TOTAL MASS FLOWRATE MEASUREMENT IN MULTIPHASE FLOW BY MEANS OF A VENTURI METER

F. Sanchez Silva[o], P. Andreussi[+], P. Di Marco[+]

[o] Instituto de Investigaciones Electricas, Mexico
[+] University of Pisa, Italy

ABSTRACT

In recent years, the needs of the oil industry ask for a simple, compact and maintenance-free device to measure the mass flowrate of two-phase and three-phase (e.g. oil-gas-water) mixtures, to be used mainly for well testing. In this work the possibility of using a device based on a Venturi nozzle for industrial multiphase mass flowrate measurements has been investigated.

In case of multiphase systems, the relationship between the overall mass flowrate and the pressure drop in a Venturi nozzle is not unique and includes also the flow quality, so that measurements of quality or holdup have to be included.

An experimental facility for the study of any combination of oil, air and water flow has been built and operated. It consists of a vertical perspex pipe of 50 mm internal diameter and about 7 m length. The facility can be operated at atmospheric pressure and at the present makes use of air, water and diesel-fuel oil. The Venturi meter has been tested in air-water and air-oil-water flow; the superficial velocities ranged up to 1.8 m/s for oil and water and up to 20 m/s for air. Conductance probes, made of two stainless steel rings mounted flush to the pipe wall and placed at different positions in the pipe and in the Venturi throat allowed the measurement of the local liquid holdup for the case of air-water flow. Conventional measurements included pressure drop and absolute pressures.

The results show that a unique relationship can be inferred among the pressure drop across the Venturi, normalized with respect to the pressure drop relative to the liquid phase flowing alone in the nozzle, and the flow quality in any combination of the three phases.

NOMENCLATURE

A	cross-section area
d	pipe diameter
g	gravitational acceleration
G	electrical conductance
H_L	holdup
J_s	superficial velocity
L	throat length
p	pressure
Re	Reynolds number
S	slip ratio
v	specific volume
x	flow quality
z	height
β	throat-pipe diameter ratio

Γ	mass flowrate
Δp	pressure drop
ε	compressibility coefficient
ρ	density
χ	Martinelli parameter

Suffixes

G	related to gas
L	related to liquid
LO	related to the total mass flowrate flowing as liquid
TP	two-phase
1	related to the inlet
2	related to the throat

INTRODUCTION

The Venturi nozzle is widely used to measure the flowrate in single-phase flow with a reduced amount of energy losses. A simple energy balance shows that in this case the mass flowrate is proportional to the square root of the measured pressure drop between the inlet and the throat. This pressure drop is almost entirely recovered (apart from the frictional and gravitational losses) after the following diverging nozzle.

More recently, several attempts have been made to extend this technique to the case of gas-liquid flow, although many of these applications concern the use of the Venturi nozzle as a quality meter (in this case,

Presented at: V International Conference on Multiphase Production, Cannes June 19-21, 1991
Published in: Multiphase Production, Ed. by A.P. Burns, Elsevier,. 1991, pp. 145-155

the total mass flowrate is measured independently). In these applications, the pressure drop does not only depend on the total mass flowrate, but also on the quality, or the liquid holdup, in the pipe, so that measurements of quality or holdup have to be included in the device. The analysis of these measurements can be based on a considerable amount of theoretical work, which has been made by a number of authors to model the two-phase flow in a Venturi nozzle, or can be based on one of the empirical correlations proposed in literature and tested against experimental data.

The results reported in the present paper concern a research project started in 1989 at the University of Pisa on the possible use of a Venturi nozzle for industrial multiphase mass flowrate measurements. The device operates coupled with a void meter (conductance/capacitance probe, or gamma-densitometer) for gas-liquid flow and with two of such instruments for three-phase gas-liquid-liquid flow measurements. The experience gained in the past (Andreussi *et al.*,1988) in the development of impedance probes for the measurement of the liquid holdup in multiphase flow has been widely used in this respect.

