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Gas Driven Circulation in an Air-Water Loop

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Abstract- An experimental research with water driven by air injected at the inlet of the vertical riser in an adiabatic air - water loop has been carried out. The experimental apparatus consists essentially of two vertical plexiglass tubes 3.8 m long, 0.08 m I.D., that are connected at the bottom by a horizontal pipe and at the top by a large open tank. Air is injected into the riser through a nozzle provided with several small radial holes. The test facility is equipped with differential pressure transducers and two quick closing valves to measure the pressure drops and the average void fraction respectively. The pressure drop across the liquid single phase region has been changed by inserting calibrated orifices into the horizontal region. The data show the effect of the air flow rate and pressure losses on the liquid flow rate, void fraction, flow pattern, and recirculation ratio. The air pumping power has been experimentally estimated versus the liquid flow rate and the pneumatic efficiency has been evaluated. A model has been developed to evaluate the liquid flow rate as a function of the gas flow rate. The model gives a good prediction of the test results and allows the predictions for different conditions.

***Index terms*-Gas driven flow, Recirculation ratio, pneumatic efficiency, two-phase pressure drops**

I. INTRODUCTION

A rather simple and low cost method to get a high flow rate in a pool type system without a mechanical pump consists in the gas injection into a liquid up flowing inside some risers. The circulation of the fluid is similar to the fluid dynamic process of chemical high-recirculation airlift reactors [1]- [2]- [3]- [4], that is adopted in some chemical and biotechnological industry to carry out slow reactions like oxidations, chlorinations, wastewater treatment and can also be applied to the generation of secondary flow in a heat transfer equipment inside a water pond. The fluid circulation is driven by the density difference between a riser, where a two-phase flow occurs (typically with a bubble flow pattern), and a down comer. A recent study of Vial et al. [5], shows the void fraction in the different sections of the reactor is the critical parameter which determines the reactor hydrodynamics: the airlift reactors can be divided in two classes, namely, the external loop airlift reactors (EL-ALR) and the internal loop airlift reactors (IL-ALR). This method presents the advantage of a more ordered, less turbulent flow due to the mildness of the shear effect on the particles suspended in the liquid, which is to the homogeneity of the shear field and the absence of high shear regions, according to Merchuk et al. [6]. The gas driven circulation enhancement has been proposed also by Ansaldo Energy Company for the design of a hybrid nuclear reactor based on an accelerator driven system (ADS): a preliminary design of the innovative and inherently safe nuclear plant based on ADS, that can transmutate the long lived transuranic and fission products, has been recently presented by the nuclear division of the Ansaldo company [7]. The configuration of the primary system is pool-type and the primary coolant (Lead-Bismuth Eutectic) circulates in enhanced natural circulation without a mechanical pump: more than 80% of the nominal flow rate at full power is provided by the gas injection at the exit of the core, in order to induce the required coolant difference density between the riser and the down comer. These facilities are characterised by a simple loop construction with no mechanically moving parts and low (pneumatic) energy supply. The magnitude of liquid circulation is one of the most important design and scale-up parameters. The design of this type of facility regards gas and liquid flow rates, void fraction (gas hold up), interfacial area, mass transfer coefficient. The hydrodynamics of the loop is controlled by the void fraction and by the pressure drop in the single phase and two phase flow regions of the loop. In order to investigate the fluid dynamic mechanisms of the gas driven circulation, an experimental research with water driven by the air that is injected at the bottom of a vertical riser in an adiabatic test rig has been carried out. Previous experiments, Refs. [8,9], were performed by means of a two-phase loop equipped with a 0.03 m inner diameter test section to investigate the pressure drops along the flow path and the effect of the initial liquid level and of the air flow rate on the water flow rate and the void fraction. A new experimental apparatus, Ref. [8], with a 0.08 m inner diameter test section, has been built to study for a given geometry the fluid-dynamics, that is the effect of the test section diameter, gas flow rate, void fraction, flow patterns and pressure losses on the liquid flow rate. The pressure drop across the liquid single phase region has been changed by inserting calibrated orifices into the horizontal region. The test rig is equipped with several differential pressure transducers and air and liquid flow meters. The average void fraction in the riser as well as the liquid level inside the Plexiglas tank and the pressure inside the injection nozzle are measured too. The runs have been carried out in a wide range of the air flow rate. The loop flow rate characteristic curve shows a strong influence of the riser length to diameter ratio and of the ratio of the single phase to the total pressure drops. The liquid flow rate is low and is not measurable in the case of "discrete bubble flow"; it is very high in the case of homogeneous bubble flow pattern. In the bubble flow with strong coalescence and in the churn- turbulent flow pattern the liquid flow rate increases as the air flow rate increases with poor efficiency. A theoretical analysis of flow in loops with gas driven circulation can be performed by means of the application of the balance of driving and resisting forces as reported in [2]. The driving force can be expressed as elevation pressure difference Δp_{el} between the down comer and the riser

