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Characterization of water-air dispersed two phase flow

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Abstract

The analysis of two phase flow has a great relevance in many industrial sectors such as nuclear and process industry. The study and the measurement of the related phenomena are particularly difficult due to the variety of the parameters that affect the flow (void fraction, flow regime, orientation, etc.). Measurement instrumentation for two phase flow is nowadays very limited even if it would be highly useful in the industrial field. Before approaching the research and development toward the realization of innovative instrumentation for two-phase flow measurement, it is fundamental a precise description of the particular flow regime of interest. Dispersed water droplets in air/gas is a possible flow regime at high gas void fractions; therefore it is important to characterize this particular flow pattern in a detailed way. To reproduce this condition in a laboratory environment it is possible to use nozzles with very small outlet diameters and high pressure water supply. In this paper the characterization of dispersed flow is performed as function of the nozzle characteristic and water inlet pressure. The tests are performed using an experimental setup realized at the Energy Department at Politecnico di Torino. The water jet is observed in a PMMA (PolyMethylMethacrylate) pipe 1.8 meters long with an inner diameter of 78 mm. High pressure water is obtained using a plunger pump and pump inlet water pressure is adjustable in the range 1-4 bar. Water pressure upstream the nozzle and air entrainment flow rate are measured and used as primary parameters of the study. A sensitivity analysis on these two parameters is performed with the purpose to find the conditions that are optimal to reproduce a dispersed flow.

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Keywords: two-phase flow; dispersed flow; nozzle; spray;

1. Introduction

In many energy and industrial systems, the characterization and the measurement of the mass flow rate is a fundamental aspect, both for performance analysis and for safety issues. Despite its importance, the evaluation of this parameter is not always a trivial problem. Usually, the easiest way is to use a dedicated device that has been previously designed and calibrated for the system of interest. A relevant limitation is that this kind of devices are capable to work only for single phase flow. Moreover, most of them are able to work only with the specific fluid for which they have

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been designed and calibrated. In the design of a thermodynamic system in which the measurement of mass flow rate is needed, for every single process a suitable instrument for the used fluid has to be chosen. The real problem comes up when two-phase flow is present. Historically, the study of the phenomena and the measurement of the related parameters are particularly difficult due to the many variables that affect the flow: the void fraction, the flow regime, the velocity of the two phases, the orientation of the flow, etc. In the past, many studies have been performed and some semi-empirical correlations for the characterization of this problem have been found, but the uncertainties of the results are very high and the range of applicability is limited. Because of the intrinsic complexity of this kind of problem, nowadays the measuring instrumentation for the evaluation of the mass flow rate in two phase condition is almost inexistent. In the last years at the Thermal-hydraulic Laboratory of the Energy Department at Politecnico di Torino several experiments on two-phase flow have been carried out at high void fraction by using different instrumentation for flow rate measurement [1, 2, 3, 4, 5]. The aim of the present paper is to design a device that can produce a dispersed flow regime at high gas void fractions, which is obtained by using nozzles with very small outlet diameters and high pressure water supply, so as to suck an air stream with water droplets dispersed in it. The breakup length, the fragmentation of the liquid jet in droplets, the interaction droplets-wall have been investigated and water pressure upstream the nozzle and air entrainment flow rate have been measured.

2. Dispersed flow

As already mentioned, there are many parameters characterizing the two phase flow. Among them, the direction of the flow is fundamental, since the gravity affects the fluid dynamics: in a vertically oriented pipe, the gravity is in the same direction of the flow and the effect of its action on the fluid is simply related to the way of the flow, i.e. upward or downward. Moreover, since the gravity acts equally on the cross section of the pipe, any symmetry is preserved. The problem is different if the pipe is horizontally oriented. Since the direction of the flow and the gravity are orthogonal, the resulting effect is a tendency to stratification of the two phases, with the liquid phase that tends to accumulate in the lower part of the pipe. The overall effect of pipe orientation, together with the velocity of the two phases and the void fraction, determine the flow pattern that occurs. An example of the possible different flow patterns is shown in Fig. 1.