STATE OF THE ART

In single-phase flow, the relationship between the mass flowrate and the pressure difference measured across the inlet section and the throat of a Venturi nozzle is given by

$$\Gamma = C\,\varepsilon\,A_2\sqrt{\frac{2\,\Delta p\,\rho_1}{1-\beta^4}} \tag{1}$$

for incompressible flow the compressibility coefficient ε is equal to 1; for compressible flow, it is less than 1 and depends upon the isoentropic coefficient of the gas, the ratio p_2/p_1 and ß. The discharge coefficient C depends upon the device geometry, is very close to 1 and is generally obtained by calibration. For a classical (Herschel) Venturi nozzle, most of the national codes (ASME, UNI, DIN) give C=0.995 in the following parameter ranges:

$$\begin{array}{ccccc} 50 & < & D & < & 250\text{ mm} \\ 0.4 & < & ß & < & 0.75 \\ 10^5 & < & Re & < & 10^6 \end{array}$$

In multiphase flow operation, a relationship exists that links the flowrate to pressure, quality and throttling ratio ß. As a first approach, the two-phase density can be used in Eq.(1), yielding

$$\Gamma = C\,\varepsilon\,A_2\sqrt{\frac{2\,\Delta p\,\rho_{TP1}}{1-\beta^4}} \tag{2}$$

For vertical flow, the pressure differential must be subtracted of the gravity head

$$\Delta p = p_1 - p_2 - \rho_{TP}\;g\;\Delta z \tag{3}$$

$$\rho_{TP} = \rho_L\,H_L + \rho_G\,(1-H_L) \tag{4}$$

Different correlations have been developed for two-phase flow operation of a Venturi meter. Chisholm (1983), disregarding gas compressibility and wall friction, lists several different correlations based on various hypotheses: zero interfacial shear stress, constant slip ratio, homogeneous flow, equal momentum flux. They usually link the ratio of the pressure drop in two-phase operation to the pressure drop that holds

when the same mass flowrate of liquid or gas flows alone in the pipe, Δp_L and Δp_G. These can be calculated from Eq.(1) once the flow quality is known.
The general form is:

$$\frac{\Delta p}{\Delta p_G} = 1 - c\,\chi - \chi^2 \tag{5}$$

where χ is the Martinelli parameter

$$\chi = \sqrt{\frac{\Delta p_L}{\Delta p_G}} \tag{6}$$

which in this case, considering Eq.(1), is given by

$$\chi = \frac{1-x}{x}\sqrt{\frac{v_L}{v_G}} \tag{7}$$

In the hypothesis of constant slip ratio (homogeneous flow occurs for S=1)

$$c = \frac{1}{S}\sqrt{\frac{v_L}{v_G}} + S\sqrt{\frac{v_G}{v_L}} \tag{8}$$

It is worth noting that, assuming $v_G / v_L >> 1$, Eq.(5) can be rearranged in the form

$$\frac{\Delta p}{\Delta p_{LO}} = 1 + \frac{v_G}{v_L}\left[\frac{x}{S}(1-x) + x^2\right] \tag{9}$$

Eq.(9) indicates that the two-phase multiplier depends upon the quality and the density ratio alone. An empirical correlation proposed by Chisholm (1983) to calculate the slip ratio in a flow restriction is

$$S = \left(\frac{v_G}{v_L}\right)^{0.25} \qquad \chi < 1 \text{ (high quality)} \tag{10}$$

$$S = \left[1 + x\left(\frac{v_G}{v_L} - 1\right)\right]^{0.5} \qquad \chi > 1 \text{ (low quality)} \tag{11}$$