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$$\Delta p_{el} = (\rho_l - \rho_m) g\, L_R \quad (1)$$

where ρ_l is the liquid density, ρ_m is the two-phase fluid average density, g is the gravity acceleration e L_R is the two-phase region length. In steady state conditions the total pressure drop equals the Δp_{el} given by (1). The driving force depends mainly on the two-phase region length and on the riser void fraction that affects the two-phase region density. So it is important to measure the average void fraction for the different flow patterns and flow rate. In order to characterize the performance of the circulation process, the air pumping power has been estimated as a function of the liquid flow rate from the experimental data and the pneumatic efficiency has been evaluated. The higher performance conditions correspond to low void fraction when bubble flow occurs and the liquid flow rate is more stable, in agreement with the Ansaldo data that were obtained in a two concentric vertical cylinders apparatus [11].

II. TEST FACILITY

The present experimental apparatus (Fig.1) consists essentially of two vertical plexiglass pipes 3.8 m long, 0.08 m I.D., namely the riser (R) and the down comer (DC), that are connected at the bottom by a horizontal pipe (HP) and at the top by a large open tank.

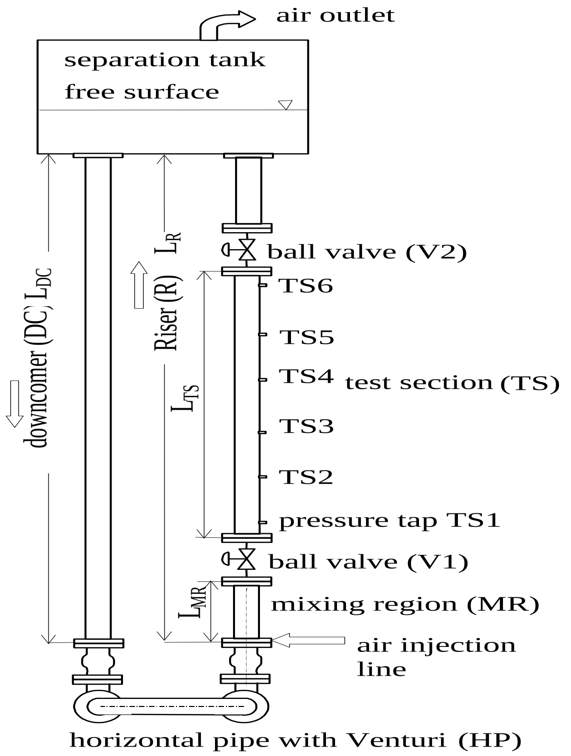

Fig. 1. Test Facility

The air is injected near the bottom of the instrumented test section (TS) and is separated at the top from the liquid free surface within the plexiglass tank. The air can be injected into the liquid either through a porous bronze device or a gas sparger with multiple small orifices. It is a typical external loop airlift system from a geometrical point of view. The mixing region between the injection point and the test section is a plexiglass pipe 0.42 m long, 0.08 m I.D.; downstream of the mixing region there is a ball valve 0.18 m long. The reference test section for the two-phase flow is a plexiglass pipe 0.08 I.D., 2.5 m long. Above the test section there is a second identical ball valve and a 0.52 m long pipe that is connected to the separation tank, where the air is separated without special device at the liquid free surface that is at atmospheric pressure. The down comer is a Plexiglas vertical pipe 3.8 m long, 0.08 m I.D. The horizontal region of the loop is a 5.81 m long, 0.082 m I.D. This region includes a Venturi meter (throat diameter 0.0349 m) and four 90 ° bends (0.140 m radius). The single phase pressure drops are changed by inserting an orifice of known diameter across the horizontal pipe: two diameters (35 and 45 mm) have been tested. As the air up flows, the density of the fluid column downstream of the injection point decreases, creating a voidage. The flow rate is controlled by the driving force due to the density difference between the down comer and the riser fluid region and by the friction pressure drop in the riser, in the separation tank, in the down comer and in the horizontal section of the loop (HP). The test rig is equipped with differential pressure transducers at several elevations, to measure the pressure drops, with air flow meters and a Venturi that is located in the horizontal pipe to measure the water flow rate; to measure the average void fraction two methods have been carried out: the quick closing valves (QCV) technique, by closing pneumatically and sharply the V1 and V2 valves, and the manometer method. The uncertainty is 1% for the differential pressure, 2.5% for the air and water flow rate, about 1% for the void fraction measurements. The air flow rate ranges up to 5000 Nl/h, at 7 bar pressure, and the liquid flow rate reaches values higher than 5 kg/s.