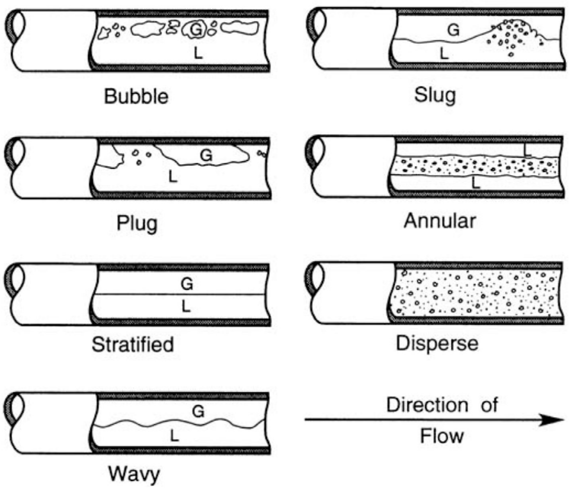

Fig. 1. Flow pattern maps inside a horizontal pipe [6].

They differ depending on the average distribution of one phase with respect to the other. The void fraction is increasing going from the first to the second column, going from the top to the bottom. As we can see, one of the flow patterns associated to high void fractions is the dispersed one. In the dispersed flow pattern one phase or component (such as drops, bubbles, or particles) is widely distributed in the other continuous phase [6].

In the present paper, a dispersed flow pattern with water droplets distributed inside air has been analyzed. A dispersed flow can be experimentally reproduced by supplying high pressure water through nozzles with very small diameters (lower than 1 mm). The dispersed flow is generated by the combination of the liquid jet from the nozzle and the air flow rate sucked inside the pipe by the liquid jet; the jet is characterized by numerous phenomena such as jet break-up, fragmentation mechanisms, droplets formation, entrainment processes and water-wall interaction [7].

3. Experimental facility and methodology

An experimental setup has been designed and built in the Thermal-hydraulic Laboratory of the Energy Department at Politecnico di Torino. Using a plunger pump, demineralized water at high pressure is atomized through a nozzle with small diameter to create the fluid dynamic condition typical of a dispersed flow pattern inside a pipe. A simplified scheme of the test facility is shown in Fig. 2.

The main components of the facility are a Water Tank (WT), an Air Pressure Regulator (APR), a Water Flow Meter (WFM), a Differential Pressure Transducer (DPT), a Pneumatic Valve (PV), a nozzle, a PolyMethylMethacrylate (PMMA) pipe and an Air Velocity Meter (AVM).