The effect of the density ratio, ρ_G / ρ_L can be predicted using Eqs.(9-11) , as reported in Fig.1: as can be seen, an increase in pressure (or in gas density) yields a lower two-phase multiplier.
Azzopardi and coworkers (1983),(1988), developed a mechanistic model of the flow in the converging and diverging section of a Venturi nozzle. They assumed annular flow conditions and took into account the effect of the dispersed droplet flow on the pressure drop. A set of equations, including empirical correlations for droplet size distribution and droplet entrainment and deposition, was obtained and integrated. Allowance was made for the growth of the boundary layers in the diffuser. The model predicts pressure profiles in the Venturi that match qualitatively those obtained in the experiments, although the pressure drop from the inlet to the throat is slightly overpredicted. The incomplete pressure recovery after the diffuser was well estimated.

APPARATUS

The flow loop (see Fig.2) consists of a vertical perspex pipe of 50 mm internal diameter and about 7 m length. The configuration can be easily altered to meet different experimental requirements, since the test section is modularly assembled. The apparatus includes the supply circuits for air, water and oil, an upper air-liquid separator, a lower oil-water separator and a storage tank. The facility can be operated at a pressure up to 0.2 MPa, and at present makes use of water, diesel-fuel oil and air at atmospheric conditions, although the use of other oils and gases is foreseen. The maximum attainable flowrates are $4 \cdot 10^3$ Nm^3/s for air (corresponding to a superficial velocity J_s= 20 m/s) and $3.5 \cdot 10^{-3}$ m^3/s (J_s= 1.8 m/s) for oil and water. The facility can be operated in any combination of single and multiphase flow.

The facility includes a section equipped with quick-closing valves for the calibration of holdup probes and the Venturi test section (see Fig.3) whose geometrical configuration can be modified. In particular, three different throats 0.36 d, 1.16 d and 4.16 d in length have been used, d being the throat diameter (25 mm).

Although up to now only experiments in upward flow were performed, the operation in downward flow is also possible.

The measuring equipment consists of a set of rotameters for the measurement of the flowrates of each of the three phases, two absolute piezoresistive pressure transducers, one differential inductive pressure transducer. A PC data acquisition system can be connected to the apparatus.

Different types of holdup probes can be installed in the apparatus: they can be subdivided mainly in conductance and capacitance probes, and can be calibrated by means of the above mentioned quick-closing valve system. In this experimental campaign, probes made of two stainless steel rings mounted flush to the internal wall of the pipe and placed at different locations in the pipe and in the Venturi throat, were used. As shown by Andreussi *et al.*(1988), for these probes the measured electrical conductance is only a function of the water holdup.

EXPERIMENTAL RESULTS

Two series of tests were performed in the apparatus: in the first one, only air-water flow was studied. The second series concerned the study of air-water-oil flow.

In the first series of tests, air-water flow was studied in the Venturi meter equipped with the three different throats available. Measurements of pressure and pressure drop across the Venturi were taken for a wide range of gas and liquid flowrates. Holdup was measured at various locations in the pipe and in the Venturi throat (see Fig.3), by means of conductance ring probes. The probes in the full pipe section were calibrated by means of the quick-closing valve apparatus. The probes in the Venturi throat were calibrated on the bench, simulating annular flow conditions by means of plexiglass rods of different diameters inserted in the measuring section. The device demonstrated to be quite insensitive to azimuthal non-uniformities in the film thickness, simulated by moving the axis of the plexiglass rod with respect to the pipe axis.

Several different combinations of air and water superficial velocities were tested, in the ranges: 0.5-1.8 m/s for water and 1.5 - 15. m/s for air.

According to available flow pattern charts, all the conditions tested were in the churn or slug flow region. Visual observation showed a strong increase of turbulence downstream of the throat, and the flow pattern revealed to be churn or annular flow.

For holdup measurements, the conductance with the pipe filled with water was taken before each experimental run. The dimensionless conductance

$$G^* = \frac{G_{TP}}{G_L} \qquad (12)$$

could then be related to the holdup by means of the calibration curve. The water temperature was kept constant by a continuous feed of fresh water in the tank and ranged from 18 to 20 °C.

