MOMENTUM TRANSFER IN SUBMERGED GAS INJECTION USING CONVERGENT-DIVERGENT NOZZLES

A.I. ARELLANO†, D. JARAMILLO†, M.A. BARRÓN‡ and G. PLASCENCIA†§

† *CIITEC-IPN, Cerrada Cecati s/n, México, D.F., C.P. 02250, México. g.plascencia@utoronto.ca*
‡ *Depto. de Materiales, UAM-Azcapotzalco, Av. San Pablo 180, México, D.F., C.P. 02200,México*
§ *Materials Sc. & Engineering, University of Toronto, 184 College St., Toronto, ON, M5S 3E4, Canada*

***Abstract*— Gas injection into liquids is common in many applications. Nozzles with simple geometries are used for injecting gases, this lead to some turbulence and thus different rates of mixing and residence times. In this paper we present a study on gas injection using convergent-divergent nozzles. Gas flow through nozzles with different diameter ratios has been studied. It was found that changes in diameter ratios have a definitive effect on the performance of these nozzles as the gas is injected into a liquid. Pressure measurements of the gas during injection were conducted so momentum transfer could be estimated; additionally high speed video allowed us to see the differences in the gas plumes as the different nozzles were used.**

***Keywords*—– Convergent-divergent nozzles, Gas injection, fluid flow.**

I. INTRODUCTION

Gas injection is used in different industrial process, mostly in those which need mixing, reacting or even only physical contact between two or more fluids. Conventional injection uses simple tubes as nozzles. Given the geometry of these nozzles, they not always are able to produce good mixing without using very high flow rates, which in turn increases processing costs. To improve the performance of the nozzles, it is possible to increase momentum transfer between the fluid phases by simply modifying the geometry of the nozzles. One possible change is using convergent-divergent (C-D) nozzles (Pougatch *et al.*, 2008).

Extensive reviews (Adjei and Richards, 1991; Brimacombe *et al.*, 1990; Devia *et al.*, 1995 and Richards *et al.*, 1986) strongly emphasize the previous comments. Furthermore, Brimacombe *et al.* (1990) predict vast usage of gas injection in melts for increasing the productivity of high quality steels. This work also opened the door for applied research on topics related to gas injection into liquids.

Although some research has been done in estimating the stirring effect of gas injection or the relationship between bubble size and bubble frequency with the hydrodynamics of the systems under study, little efforts have been reported on the design of injection nozzles. As already mentioned, injection is usually done using nozzles with constant cross sectional areas; however, if the purpose of injecting the gas into the liquid is to increase the contact area between phases or simply improve mixing conditions within a reactor, then a change in nozzle design may be suitable. One possible change to nozzle design is the use of C-D nozzles. There are few reports that document the use of these nozzles as injection devices.

In all submerged injection applications the principal requirement for the injection device design is a prior knowledge of the jet or bubble shape and dimensions, which primarily depend upon the nozzle type, size and depth of submergence (Dahikar *et al*., 2007).

In the present study, we tested the injection of air into a fixed volume of water using several C-D nozzles with different diameter ratio to characterize the plumes obtained by means of in-line pressure measurements and also by looking at specific bubble or jetting features. Experimental results on the momentum transfer between the air and the water are also presented. The experimental observations are coupled with flow patterns calculated using CFD analysis.

II. FLUID FLOW IN CONVERGENT-DIVERGENT NOZZLES

As the gas passes through a C-D nozzle, it goes through different changes in volume, pressure, and velocity (Szekely, 1979), therefore, the flow pattern change accordingly. In order to estimate how the flow pattern is affected by changing the geometry of the nozzle, some CFD calculations using the $\kappa-\varepsilon$ turbulence model were conducted (Arellano, 2012). Table 1 shows the dimensions of the nozzles tested while Fig. 1; illustrates the nozzles calculated.

Results for the gas fluid flow in the different nozzles are shown in Fig. 2. It is evident from this figure that the flow patterns change quite drastically as the diameter ratio changes.

