular analysis to find out which are the parameters that control its dynamics so to apply the most suitable equations. This methodology has to be applied case by case.

If a pressure drop inside a duct containing also water causes a gas expansion, we have as a consequence that the entire processes of flow dynamics changes as the flow structure changes

The most important parameters contributing to draw a particular shape of a two phase flow flowing inside an horizontal fixed duct are various.

The most important are:

- Volumetric ratio of each phase
- Pressure
- Heat transfer through the duct walls

1. Triphase electrical balance motor
2. Double Hooke's joint
3. Magnetic Pick-up
4. Centifugel pump
5. Transparent Duct
6. Ball valve
7. By - Pass Valve
8. Lamination valve
9. Ball valve
10. Aero meter
11. Ball valve
12. Water tank
13. Water flow rate

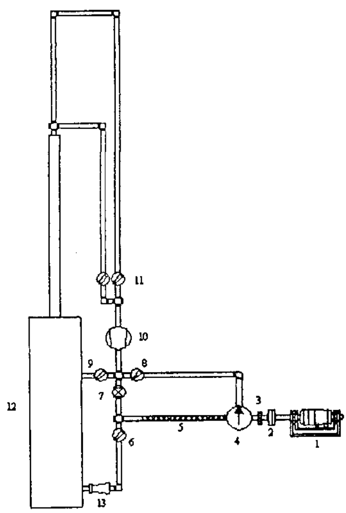

Figure 2: Experimental facility

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- Density and viscosity of each phase
- Geometrical shape and section of the duct
- Duct position
- Flow direction
- Injection of each phase

2 Two phase flow in horizontal duct

The possible shape of a two phase flow inside an horizontal duct are more numerous than those in a vertical duct due to the gravity effect tending to divide the two phases and to create an horizontal stratification.
In the first configuration the bubbles go to the upper side of the duct. If the gas flow rate increases some bubbles combine to form one bubble. This new configuration is called Plug flow.
If water and gas flow rate decrease, we have a new typology of two phase flow. It is called stratified flow. If the gas flow rate increases some waves begin to form and we obtain what we call the wave flow. If the waves get to the upper wall of the duct we will have the slug flow.
Finally, with low water and high gas flow rate, we will have the annular flow. Such flow takes up almost the entire section of the duct.(fig.1).
It's easy to notice how all these configurations of two phase flow can change the flow dynamics characteristic of a centrifugal pump since till it arrives in blocking condition.

3 Experimental Facility

In order to visualize the two phase flow rate the aspiration duct and the external flange of the impeller are transparent (fig 3). In this way it is possible to observe the behaviour of the two phase flow outside and inside the impeller. The flow is visualized in the transparent duct to study the flow field characteristics in the stationary case to understand the distribution of the gas phase inside the impeller is. For the recording of the frames a high speed CCD camera is used. The dissipation phenomena are quantified by the electrical balanced motor. The amplitude of the rotation around the zero value of the rotation axis is strongly related with the quantitative presence and permanence of the gas phase inside the impeller

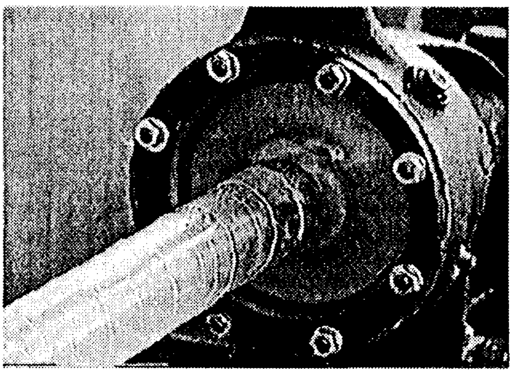

Figure 3: Pump working with two phase

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3.1 Methodology

The initial tests are carried out injecting just water inside the duct and considering pressure and temperature of the water and of the external environment as limiting conditions.
In this way it is possible to draw the characteristic line of the pump changing the rpm and to record the rpm value, the volumetric flow rate the pressure drop between the outlet and the inlet of the impeller and the medium value of the torque soaked in the rotor.
Further frames for each conditions of rpm regime are recorded to understand the real flow dynamics of the impeller and the triangle of the velocities. During the second phase a given gas percentage is injected inside the duct. So it is possible to control this particular two phase flow and to analyse it.
The two phase flow is classified by the classical of Backer and Bell abacus (fig. 4) which correlates the gas flow rate and the water flow rate using the following relationship