III. TEST RESULTS

The research main aim is to investigate the effect of the gas flow rate (or gas superficial velocity) on the liquid flow rate (or liquid superficial velocity), on the void fraction and on the pressure drops for a given geometry. The mass gas flow rate W_g is changed, during the test, by means of a hand controlled valve that is placed in a pipe connected to the air supply system. Fig. 2 shows the mass liquid flow rate versus the mass gas flow rate for all the runs. The strong influence of the orifice in the horizontal single phase region is evident: at a given gas flow rate the liquid flow rate decreases with the orifice diameter, as the pressure drop in the single phase region increases. All the runs show a typical trend with a low scatter of experimental data and confirm the previous results [8]- [9]- [10]. Within the investigated parameters range the mass liquid flow rate (that can reach about 5.5 kg/s) to the mass gas flow rate (that can reach about 4.5 g/s) ratio is rather high (between 1200 and 10 000).

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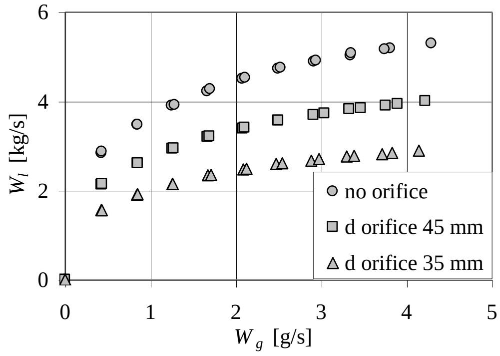

Fig. 2. Liquid flow rate versus gas flow rate

Fig. 3 shows a quadratic relationship between the gas superficial velocity jg and the mixture superficial velocity j. The flow quality is given by

$$x = \frac{\rho_g j_g}{\rho_g j_g + \rho_l j_l} \quad (2)$$

Fig. 4 shows that the flow quality increases with the superficial gas velocity. It decreases with the orifice diameter. Fig. 5 presents the experimental results of the void fraction, measured through the quick closing valve technique (QCV), versus the gas flow rate. The measured void fraction increases with W_g and it is lower than 35% within the test range. The higher quality and void fraction values at lower orifice diameter for a given gas flow rate is obviously due to the lower liquid flow rate when the single phase pressure loss through the orifice is higher. To verify the QCV technique void fraction data several differential pressure measurement along the test section have been carried out (manometer method) with high pressure side of the transducer connected to the top pressure tap (Fig. 1); the measured differential pressure across a Δz length (from the inlet up to the pressure tap) can be expressed as

$$[\Delta p]_{meas} = (\rho_l - \rho_g)\alpha\, g\, \Delta z - (\Delta p)_f \quad (3)$$

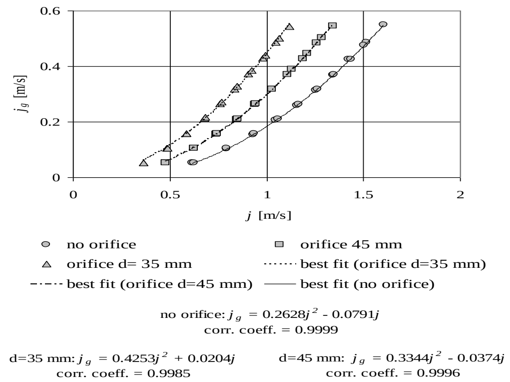

Fig. 3. Gas superficial velocity versus mixture superficial velocity

The void fraction either measured by means of the QCV technique or derived through (3) from the pressure drop measurement (manometer method) assumes the same values if the gas flow is closed after the quick closing valve closure by a few seconds.

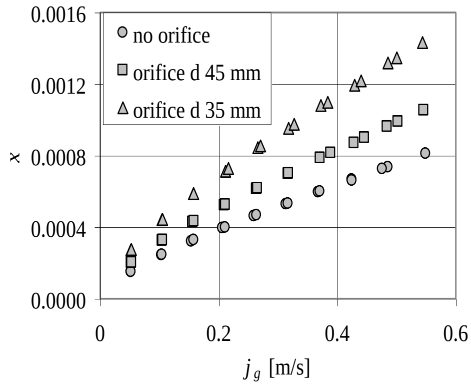

Fig.4. Flow quality versus gas superficial velocity

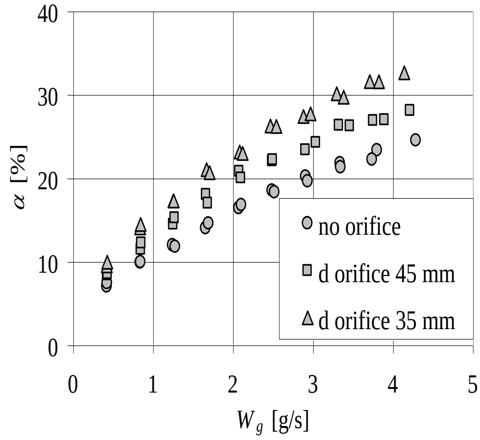

Fig. 5. Void fraction versus gas flow rate

The actual test section pressure drop [Δp] is the sum of elevation head and friction pressure drop across the length of 0.48, 0.96, 1.40, 1.92, 2.4 m, where the pressure taps are located along the test section (Fig. 1).