For nozzle 1, flow patterns with convex shape develop, the maximum gas velocity establishes at exactly the centre of the nozzle's throat. Some vorticity also evolves going through four stages of development, (1) generation or formation, (2) Stable laminar phase, (3) unstable or wavy phase, and (4) turbulent phase (Zare-Bethash *et al.*, 2009). Nozzle 2 also experiences the maximum gas velocity at the throat's centre, however at the nozzle's outlet some of the gas backflows moving

Table 1. Nozzle dimensions

Nozzle	Inlet diameter (m)	Throat diameter (m)	Outlet diameter (m)
1	0.02	0.005	0.01
2	0.01	0.005	0.02
3	0.01	0.005	0.01
4	0.02	0.02	0.02

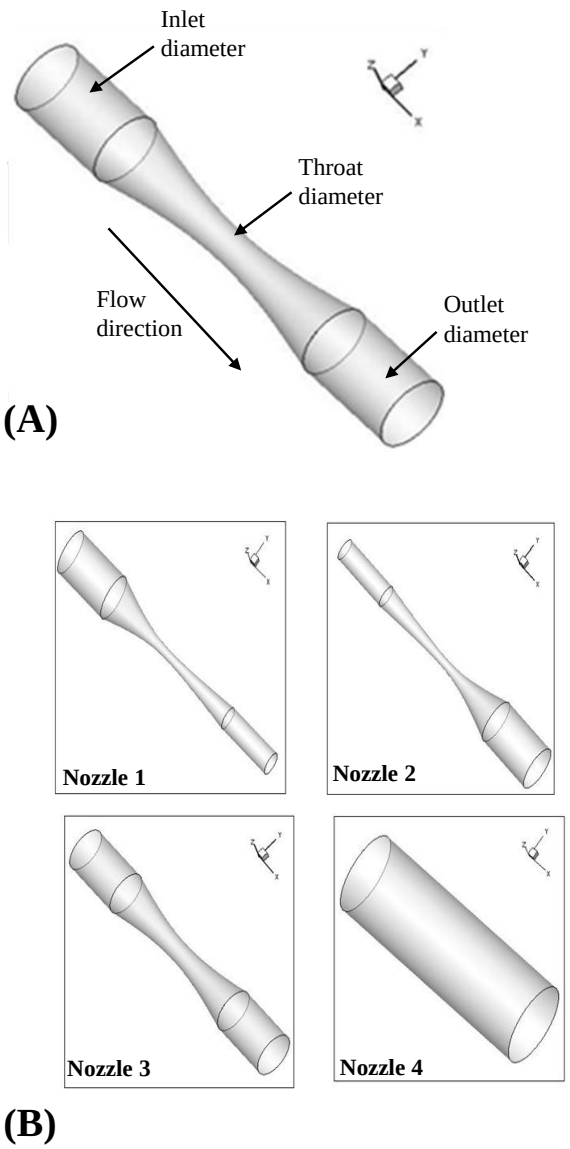

Fig. 1. (A) General description of a convergent-divergent nozzle. (B) Nozzles used for calculation.