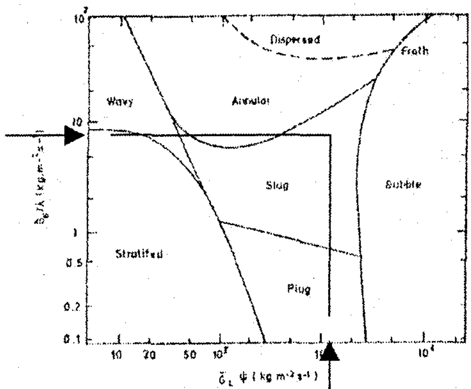

Figure 4: Becker Abacus and two phase flow

$$\overline{G}_G = \frac{\overline{M}_G}{A} \qquad \overline{G}_L = \frac{\overline{M}_L}{A} \qquad (1)$$

Where $\overline{M}_G$ and $\overline{M}_L$ are the mass flow rate of the gas end of the liquid phase and A is the section of crossing of the entire flow.
Trough the transparent and long duct the two phase flow is entirely developed and so it is possible to analyse the shape and the size of the gas bubbles and to study the different behaviour of the torque when working with water and with air and gas. In fig 5 it is possible to see the pump working with a ratio air/water equal to 30 percent of the entire volume of the pump(between inlet and outlet)

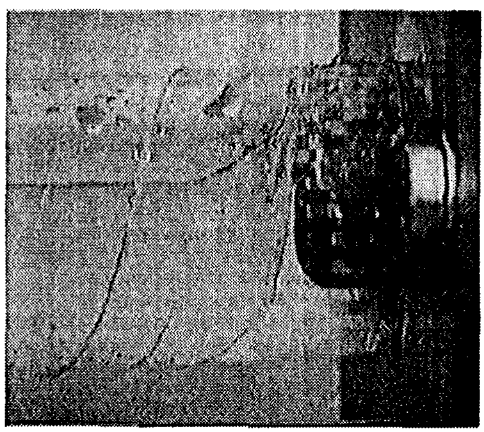
Figure 5: Transparent duct and stratified flow near

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4 Flow dynamics field

In this experimental work a radial blade impeller is used. Fig 4 shows the transparent duct and flange that permits to observe the motion of the mobile duct.
The first qualitative tests inside the impeller show an interesting variation of the torque in the presence of air bubbles. However it is possible to notice how the air bubbles follow the flow dynamics field.

Fig 6 shows the impeller duct during its rotation with air bubbles. Following the direction of the rotation it is possible to see how the bubbles place themselves. Their concentration is greater at the bottom of the figure near the blade on the right where a field of high pressure is located. On the second blade there is a field of low pressure and the concentration of bubbles is smaller. This distribution changes the characteristic of the pump and the transfer momentum from the mobile duct to the liquid flow.

This phenomenon depends principally, on the shape, size, and concentration of the bubble inside the impeller.

4.1 Objectives

In this paper the attention is fixed on the problems beginning when a two phase flow becomes slug flow and crosses the impeller. To have slug flow conditions the limit conditions of the entire apparatus are:

Table 1: instrumental setup

RPM	1250
Water flow rate:	$\dot{V}_L$ = 7600 l/h = 0.0021 m^3/s
Air flow rate	$\dot{V}_G$ = 72 l/h= 0.02*10^{-3} m^3/s
$\dot{M}_L$	2.1 kg/s:
$\dot{M}_G$	0.02 kg/s

Where A is the normal section of the duct and because of the diameter is 50mm the section value is:

$$A = \frac{\pi(0.050)^2}{4} = 0.002m^2$$

$$\dot{M}_L = 2.1 \text{ kg/s}$$

Taking in account the eqn. 1

$$\overline{G}_L = \frac{\overline{M}_L}{A}$$

follows:

$$\overline{G}_L = \frac{\overline{M}_L}{A} = \frac{2.1}{0.002} = 1050 \frac{Kg}{m^2 s}$$

For air

$$\dot{M}_G = 0.02 \; kg/s$$

and

$$\overline{G}_G = \frac{\overline{M}_G}{A} = \frac{0.02}{0.002} = 10 \frac{Kg}{m^2 s}$$

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The presence of the slug flow in the duct induces some abnormal conditions inside the plant and in the working pump. These anomalies depends on the particular shape and size of the bubbles and on the global flow rate of the gas phase.

5 Experimental data

In the first step is injected the gas phase so to obtain only one bubble having a volume about 10^{-5} m^3. This bubble keeps on moving until it gets to the upper side of the duct near the inlet section of the pump. Immediately before the inlet section (see fig 5) the two phase flow is clearly separated with the gas phase at the top and the liquid phase at the bottom.
The flow dynamics model of the radial impeller will be surely changed. In fact the pump works with two stratified phases.
The configuration of the new flow field can be seen in the frame recorded with the high velocity CCD camera in fig 7.
It is possible to see that inside the impeller gas and liquid phase are still separated .
It is highly probable having some kinds of behaviour of the pump changing the air flow rate

5.1 Phenomenon Description

We have performed three situations.
1.Formation of one bubble with volume less then pump volume
2.Formation of a lot of bubble in large term
3.Formation of bubble in short term
In the first case, if the bubble volume is less then pump volume. In this case the air phase is included between two liquid phases, in the outlet section and in the inlet section. In this way we have an intermittent behaviour of the because the pump has to transfer the torque to a fluid with density smaller than the first one.
In the second case an important correlation between the frequency of the bubble generation and the capacity of the pump to move the two phase flow exists. If the section it will always function in an intermittent way.