In the second series of tests, air-oil-water flow was studied in order to extend the results to three-phase flow. In these experiments, only pressure and pressure drop measurements were taken for the flow of oil, oil-water, oil-air and oil-air-water mixtures. The superficial velocities ranged as follows:

from 2 m/s to 11. m/s for air;
from 0.3 m/s to 1.4 m/s for water;
from 0.1 m/s to 1.2 m/s for oil.

The pressure trends in the Venturi meter relative to air-water experiments are shown in Figs.4-5 for two different gas superficial velocities: as can be seen, the pressure recovery after the diffuser is very low, as noted previously by other experimenters. This could be due to the fact that most of the pressure drop is needed to accelerate the liquid in the throat, and the corresponding energy is then lost in the diffuser.

Holdup measured in the Venturi section are shown in Figs.6-7. As can be seen, measurements in the throat indicate the presence of a continuous layer of liquid near the walls, and the values of the holdup are typical of annular or slug flow conditions. From a simple mass balance in homogeneous flow conditions, it can be deduced that a relevant part of the liquid forms a dispersed phase in the gas core: this discontinuous phase cannot be detected by a conductance probe.

All the measurements of the holdup can be related to the flow quality by a unique relationship, as shown in Fig.8, that reports the data for the probe located in the full pipe and in the Venturi medium throat. In this way, the derivation of the quality from holdup measurements appears to be feasible.

The pressure drop multiplier, $\Delta p/\Delta p_L$, is shown in Fig.9. As can be seen, the dependence of this parameter from the flow quality alone, as predicted by theory, is clearly confirmed. It should be considered that the theoretical predictions, expressed by Eqs. (9-11), were originally developed for orifices: therefore the theoretical results fit quite well the data referring to the short throat.

For a longer throat, a reduced value of the mean slip with respect to the value used in Eq.(11) is to be expected, since the gas drag accelerates the liquid along the throat. In fact, calculating the mean slip by the empirical equation

$$S = \left[1 + 0.4 \text{ x} \left(\frac{v_G}{v_L} - 1 \right)\right]^{0.5} \qquad (13)$$

where the coefficient 0.4 replaces the value 1.0 given by Chisholm (1983), the dashed line in Fig.9 is obtained, which fits the data of the medium throat.

Finally, for air-oil-water flow, the pressure drop multiplier, $\Delta p/\Delta p_L$, (where L refers to the global oil-water phase) is shown in Fig.10. Also in this case, the dependence of this parameter from the flow quality alone seems to be confirmed. A comparison between the measured two-phase multiplier and the one computed by means of Eqs.(9) and (13) is also reported.

CONCLUSIONS

The results reported in the present paper indicate that a Venturi nozzle can be employed for the measurement of the total mass flowrate in two/three-phase flow systems. In particular it has been shown that both the pressure drop multiplier and the mean liquid holdup before the nozzle and in the throat depend only on the flow quality. In these experiments, the local holdup has been measured by means of a conductance probe.

Present measurements, which cover a wide range of gas and liquid flowrates and different nozzle geometries, have been tentatively correlated by a semiempirical equation proposed by Chisholm (1983). This equation is based on the assumption of a constant slip ratio between the gas and the liquid phases.

The measurements , also reported in the paper, of the mean liquid holdup at various locations before, after and at the Venturi throat will allow in the future the development of more sophisticated methods for data reduction.