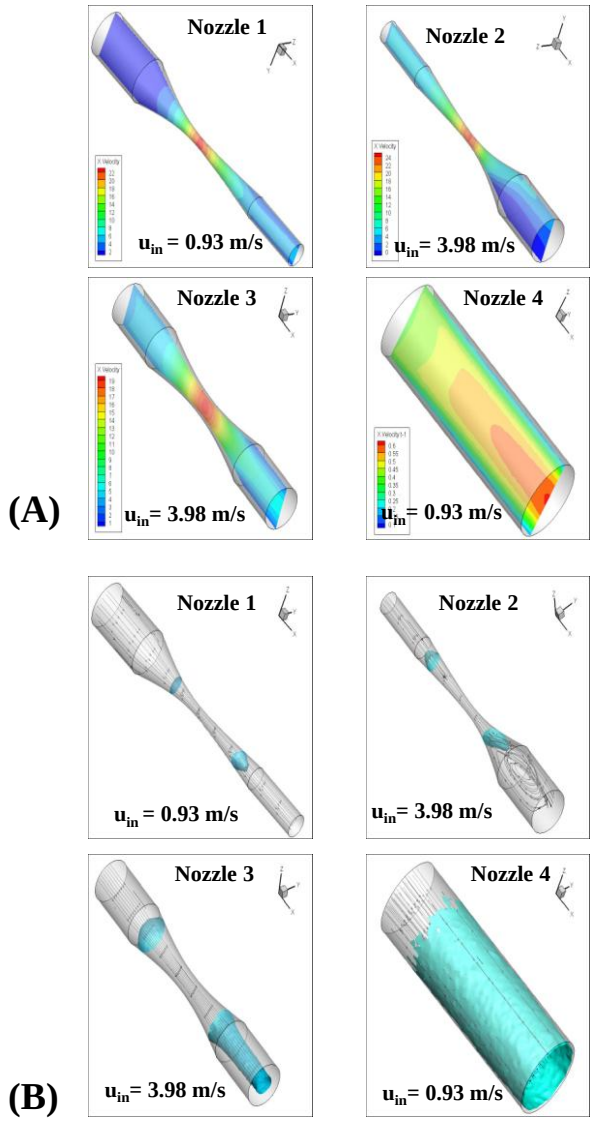

Fig. 2. (A) Velocity profile along the nozzles axis. (B) Flow pattern in each nozzle as the gas passes through. u_{in} is the inlet gas velocity.

back to the nozzle; this undesirable effect is due to the sudden expansion in the outlet diameter. This backflow effect is called the "siphon" effect and it takes place when the momentum in the final section of the nozzle is smaller than the forces acting on the last part of the device.

Nozzle 3 shows a similar velocity distribution as nozzles 1 and 2, but for this particular nozzle, it seems like the gas does not lose as much energy at the nozzle outlet as in the case of nozzle 2.

In the case of nozzle 4 which represents a straight tube, it is evident that little velocity gradients develop along its axis, thus rendering its capacity to exchange momentum at its discharge.

In every case the results from the numerical simulations refer only to the central plane of the nozzles.

After running these calculations, we were able to understand how the nozzle geometry affects the gas flow. The information gathered at this point was useful in order to estimate the momentum transfer between the air and the water. The following experimental procedure was conducted.

III. EXPERIMENTAL

A. Materials

Different acrylic nozzles were machined accordingly to the dimensions in Table 1. On one side of these nozzles along their axis, three holes were drilled to connect pressure transducers (Omega PX 4100) in the inlet, the throat and outlet sections of the nozzles. A fourth pressure transducer was installed in the gas supply line before the nozzle. The transducers were connected to a data acquisition unit which in turn was connected to a PC.

The air gas supplied to the nozzles by means of a compressor. Stainless steel tubing was used to connect the compressor to the nozzles. At the nozzles outlet, a brass connector with a valve was attached to a water

reservoir made of acrylic; the volume of water contained in such reservoir is 0.125 m^3. The amount of gas supplied to the experimental set up was measured by an air flowmeter (Omega FMA A 2000).

B. Method

Once the set up was ready, several experiments were conducted. A typical experiment consisted in filling up the water reservoir, once the container was filled with water, the air was allowed to flow through the nozzles, as the air passed by the data acquisition system began to record pressure variations in each section of the nozzle as well as in the main line. As the gas penetrated the water, two high speed cameras were recording the plume evolution. One of the cameras was placed in front of the nozzle outlet and the second camera was placed on the side of the gas discharge. Several air flow rates from 30 to 70 L/min of air were tested with each nozzle. Each experiment lasted for five minutes and was repeated five times to ensure reproducibility.