$[\Delta p]$ can be derived from $[\Delta p]_{meas}$ through

$[\Delta p]=\rho_l g \Delta z-[\Delta p]_{meas}$ (4)

Fig. 6 shows the test section $[\Delta p]$, derived by (4), versus the flow quality.

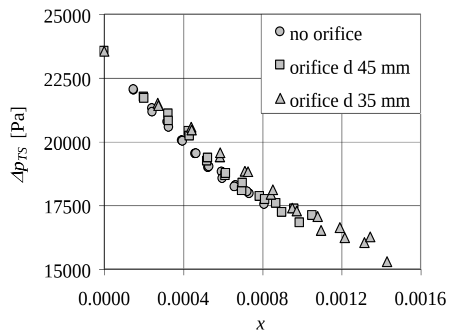

Fig. 6. Test section pressure drop versus flow quality

The decrease of $[\Delta p]$ with the flow quality shows the strong effect of the elevation head decrease as the air flow rate increases. The pressure gradient along the channel is about constant at a given flow rate. The insertion of an orifice has a minor effect. Fig.7 shows the gas relative pressure within the sparger versus the air flow rate. It is independent of the orifice diameter and increases at the

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higher gas flow rate, due to the pressure loss through the sparger holes.

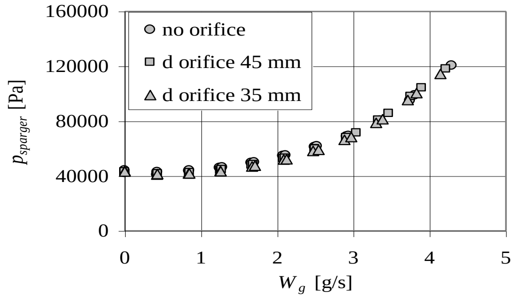

Fig. 7. Relative gas pressure within the sparger versus gas flow rate

The void fraction averaged along the Δz long region of the test section can be derived from (3)

$$\alpha = \frac{[\Delta p_f]_{meas} + (\Delta p)_f}{(\rho_l - \rho_g) g \, \Delta z} \quad (5)$$

Fig. 8 shows the void fraction derived through (5) from the pressure drop measurements (manometer method) with reference to four different control volumes (1-3, 1-4, 1-5 and 1-6 as shown in Fig. 1) by adopting the hypothesis that the pressure drop due to friction can be neglected ($(\Delta p)_f$ = 0) , that corresponds to the minimum void fraction); in fact the two-phase flow friction pressure drop cannot be directly measured but it is anyway rather low for the present conditions. The average void fraction that is measured within the different channel volumes decreases slightly as the reference volume increases as expected owing to the entrance effect. The average void fraction data reported below refer to the 2.4 m height volume (TS1-TS6).

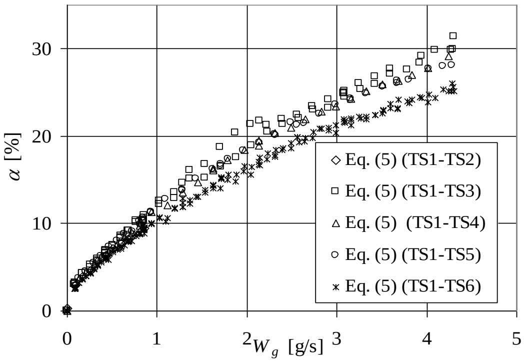

Fig. 8. Void fraction estimated by (5) with $(\Delta p)_f$= 0 at different elevation versus gas flow rate

The loop has been experimentally characterised by measuring the pressure drops across the down comer as well as across the bottom region of the loop, that is most horizontal, where only liquid flows as it is observed through the plexiglas wall (complete air separation). Fig. 9 presents the pressure drops versus the liquid flow rate for the three typical loop configurations. The strong effect of the orifice diameter can be seen.

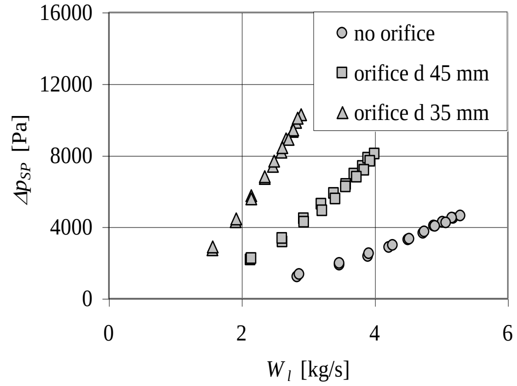

Fig. 9. Pressure drops across the single phase region versus liquid flow rate

As regards the flow pattern the test section transparency allowed to see the flow structure. Pictures have been shot with a stroboscopic light and a bubble flow is observed at lower flow rate, while at higher flow rate and void fraction a transition from bubble to churn flow occurs [10]. Movies by means of a video camera "Sony TRV35E" have been obtained too.