REFERENCES

Andreussi, P., Di Donfrancesco, A. and Messia, M. (1988) 'An impedance method for the measurement of liquid holdup in two phase flow', *Int. J. Multiph. Flow*, 14,6,pp.777-785

Azzopardi, B.J. and Govan, A.H. (1983) 'The modelling of Venturi scrubbers', Filtech Conference

Azzopardi, B.J., Texeira, S.F., Govan, A.H. and Bott, T.R. (1983) 'An improved model for annular flow in a Venturi', AERE-R13060

Chisholm, D. (1983) '*Two-phase flow in pipelines and heat exchangers*', G.Goldwin, London, Ch.11

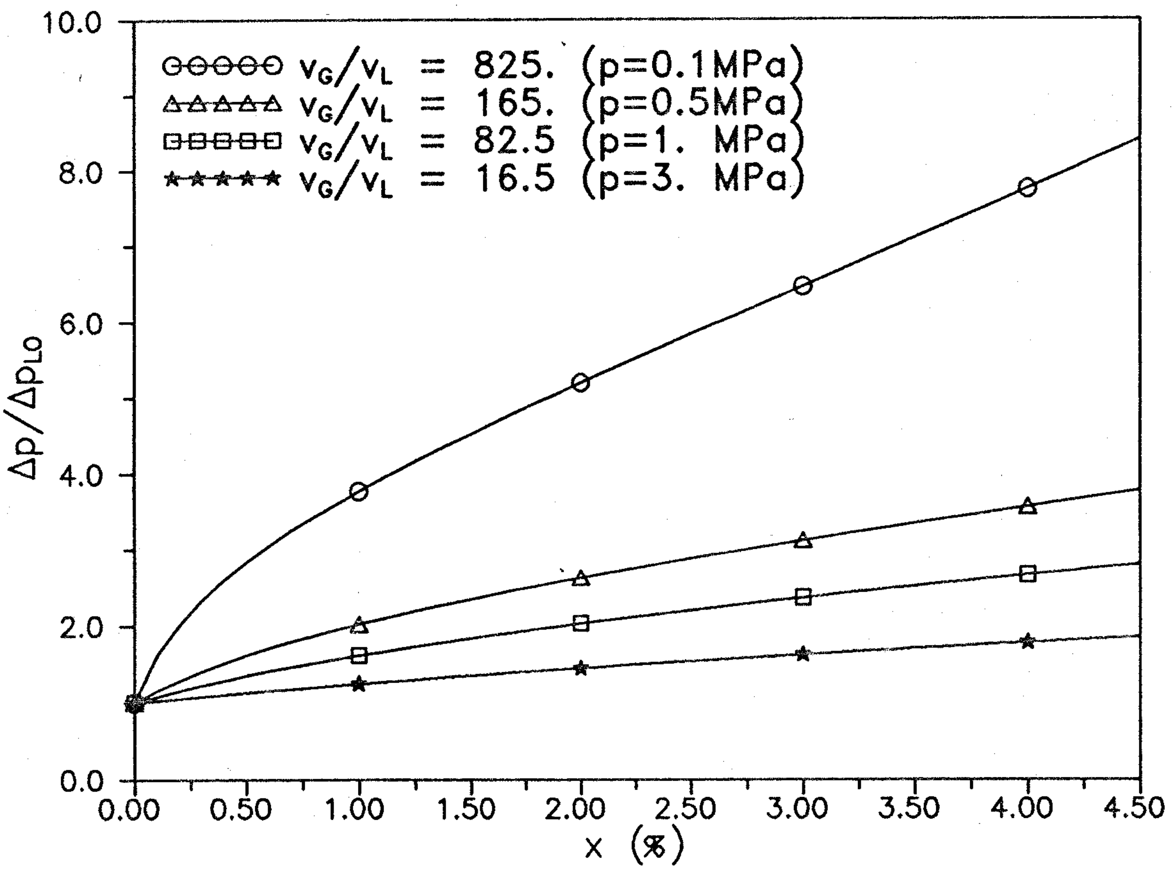


Fig. 1: Effect of pressure, theoretical prediction

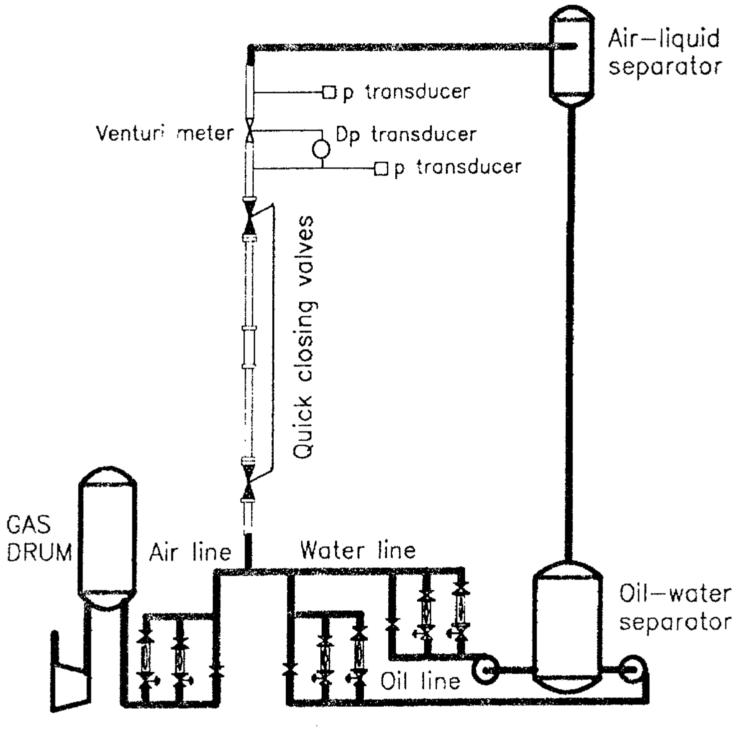
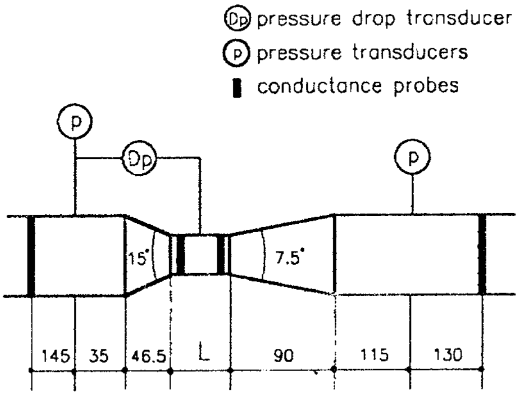