IV. RESULTS AND DISCUSSION

Figure 4, shows the initial readings from the pressure transducers for each of the 5 tests conducted as air is injected into water at a flowrate of 60 L/min, using nozzle 1. As seen in this figure, except from test 3, the maximum pressure for breaking the water volume and inserting the initial gas bubbles are quite similar, In the case of test 3 it takes longer time to introduce the initial gas bubble into the liquid; however the pressure level is slightly lower than the other four experiments. This can be attributed to the motion of the liquid. All tests except the third one were conducted when the liquid remained still. In case of the third test, some external stirring was provided by means of a mechanical propeller (150 rpm, 2 minutes). The intention of running this test in such fashion was to record the pressure drop response when injecting the gas into moving water. As is evident in fig 4, there is a change in this variable. In no other test external stirring was used. Therefore as indicated in Fig. 4, it is evident that in order to introduce the gas phase into the liquid one, the state of forces acting on the liquid has to be modified. As the gas pushes away the water so the initial gas bubbles penetrate the liquid, it has to transfer

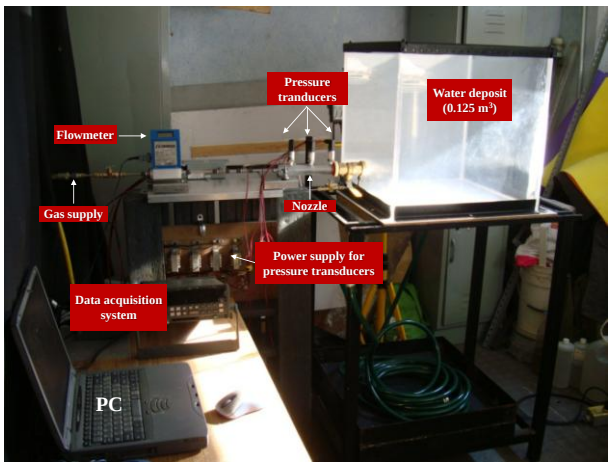

Fig. 3. Experimental set up.

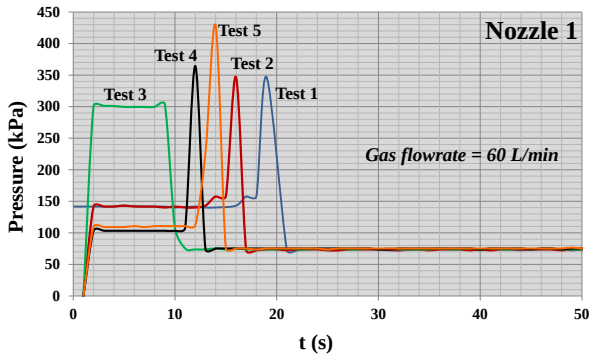

Fig. 4. Initial air injection in water at 60 L/min using nozzle 1.

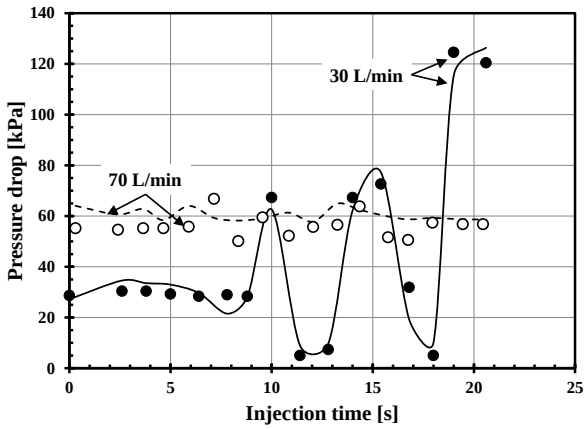

Fig. 5. Pressure drop comparison for gas injection using nozzle 1 at 30 and 70 L/min. (Points indicate experimental measurements, lines calculated values).

certain amount of momentum. Similar plots were found for the different nozzles tested.

In terms of the pressure drop, there is a good relationship between our CFD calculations and the experimental measurements. The comparison between the simulations and the results are shown in fig 5 below:

As is evident in Fig. 5, there is good agreement between calculated and measured pressure drop. The pressure drop reported is the difference in pressure between the nozzle outlet and inlet.

On the other hand, the amount of momentum transferred from the gas to the liquid can be estimated using the following equation

$$\int npdA = \int \rho V dV \,, \qquad (1)$$

that represents the area under the curve in the pressure vs time plots. The estimated momentum transfer for nozzles 1 to 3 is shown in Fig. 6.