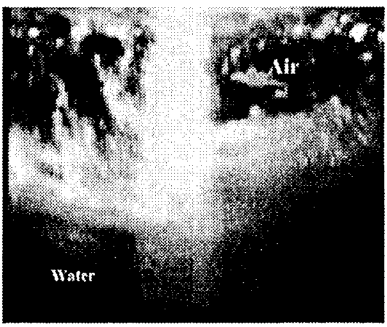

Figure 6: Separation inside a moving duct between air and water in slug flow condition

Figure 7: Visualisation of the Δp on the blade-blade surfaces

If the bubble formation is faster than the capacity of the pump moving the gas phase near the inlet section can form, because of coalescence, bubbles with a volume greater than the pump volume. If this happens the pump can't work and the gas phase will remain inside the impeller.

In real conditions these three behaviours will be present and the pump will function in irregular intermittent condition until the bubble volume will be smaller than the impeller volume

5.2 Qualitatively representation

Fig.8 shows the three different situation we can have with slug flow conditions It is shown the behaviour of the pump if we change the air bubble injection time. During the phase 1 the pump works with a periodic two phase flow. The presence of a large bubble inside the impeller reduces the water flow rate. The air volume in this phase is still smaller than the impeller volume. In this way the pump is able to push away the air bubble.

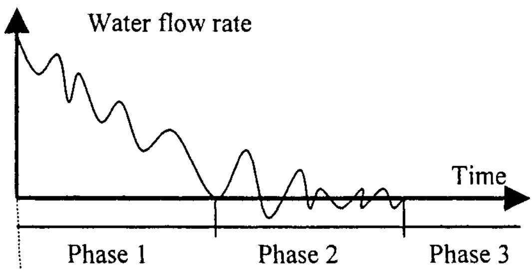

Figure 8: Qualitatively representation of the Phenomenon vs. time

If the bubbles volume increases for some reasons (different injection pressure, coalescence phenomenon) and becomes bigger than the impeller volume, the pump will work only with air and the water flow rate will turn down to zero.

At this point we have the reflux phenomenon due to the presence of the water body force.

The frequency around the zero value of the water flow rate increases until it becomes constant at zero .This is the phase 3. Inside the impeller there is only air and the water flow rate is always zero.

6 Numerical approach

This numerical approach analyses the mechanism forming the interface surface separating water and gas (in this case air) inside the impeller.

The theory is supported by the following hypothesis .

1.Perfect fluids
2.Negligible Body forces
3.Angular velocity = const.
4.Temperature=cost
5.Periodic regime

6.Rectangular blade

By vectorial Euler's Equation :In cylindrical coordinates and taking in account hypothesis 2,3,6 we can write

$$\rho \cdot \overline{F} - \nabla p = \rho \cdot \overline{V} \cdot \nabla \overline{V} + \rho \frac{\partial V}{\partial t} \tag{2}$$

$$\begin{cases} -\dfrac{\partial p}{\partial r} = \rho \cdot \left(V_r \cdot \dfrac{\partial V_r}{\partial r} + \dfrac{V_\phi}{r} \cdot \dfrac{\partial V_r}{\partial \phi} - \dfrac{V_\phi^2}{r} \right) \\ -\dfrac{1 \partial p}{r \partial \phi} = \rho \cdot \left(V_r \cdot \dfrac{\partial V_\phi}{\partial r} + \dfrac{V_\phi}{r} \cdot \dfrac{\partial V_\phi}{\partial \phi} - \dfrac{V_r V_\phi}{r} \right) \end{cases} \tag{3}$$

Integrating these two equations and considering that inside the impeller there is water in one case and gas in the other, the pressure field will be as follows :

6.1 Water

The velocity components related to the hypotheses are:

$$\begin{cases} V\phi = \omega_e r \\ V_r = \dfrac{V_e r_e}{r} \end{cases} \tag{4}$$

and Ve is given by:

$$2\pi V_e r_e h = Q_w \tag{5}$$

substituting eqn .5) in eqn. 4) :

$$\begin{cases} \nabla p \varphi = \dfrac{1}{r} \dfrac{\partial p}{\partial \phi} = -\dfrac{2 V_e \omega\, r_e}{r} \rho \\ \nabla p_r = \dfrac{\partial p}{\partial r} = \rho \dfrac{V_e^2 r_e^2}{r^3} + \rho \omega^2 r \end{cases} \tag{6}$$