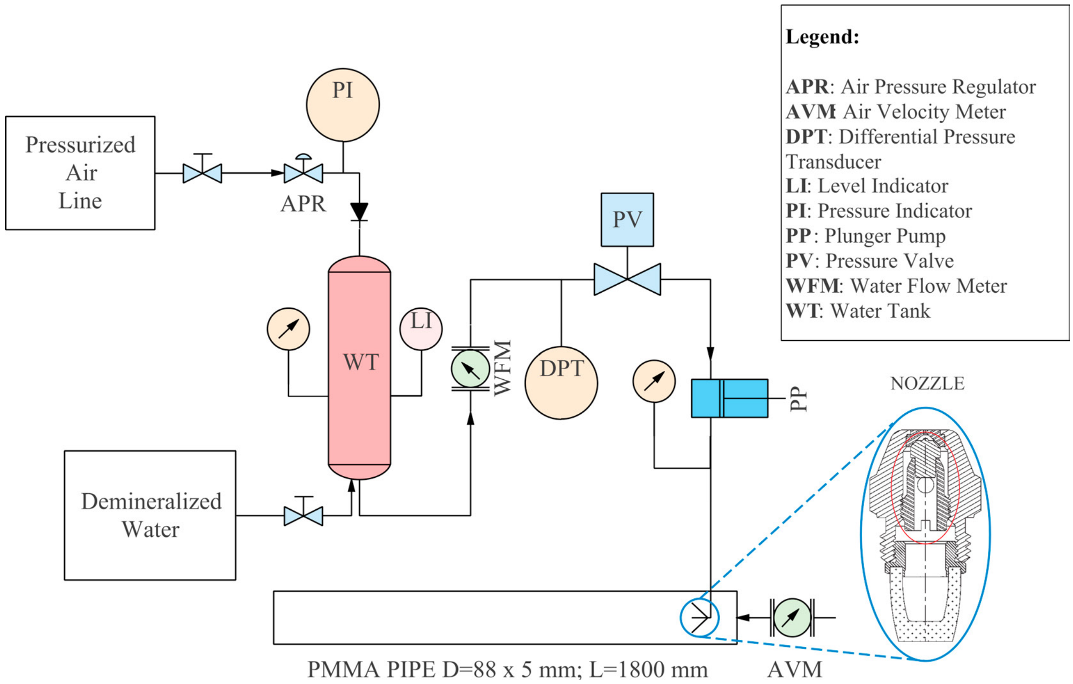

Fig. 2. Test facility layout and nozzle cutaway.

The demineralized water is contained inside the WT, which consists of a stainless steel tube 850 mm long (88,9 x 3 mm) with two rounded caps at the ends; the lower end is connected to the rest of the experimental setup whereas the pressurized air line is connected to the upper end. Thanks to the APR, the air pressure can be regulated in order to modify the pressure of the supply water for the pump. The WFM, at the exit of the WT, measures the volumetric water flow rate during the tests. The DPT is used as a gauge pressure transducer to measure the pressure of the supply water. The PV is operated together with the Plunger Pump: an electric solenoid for pneumatic actuators is linked to the PP electric supply; when the pump is off, the PV is normally closed; when the PP is turned on, the PV opens and the water can flow through the valve and reach the pump. The PP characteristics are listed in the Table 1.

Table 1. Plunger pump technical characteristics [8].

Pump Model	1CX013ELS
Flow	0.492 lpm
Pressure range	6.9 - 69 bar
Inlet Pressure range	Flooded to 4.1 bar

A Pulse Hose, connected to the discharge line of the pump, smooths pressure wave oscillations in order to have a more regular and constant pressure at the outlet. Then high pressure water passes through the small diameter of the nozzle where it is atomized inside the pipe where the dispersed flow is studied. Moreover, an AVM, installed at the inlet of the pipe just before the nozzle, measures the air entrainment velocity inside the pipe.

Five different nozzles have been used in the tests. The used nozzles were obtained by removing the distributor from common Monarch 60°R type nozzles (cutaway in Fig. 2) of different sizes [9]. This modification allows the generation of a turbulent jet, differently from the original Monarch nozzle that generates a very fine atomized spray; the characteristics of the spray generated by the modified nozzles are obviously different from the ones declared in the Monarch nozzle data sheets.

The modified Monarch 60°R nozzles are of the types 1.25, 1.75, 2.25, 3.00 and 3.50. In the original Monarch nozzles, the type number corresponds to the nominal volumetric flow rate expressed in gph obtained with an inlet pressure of 7 bar [10]; since the distributors have been removed from the Monarch nozzles, the volumetric flow rate through the modified nozzles will not correspond to the type number of the original Monarch nozzles. Every nozzle has been tested at six different pressures in the water tank (1, 1.5, 2, 2.5, 3 and 4 barg) varying the inlet air pressure. Each test has been repeated five times and the average value and the correspondent standard deviation have been computed. In Table 2 the measured parameters are reported along with the corresponding measurement instrument.

The flow is contained in a PMMA pipe having an inner diameter of 78 mm, an outer diameter of 88 mm and a length of 1850 mm. All the networking piping is made of stainless steel ID=4 mm, OD=6 mm.

Table 2. Measurement instrumentation

Parameter	Measurement instrument	Range	Accuracy
Water tank pressure	WIKA manometer	0 - 10 bar	0.2 bar
Pump inlet pressure	ROSEMOUNT 1151 pressure transducer	0 - 7 bar	0.01 bar
Pump outlet pressure	Allemano precision manometer	0 - 100 kg/cm^2	1 kg/cm^2
Pump outlet pressure	Gould Statham PA822-2M pressure transducer	0 - 2000 psia	0.11 psi
Water flow rate	ASA meter	0 - 100 l/h	2 l/h
Entrained air velocity	TESTOvent	0.4 - 60 m/s	0.1 m/s

4. Results

Some typical time behaviors of the water pressure upstream the nozzle are reported in Fig. 3 for a constant pressure in the water tank of 2 barg. The diagram shows that the smaller the nozzle size is, the higher the pressure upstream the nozzle is. In addition, decreasing the nozzle diameter the amplitude of pressure oscillation upstream the nozzle increases. Negligible oscillations occur with nozzle types 3.00 and 3.50, while the maximum oscillation amplitude (almost 20 bar) is observed with the nozzle type 1.25.