As it can be seen in this figure, using nozzle 2 gives the maximum momentum transfer with a gas flowrate of 70 L/min. This nozzle goes from a small diameter in the inlet to a large diameter in the outlet. This nozzle experiences the siphon effect due to its outlet to inlet diameter ratio; as some gas backflow occurs, it accelerates the gas at the nozzle's outlet so it can transfer more momentum as the gas flowrate (velocity) increases.

Nozzles 1 and 3 behave in an opposite manner between them. Nozzle 1 is able to transfer more momentum at lower flowrates due to its smaller outlet diame-

ter; as less gas passes through this nozzle it accelerates as it flows into the small outlet section, however as more gas is added to the nozzle, it chokes limiting the amount of gas coming out of it, thus rendering the ability of this nozzle to transfer momentum. On the other hand, nozzle 3 has an outlet to inlet diameter ratio of 1 which means that the entrance and outlet sections of this nozzle have the same area. This nozzle works in a similar fashion as Nozzle 2, however compared to the later, it can transfer more momentum at a lower gas flowrate.

Another similitude between the three nozzles is that after experiencing a maximum in momentum transfer it goes to a lower value when more gas is supplied (higher gas flowrate); this effect has more to do with the random nature of turbulence than with the performance of the nozzle. Intuitively it can be expected that as more gas is provided to the system, the more momentum will be transferred, however as seen in this plot it is quite evident that not necessarily more momentum will be transferred by injecting more gas to the water. This observation is in good agreement with those made (Hoefele and Brimacombe 1979).

Visual evidence of such effect is closely related to the penetration of gas into the liquid. Fig. 7, shows a series of high velocity photographs taken as the gas initially was injected into the water using nozzle 1.

As seen in this series of pictures, there is more gas penetration when the air is blown at 30 L/min, which corresponds with the maximum momentum transferred for this nozzle. As the gas flowrate increased to 70 L/min, less gas penetration into the liquid is observed, this is a clear indication of the declining in the momentum transfer, as indicated in Fig. 6. In trials with nozzle 3, image analysis indicates that as the gas flowrate increases, the more gas penetration is shown.

V. CONCLUSIONS

Gas flow in convergent-divergent nozzles gas was simulated numerically. It was found that depending on the nozzle's outlet to inlet diameter ratio, the gas flow patterns change quite drastically. Such flow patterns affect the way in which momentum is transferred from the gas (air) to a liquid (water) as the former is injected into the later, using this C-D nozzles. The change in diameter

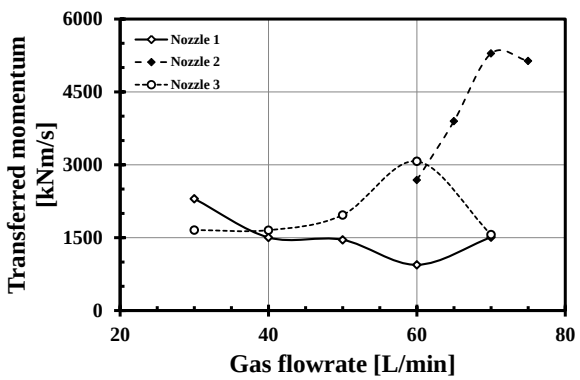

Fig. 6. Transferred momentum from the gas to the liquid using nozzles 1, 2, and 3.