The integration of this system gives :

$$p = -\rho \frac{V_e^2 r_e^2}{2r^2} + \rho \frac{\omega^2}{2} r^2 - 2\rho V_e r_e \omega \phi + C \tag{7}$$

$$p = -\rho V_r^2 + \rho \frac{V_\phi^2}{2} - 2\rho V_r V_\phi \phi + C$$

The integration of this two equations between r_i and r_e and between two sequential blades gives:

$$\Delta p_{\max} = -\rho\left(\frac{V_{r_e}^2}{2} - \frac{V_{ri}^2}{2}\right) + \rho\left(\frac{V_{\phi_e}^2}{2} - \frac{V_{\phi_i}^2}{2}\right) \tag{8}$$

$$\Delta p_\phi = -2\rho V_e \varpi r_e \Delta\phi = -2V_r V_\phi \Delta\phi$$

C is calculated by the following limit condition:

$\omega = 0 \Rightarrow C = P_s = \rho g h$

6.2 Gas

It is possible now to integrate the gas phase. In this case we consider only the presence of gas phase inside the impeller.

Applying the Euler's equation and taking in account the new variable ρ and applying the perfect gas equation the ρ function will be:

$$\rho(r,\phi) = f[p(r,\phi)] \tag{9}$$

In this way we can write:

$$\rho = \frac{pM}{RT} \tag{10}$$

In order with the hp. 4 (T= const)

$$\rho = Kp \tag{11}$$

It is now possible to solve pressure field only for the gas phase inside the impeller.

Watching the diagram of fig x during the phase water flow rate is equal zero. Inside the impeller exist only the gas phase and it remain inside.

So the equation of the velocity will be:

$$\begin{cases} V\phi = \omega\ r \\ V_r = 0 \end{cases} \tag{12}$$

and eqn 6 will be

$$\begin{cases} -\frac{1}{r}\frac{\partial p}{\partial \phi} = 0 \\ -\frac{\partial p}{\partial r} = \rho\left(\frac{\omega^2 r^2}{r}\right) \end{cases} \Rightarrow \begin{cases} p = C_1 \\ \frac{\partial p}{\partial r} = Kp\omega^2 r \end{cases} \Rightarrow \begin{cases} p_r = C_1 \\ \frac{\partial p}{\partial r} = C_2 e^{\frac{k}{2}\omega^2 r^2} \end{cases} \tag{13}$$

The description of the entire pressure field is given by:

$$p(r,\phi) = C_1 + C_2 e^{\frac{k}{2}\omega^2 r^2} \tag{14}$$

If $\omega=0 \Rightarrow C_2 = p_{a0}$ and $C_1 = 0$

The pressure field in this case is described by

$$p(r,\phi) = p_{ao} e^{\frac{k}{2}\omega^2 r^2} \tag{15}$$

7 Results

This behaviour is typical when a many droplets coalesce and become few large droplet. Often this phenomenon begins when there are particular plant conditions

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like losses near the inlet flange or diluition of high percentage of gas inside the liquid. This phenomenon begins slowly until to the rapid stop of flow rate. If the volume of the air bubble is smaller than the impeller volume the two phase are stratified and an interface surface exists. The gas phase is included between the liquid phase before and above.

Water pushes the gas phase and the pressure inside the bubble increases. The interface surface moving itself toward the outlet of the impeller increases the pressure inside the gas phase. In this way it is possible to plot the line of separation between the gas and the liquid phase.
In fact this interface is characterized by the same pressure value:

$$p_w(r,\phi) = p_a(r) \tag{16}$$

Fixing ϕ and computing r value which to set at zero the equation we find the points of the interface surface between the two phases inside the impeller like showed in the figure.

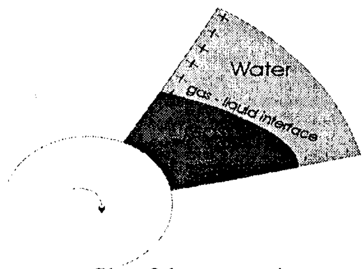

Figure 9 Profile of the separation surface gas - liquid

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Letter	**Greek letters**	**Subscripts**
M=mass flow rate Kg/s	μ= viscosity Kg/ms	a=air
V=velocity m/s	ρ=density Kg/m^3	l=liquid
T=temperature °C	ϕ=angular position deg	w=water
r=radius m	ω=angular velocity 1/s	g=gas
g= gravity accleration m/s^2		
p=pressure Mpa		