In Fig. 4, water pressure upstream the nozzle is reported for different nozzles as a function of the pressure in the water tank. It can be observed that for constant values of pressure in the water tank, the pressure upstream the nozzle decreases for increasing nominal flow rate of the nozzle. On the other hand, for a fixed nozzle, the water pressure upstream the nozzle increases as the pressure inside the tank increases.

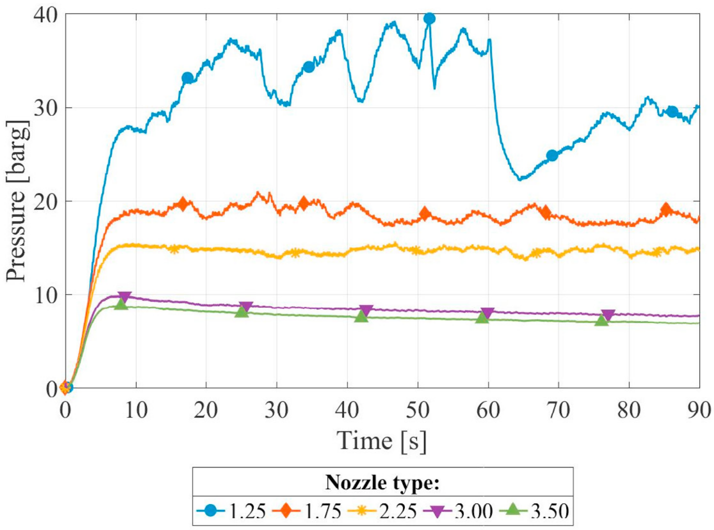

Fig. 3. Water pressure upstream the nozzle for every nozzle with 2 barg of pressure inside the tank.

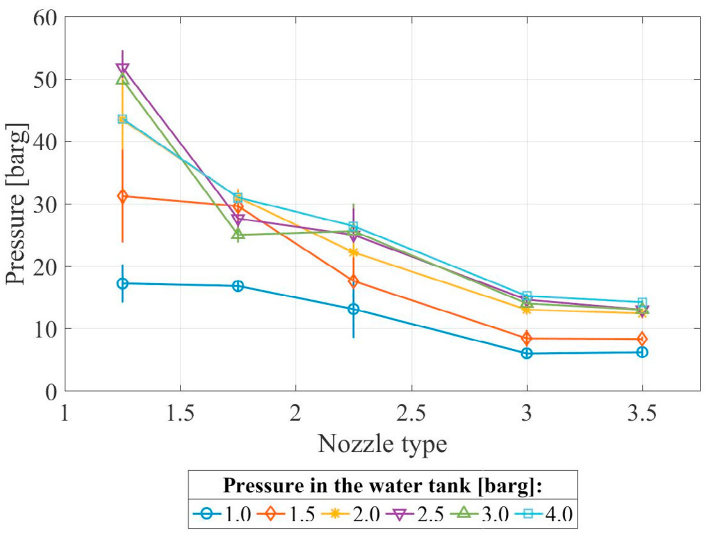

Fig. 4. Water pressure upstream the nozzle for the different nozzle types.

Fig. 5 shows the water volumetric flow rate through the five nozzles as a function of the water tank pressure. It can be noticed that, generally, the volumetric flow rate increases with the water tank pressure and the effect of different nozzle types is limited. When the pressure in the water tank is higher than 3 bar, the pump is operating beyond the nominal range declared in its data sheet and the sealing valve at the pump inlet is not leak-tight; therefore a continuous leakage of water occurs through the plunger head, which causes an increase of the water flow rate through the pump.

Fig. 6 shows the air velocity at the inlet of the PMMA pipe. It can be noticed that for every nozzle the air velocity is directly proportional to the water pressure upstream the nozzle. Since, as it is shown in Fig. 4, the water pressure upstream the nozzle can be easily adjusted varying the water tank pressure and the nozzle size, it is possible to obtain the desired air velocity inside the pipe.