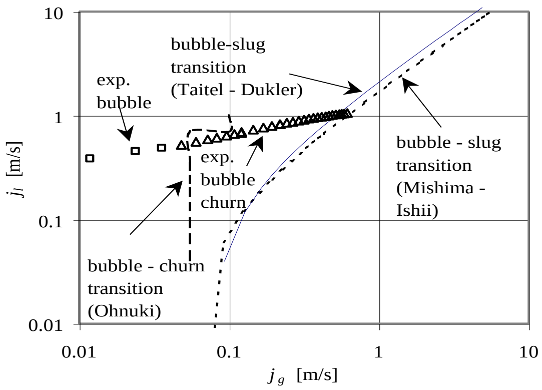

Fig. 10. Flow pattern map

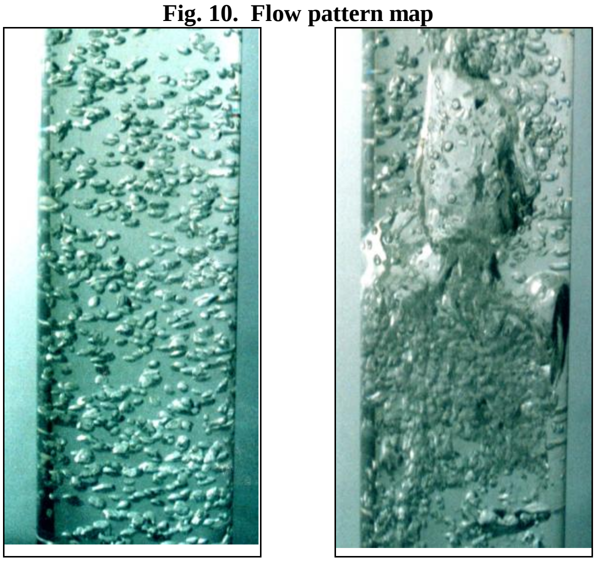

Fig. 11. Flow pattern pictures: from bubble flow, on the left, to churn flow, on the right

Fig. 10 presents the flow pattern map with the present test data and the transition lines predicted by Taitel [12], Mishima [13], and Ohnuki [14]: the transition from bubble to churn flow predicted by Ohnuki seems in good

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agreement with the experimental data, while the tested gas flow rate did not allow to observe the transition to annular flow in agreement with [13] and [14]. Fig. 11 shows some flow pattern pictures, shot by means of a stroboscopic light technique.

IV. ANALYSIS

To study the experimental results from a theoretical and modelling point of view, the measured void fraction, pressure drops and liquid flow rate have been compared with the model prediction based on a balance of driving and resisting force

$$(\rho_l - \rho_g)\alpha L_R g = (\Delta p)_{f,SP} + (\Delta p)_{f,TP} \quad (6)$$

by using some semi-empirical correlations for the void fraction and pressure drops evaluation where $(\Delta p)_{f,SP}$ and $(\Delta p)_{f,TP}$ refer to the whole loop including the area change losses. Fig. 12 shows the experimental data of the left hand side of (6) versus the gas flow rate. The uncertainty is the same as for void fraction.

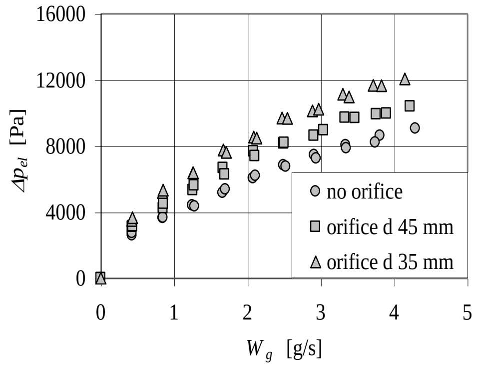

Fig. 12. Elevation head versus gas flow rate

The model aim is to estimate the liquid flow rate, the pressure drops and the void fraction and is similar to the model proposed by Sanders [2]. The main assumptions are that the liquid phase is incompressible water, the void fraction in the down comer is zero while the void fraction in the riser is uniform along the channel for a given mass gas flow rate. The model neglects the losses in the separator tank while it includes the two-phase pressure losses through the ball valves and at the inlet of the tank. These assumptions are based on the ground that a complete gas separation occurs in the air separation tank and that the gas injection point is just at the bottom of the riser. To study the two-phase flow across the test section, separated flow void fraction correlations like the Hills 15], and the CISE [16], ones and, for comparison purpose, the homogeneous void fraction model have been adopted. The Hills correlation derives from the Zuber and Findlay model [17]

$$\alpha = \frac{j_g}{C_o j^n + C_1} \quad (7)$$

Where the exponent n=0.93 and C_0=1.35 and C_1=0.24. The CISE correlation [18], is a recommended empirical correlation in terms of the slip ratio. Both Hills and the CISE correlations predict cross-sectional void fractions, while the present experimental method gives a volumetric void fraction, but the assumption that it is uniform along the channel seems appropriate on the ground of the pressure drop measurement at different test section elevation, according to [10]. There is a fairly good agreement with either Hills or CISE predictions, although it has to be observed that the test section friction pressure drop is neglected to get the experimental void fraction by means of the manometer method; so the Hills correlation to a larger extent and the CISE correlation more slightly under predict the data [8]. The homogeneous model strongly over predicts the data as it is expected. The two-phase friction pressure drop has been evaluated by the Friedel correlation [19]; the two-phase pressure loss through the ball valves is estimated by using the homogeneous model. The liquid flow rate prediction is compared with the data in Fig. 13: the agreement is rather good.