Fig.2: Scheme of the experimental loop



Available throat lengths L : 9, 29, 104

Fig.3: Scheme of the Venturi meter

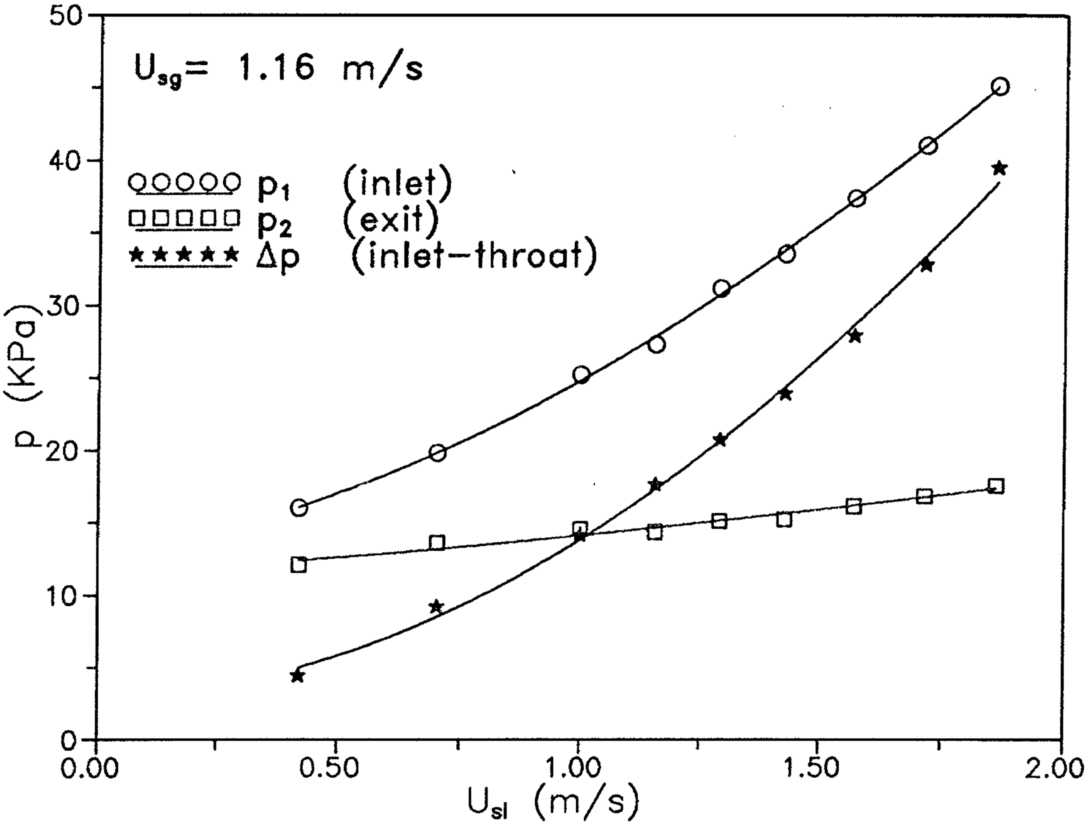


Fig. 4: Pressure in the Venturi, low velocity