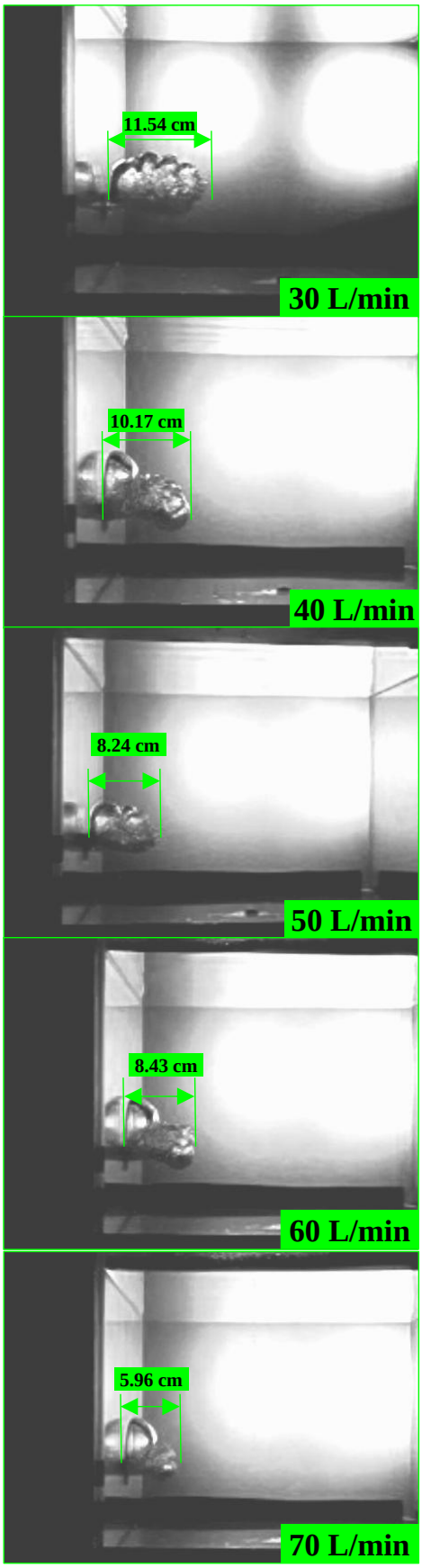

Fig. 7. Penetration of gas into the liquid pool as a function of the gas flowrate. In every case nozzle 1 was used to inject the gas.

ratios also impacts the amount of momentum that can be transferred from the gas to the liquid. It is observed that for a fixed volume of liquid, it is possible to improve mixing conditions by injecting less volume of gas, in other words, to achieve good mixing conditions, is not necessary to add significant gas volumes as intuitively expected.

ACKNOWLEDGEMENTS

The authors appreciate funding for this project from SIP-IPN grants.

REFERENCES

Adjei, E. and G.C. Richards, "Physical modelling of mass transfer in a Peirce-Smith converter," *Proc. Copper/Cobre 91*, Ottawa, Canada, **4**, 377–388 (1991).

Arellano, A.I., *Estudio de la dinámica jet-mata con toberas convergentes-divergentes en convertidores de cobre*, M. Sc. dissertation, CIITEC - IPN, México (2012).

Brimacombe, J.K., K. Nakanishi, P.E. Anagbo and G.G. Richards, "Process dynamics: Gas-liquid", *Proc. Elliot Symposium in Chemical Process Meta llurgy*, Cambridge, USA, 343–412 (1990).

Dahikar, S.K., S.S. Gulawani, J.B. Joshi, M.S. Shah, C.S. Rama Preasad and D.S. Shulka, "Effect nozzle diameter and its orientation on the flow pattern and plume dimensions in gas-liquid jets reactors," *Chemical Engineering Science*, **62**, 7471-7483 (2007).

Devia, M.I., R.H. Fuentes and F.J. Guevara, "Gaseous injection phenomenology in Peirce-Smith converters," *Proc. Copper/Cobre 95*, Santiago, Chile, **4,** 239–253 (1995).

Hoefele, E.O. and J.K. Brimacombe, "Flow regimes in submerged gas injection," *Metallurgical Transactions B*, **10B**, 631-648 (1979).

Pougatch, K., M. Salcudean, E. Chan and B. Knapper B., "Modelling of gas-liquid flow in a convergent-divergent nozzle," *Chemical Engineering Science*, **63**, 4176-4188 (2008).

Richards, G.G., K.J. Legeard and A.A. Bustos, "Bath slopping & splashing in the copper converter," *Proc. The Reinhardt Schuhmann International Symposium*, Colorado Springs, USA, 385–402 (1986).

Szekely, J., *Fluid flow phenomena in metals processing*, Academic Press, New York (1979).

Zare-Bethash, H., K. Kontis, N. Góngora-Orozco and K. Takayama, "Compressible vortex loops: Effect of nozzle geometry," *International Journal of Heat and Fluid Flow*, **30**, 561-576 (2009).

Received: August 28, 2013
Accepted: February 18, 2014
Recommended by Subject Editor: Walter Ambrosini