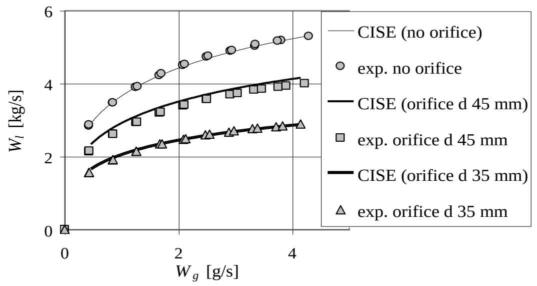

Fig.13. Predicted and experimental liquid flow rate versus gas flow rate

A statistical analysis of the pressure drop data, that has been carried out at different flow rate, shows that the standard deviation increases strongly with flow rate in correspondence with the transition from bubble to bubble-churn and eventually to churn flow. That is why the liquid flow rate curve presents a shape like that shown in Fig.13, and it is not convenient to increase the air flow rate above certain values because the liquid flow rate increase becomes lower due to the bubble associated dissipation, in agreement with the findings of Merchuk et al. [6]. In order to study the performance of this circulation process, that is the power dissipation in the loop, that is equal to the hydraulic power transferred from the gas to the liquid, and the power given by the pressurized air flow (pneumatic power), the following assumptions have been adopted:

- the work done by the gas on the liquid and vice versa is consistent with an isothermal expansion of the gas;
- the energy dissipation inside the gas phase is negligible;
- the temperature of the liquid can be considered constant;
- the kinetic energy change is negligible;
- the potential energy of the gas is negligible.

The hydraulic power is estimated by the relation that is valid for incompressible fluids

$$P_h = Q_l \cdot \Delta p_{el} \quad (8)$$

where Ql is the volumetric liquid flow rate.

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So the measurement (as well as the prediction) of the liquid flow rate and of the pressure drops allow to evaluate the power needed to circulate the liquid. The pneumatic compression power, that is needed to inject air in the loop through the air sparger, is estimated by

$$P_p = W_g \int_{p_a}^{p_m} v\, dp \qquad (9)$$

A typical thermodynamic process is either an adiabatic or an isothermal compression. So the power needed to compress the gas is for an adiabatic process

$$P_{pad} = W_g \frac{k}{k-1} R T_a \left[\left(\frac{p_m}{p_a} \right)^{\frac{k-1}{k}} - 1 \right] \qquad (10)$$

and for an isothermal process

$$P_{pis} = W_g R T_a \ln\left(\frac{p_m}{p_a} \right) \qquad (11)$$

where p_m is the pressure inside the sparger (fig. 7), p_a is the atmospheric pressure, T_a is the ambient temperature, k is the ratio between the gas heat capacities at constant pressure and constant volume respectively and R is the ideal gas constant. Fig. 14 shows the estimated hydraulic power versus the air flow rate for different orifice diameter. The power increases about linearly with the gas flow rate and with the reduction of the singular single phase pressure drops. The hydraulic power versus the liquid flow rate is shown in Fig. 15. The hydraulic power increases strongly with the liquid flow rate and more as the single phase region is more orificed. At lower single-phase pressure drops higher liquid flow rate and lower hydraulic power can be reached.

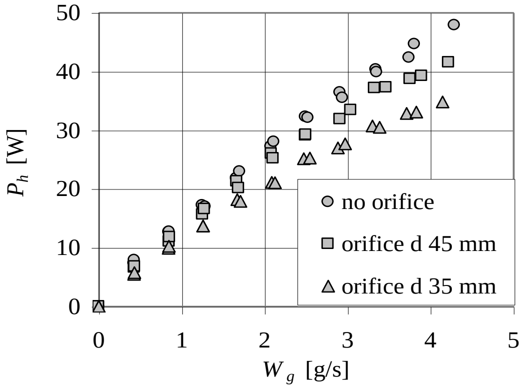

Fig. 14. Hydraulic power versus gas flow rate

It can be deduced the importance of the design of the down comer and bottom region of the reactors, that has to perform the objective to minimize the single phase pressure drops. The compression power is a function of the gas pressure inside the sparger. The adiabatic compression power increases with the gas flow rate (Fig.16) and strongly with the liquid flow rate (Fig.17).The strong increase of the compression power, especially in presence of the orifices, points out the poor performance of the liquid circulation at higher gas flow rate, that is more evident in Fig.18, where the ratio between the liquid hydraulic pumping power and the gas pneumatic compression power is shown. Such a figure shows the runs carried out with no orifice and with the two orifices inserted and the curves at constant gas flow rate W_g.