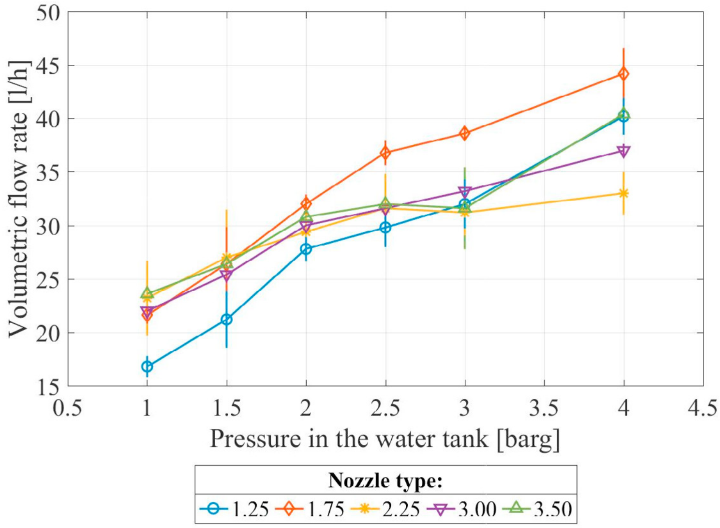

Fig. 5. Volumetric water flow rate.

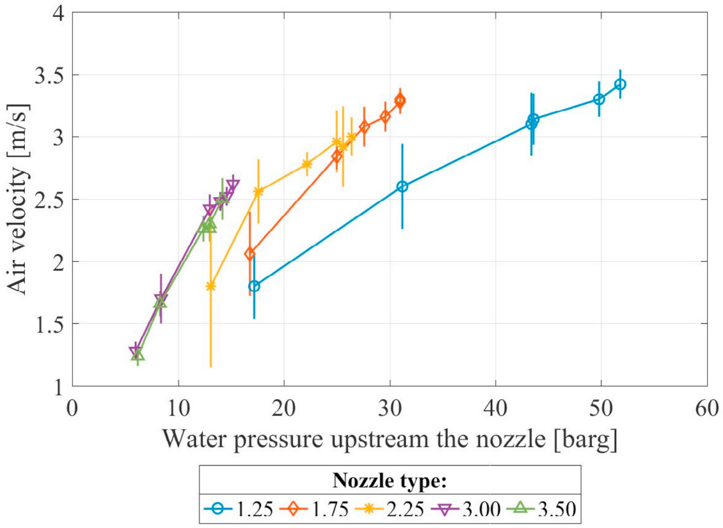

Fig. 6. Air velocity at the PMMA pipe inlet.

The air velocity, which is a particularly important parameter, since it affects the characteristics of the dispersed flow (flow rate, void fraction and flow pattern), depends on the water velocity at the nozzle outlet and therefore on the water flow rate and nozzle size. By knowing the water flow rate and the air velocity, the total flow rate for the dispersed flow pattern can be derived.

Five relative pressure taps are located along the PMMA pipe; the measurements show a depression in the pipe due to the jet that operates as a Venturi section, sucking air from the outside as can be observed in Fig. 7. The two curves are associated respectively to a water tank pressure equal to 1 barg and 3 barg. Decreasing the nozzle diameter the depression in the PMMA pipe increases; this higher depression increases the suction of air so the entrained air velocity is higher for lower nozzle diameters. The minimum for every curve is located in correspondence of the nozzle tip; this is the maximum depression reached inside the pipe, similarly to what occurs in the throat of a Venturi pipe. Moreover, the higher is the pressure reduction, the higher is the flow rate of air sucked into the pipe.

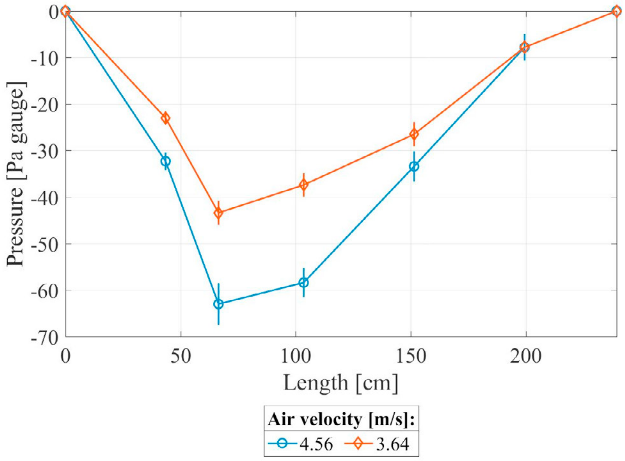

Fig. 7. Relative pressure as a function of the distance from the air suction; nozzle type 1.75.