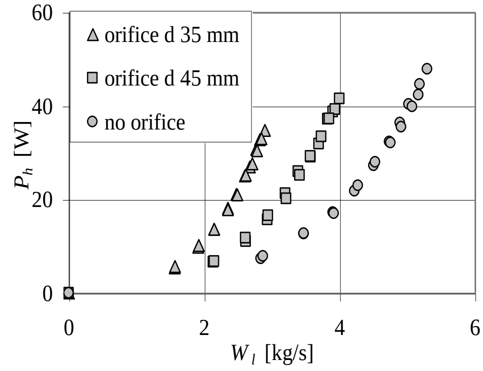

Fig. 15. Hydraulic power versus liquid flow rate

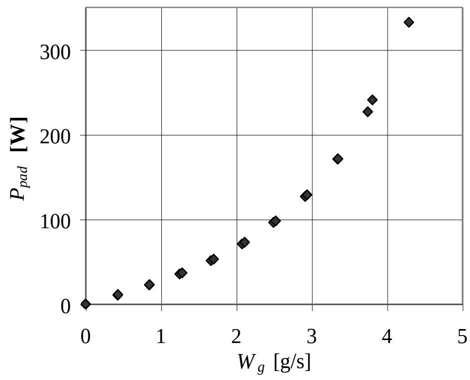

Fig. 16. Adiabatic compression power versus gas flow rate

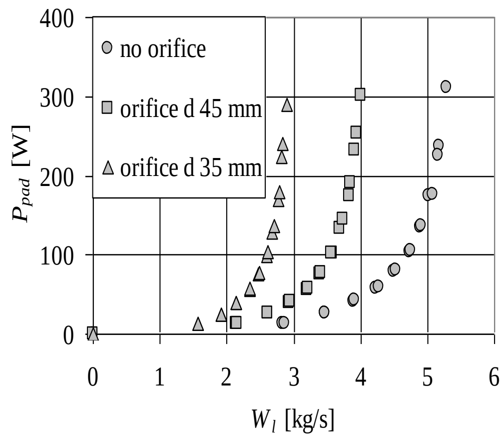

Fig.17. Adiabatic compression power versus liquid flow rate

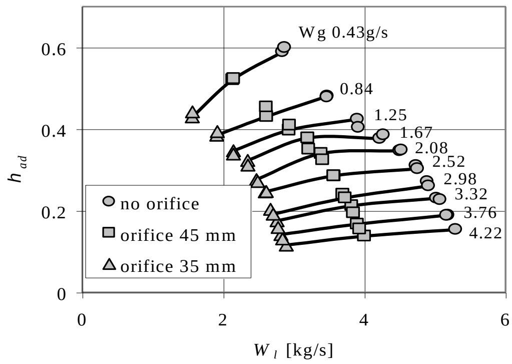

Fig. 18. Gas driven circulation performance

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V. CONCLUSION

The gas driven circulation in a loop is a rather simple method to get a rather high liquid flow rate by means of the injection of the gas phase at the bottom of the riser, with no moving parts. The main application at present concerns the chemical airlift reactors; it seems promising for the nuclear accelerator driven systems too. The present investigation shows the dependence of the liquid flow rate on the gas flow rate: the ratio is higher than 1200. There is a sort of feedback between the liquid flow rate and the flow quality that in turns affects the circulation. The dependence of gas superficial velocity on the mixture superficial velocity is quadratic. For the present loop geometry the single phase pressure drop, that can be well predicted, plays a major role: the major contribution is due to the pressure drops along the horizontal section of the loop, that includes the pipes, the bends and the Venturi, and there is a significant two-phase flow loss through the ball valves at the ends of the test section. The two-phase flow main parameters depend strongly on the geometry; the Hills and CISE correlations agree fairly well with the void fraction experimental data. A theoretical model on the basis of the balance of the driving and resisting forces, by adopting the Friedel correlation for the two-phase friction pressure drop, predicts satisfactorily the liquid flow rate and can be applied to different geometries. As regards the flow pattern the test section transparency allowed us to see the flow structure: pictures have been shot with a stroboscopic light and a bubble flow is observed at lower flow rate, whereas at higher flow rate and void fraction a transition from bubble to churn flow can be seen. The most efficient gas driven circulation is obtained at flow rate not too high, when a two phase bubbly flow occurs along the riser; moreover for such conditions the liquid flow rate is more regular with small oscillations. On the contrary when the transition to churn flow occurs, the bubble associated energy dissipation becomes increasingly higher and the circulation performance becomes more and poorer at higher flow rate.

VI. AKNOWLEDGEMENT

Research supported by the Italian Education Ministry.