In Fig. 8 and Fig. 9 images taken from tests performed at 2 barg with the nozzle type 1.25 are shown. In particular, Fig. 8 shows the jet at the nozzle outlet and its fragmentation after 50 cm. At the nozzle outlet, thanks to the removal of the nozzle inner distributor, the jet remains straight and confined up to 15-20 cm. After 20 cm, due to surface instability phenomena, the fragmentation of the jet begins and after 50 cm is evident. In Fig. 9 it is possible to see that the flow pattern after 1.8 m is a fully dispersed one with very small droplet diameters. Therefore the device is able to provide the desired flow pattern. For every analyzed nozzle, and at any supply pressure within the pump range, the droplets hit the pipe wall after at least 50 cm from the nozzle tip. This length will be considered when the equipment in the spool-piece for two-phase flow measurement [1] will be mounted. In fact, if the pipe surface is wet the data from the capacitance probe, which is an important component of the spool-piece, are distorted and the dispersed flow is not correctly characterized.

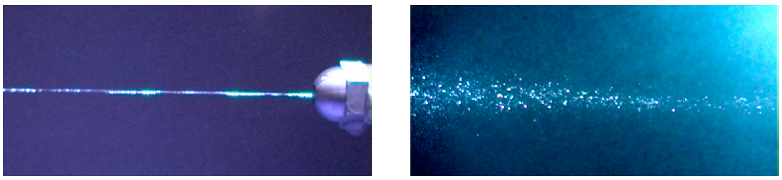

Fig. 8. Jet at the nozzle outlet (left) and after 50 cm (right); nozzle type 1.25 at 2 barg.

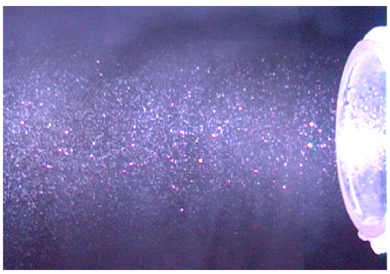

Fig. 9. Dispersed flow at the pipe outlet; nozzle type 1.25 at 2 barg.

5. Conclusion

The development of two-phase measurement instrumentation is a relevant issue in many industrial sectors such as nuclear and process industry. In this work a dispersed water-air two phase flow has been produced using a plunger pump to reach relatively high pressure. The results show that the volumetric pump operates in a nominal condition in a limited inlet pressure range. To avoid cavitation or leakages in the pump the inlet pressure should be chosen carefully. Varying the pressure in the water tank and the adopted type of nozzle, it is possible to obtain different water pressures. It has been observed that the dominant parameter is the nozzle size more than the water supply pressure to the pump. For the characterization of the two-phase flow the air entrainment velocity is a fundamental parameter. The air velocity depends on the pressure in the water tank and the nozzle size. As previously seen, also in this case the effect of the pressure variation has a stronger effect on the resulting air velocity. In future work a previously developed spool-piece, specifically designed to measure all the relevant two-phase flow parameters [1], will be introduced in the experimental facility. The aim is to perform a new experimental campaign investigating the dispersed flow pattern to enlarge the available data set acquired in the past. Using a Venturi flow meter and a capacitance probe the collected data will be used toward the development of two-phase flow measurement instrumentation.

Having analyzed the results presented above, in the previously mentioned future experiments the nozzle types 1.75 and 2.25 will be used to produce a dispersed flow pattern, since these nozzles, even reaching a relatively high pressure and consequently producing a relevant air entrainment velocity, show much lower oscillation than the smaller one (type 1.25). The two bigger nozzles (types 3.00 and 3.50) are very stable but the water pressure upstream the nozzle is lower and the air entrainment is reduced.

Acknowledgments

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