NOMENCLATURE

C_0 ,C_1	Drift flux parameters	
d	Diameter	m
g	Gravity Acceleration	m/s^2
j	Superficial velocity	m/s
k	Heat capacities ratio c_p/c_v	
L	Length	m
p, Δp	Pressure, pressure drop	Pa
P	Power	W
Q	Volumetric flow rate	m^3/s
R	Ideal gas constant	kJ/kg K
Ta	Ambient temperature	°C
v	Specific volume	m^3/kg
W	Mass flow rate	g/s, kg/s
x	Flow quality	
α	Void fraction	
Δz	Axial step length	m
η	Circulation performance	
ρ	Density	kg/m^3

Subscripts

a	Ambient
ad	Adiabatic
DC	Down comer
el	Elevation
f	Friction
g	Gas
h	Hydraulic
in	Inlet
is	Isothermal
l	Liquid
meas	Measured
p	Pneumatic
pred	Predicted
R	Riser
SP	Single- Phase
TP	Two- Phase
tot	Total
TS	Test section

REFERENCES

[1] J. Korpijarvi, P. Oinas and J. Reunanen, "Hydrodynamics and mass transfer in an airlift reactor", Chemical Eng. Science, 54, pp. 2255-2262, 1999.

[2] D. A. Sanders, H. Cawte and A. D. Hudson, "Modelling of the fluid dynamic processes in a high-recirculation airlift reactor", Int. J. Energy Res., 25, pp. 487-500, 2001.

[3] W.P. Zhang, Q. Huang, C. Yang, Z.S. Mao, "Hydrodynamics, mixing and mass/ heat transfer in an airlift internal loop reactor", Ind. Eng. Chem.Res., 128, Beijing, China, 2011.

[4] W. P. Zhang, Y. M. Yong, G. J. Zhang, C. Yang, Z. S. Mao, "Micro- mixing characteristics and bubble behaviour in an airlift internal loop reactor with low height to diameter", Procs. 14th European Conference on Mixing, 529, Warsaw, Poland, 2102.

[5] Ch. Vial, S. Poncin, G. Wild, N. Midoux, "Experimental and theoretical analysis of the hydrodynamics in the riser of an external loop airlift reactor", Chemical Engineering Science, 57, pp. 4745-4762, 2002.

[6] J. C. Merchuk, I. Berzin, "Distribution of energy dissipation in airlift reactors", Chemical Engineering Science, 50, pp. 2225-2233, 1995.

[7] Ansaldo Nucleare, Enea, "XADX Pb-Bi cooled experimental accelerator driven system, reference configuration", ADS 1 SIFX 0500- Rev-0, June 2001.

[8] M. De Salve, M. Malandrone, B. Panella and B. Piano, "Deflussi bifase aria-acqua indotti da differenze di densità" (in Italian), Procs. XVII Congr. Nazionale Sulla Trasmissione Del Calore, II, pp. 715-726, Ferrara, 1999.

[9] M. De Salve, M. Malandrone, B. Panella, B. Piano, "Frazione di vuoto e regimi di deflusso in un circuito con circolazione bifase assistita con iniezione di gas" (in Italian),

ISSN: 2277-3754
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International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 5, November 2014
Procs. XVIII Congr. Nazionale Sulla Trasmissione del Calore, pp. 571-581, Cernobbio, 2000.

[10] M. De Salve, M. Malandrone, B. Panella, "Gas driven circulation in an adiabatic air-water loop with reference to accelerator driven systems", Procs. ASME ICONE10, 10th Conf. on Nuclear Eng., Paper N.22546, CD Rom, 2002.

[11] L.Cinotti (Ansaldo Company), Personal communication, 2003.

[12] Y. Taitel and A. E. Dukler, "Flow regime transitions for vertical upward gas-liquid flow: a preliminary approach through physical modeling", AIChe 70th Annual Meeting, 1977, reported in "Convective Boiling and Condensation" by J. G .Collier and J. R. Thome, 1996.

[13] K. Mishima and M. Ishii, "Flow regime transition criteria for upward two-phase flow in vertical tubes", Int. J. Heat Mass Transfer, 27, pp. 723-737, 1984.

[14] A. Ohnuki, H. Akimoto, "Experimental study on transition of flow pattern and phase distribution in upward air-water two-phase flow along a large vertical pipe", Int. J. Multiphase flow, 26, pp. 376-386, 2000.

[15] J. H. Hills, "The operation of a bubble column at high throughputs. Gas holdup measurements", Chemical Eng. J, 12, pp. 89-99, 1976.

[16] A. Premoli, D. Francesco, A. Prina, "An empirical correlation for evaluating two-phase mixture density under adiabatic conditions", European Two-phase Flow Group Meeting, Milan, 1970.

[17] N. Zuber and J. A. Findlay, "Average volumetric concentration in two-phase flow systems", J. Heat Transfer, 87, 4, 1965.

[18] P. B. Whalley, "Boiling Condensation and Gas-liquid Flow", Clarendon Press, Oxford, 1987.

[19] L. Friedel, "Improved friction pressure drop correlations for horizontal and vertical two-phase flow", European Two-phase Flow Group Meeting, Ispra, 1979.