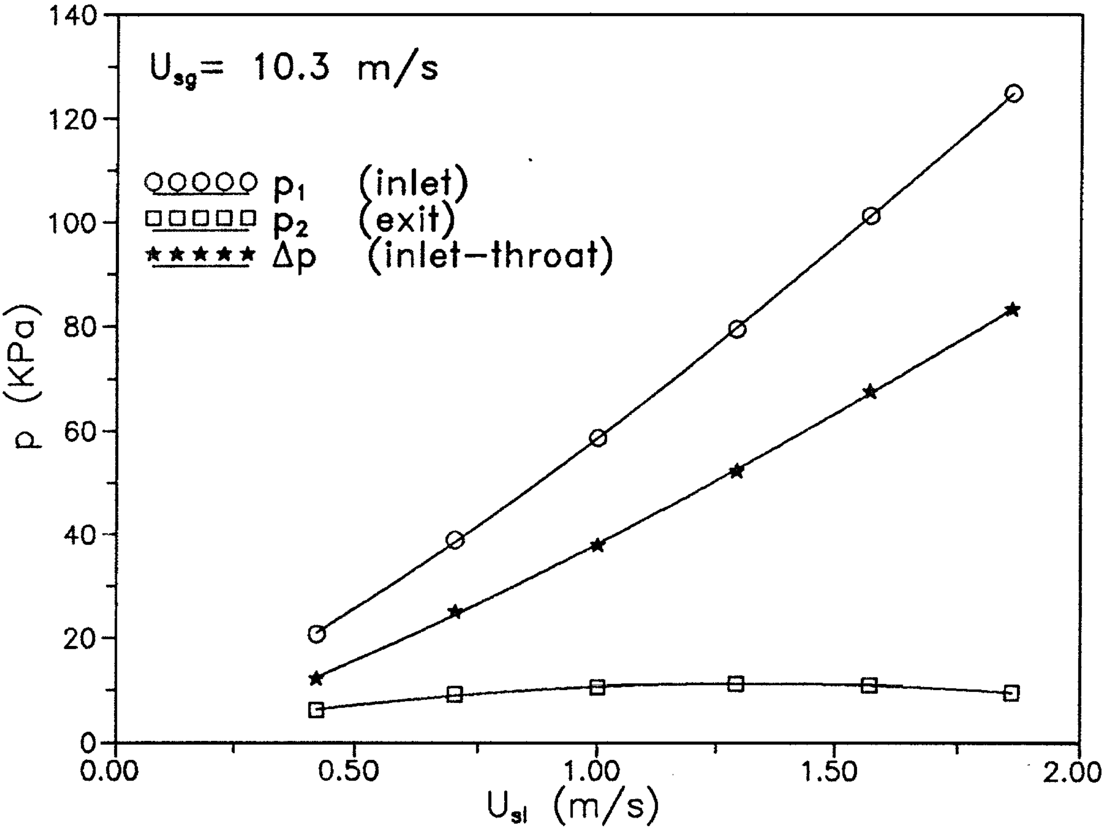


Fig. 5: Pressure in the Venturi, high velocity

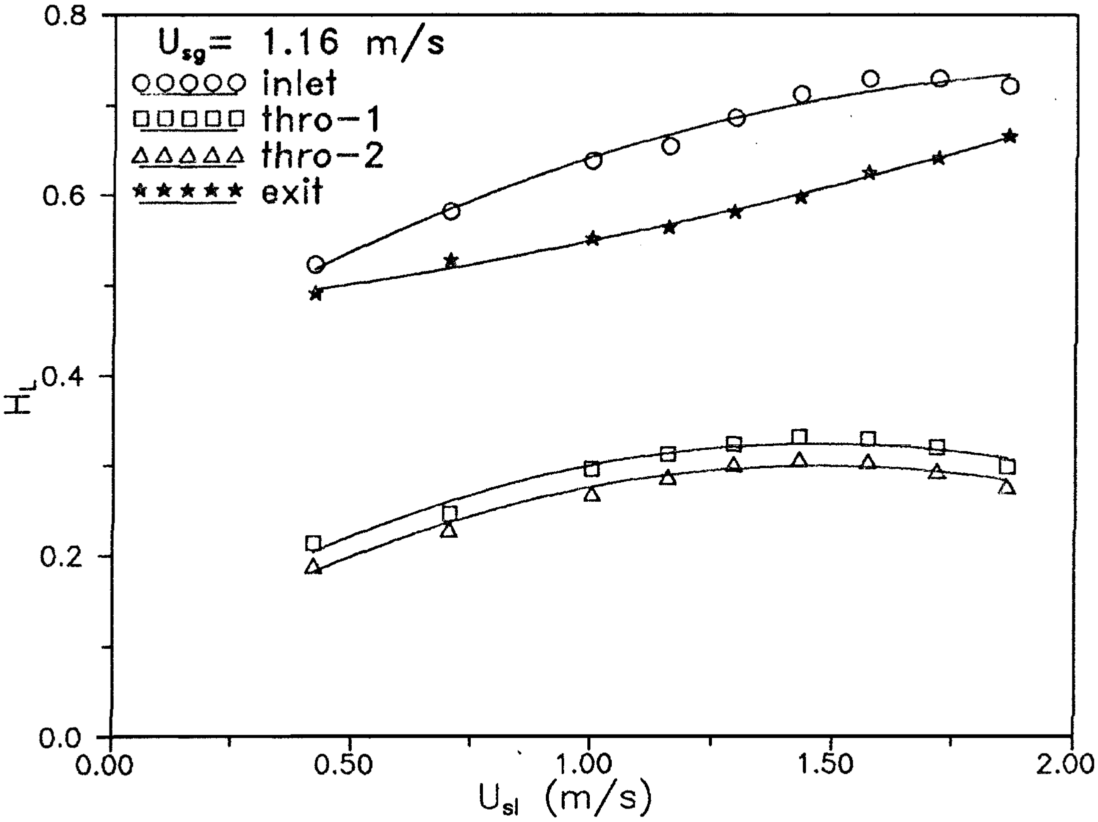


Fig. 6: Hold-up in the Venturi, low velocity

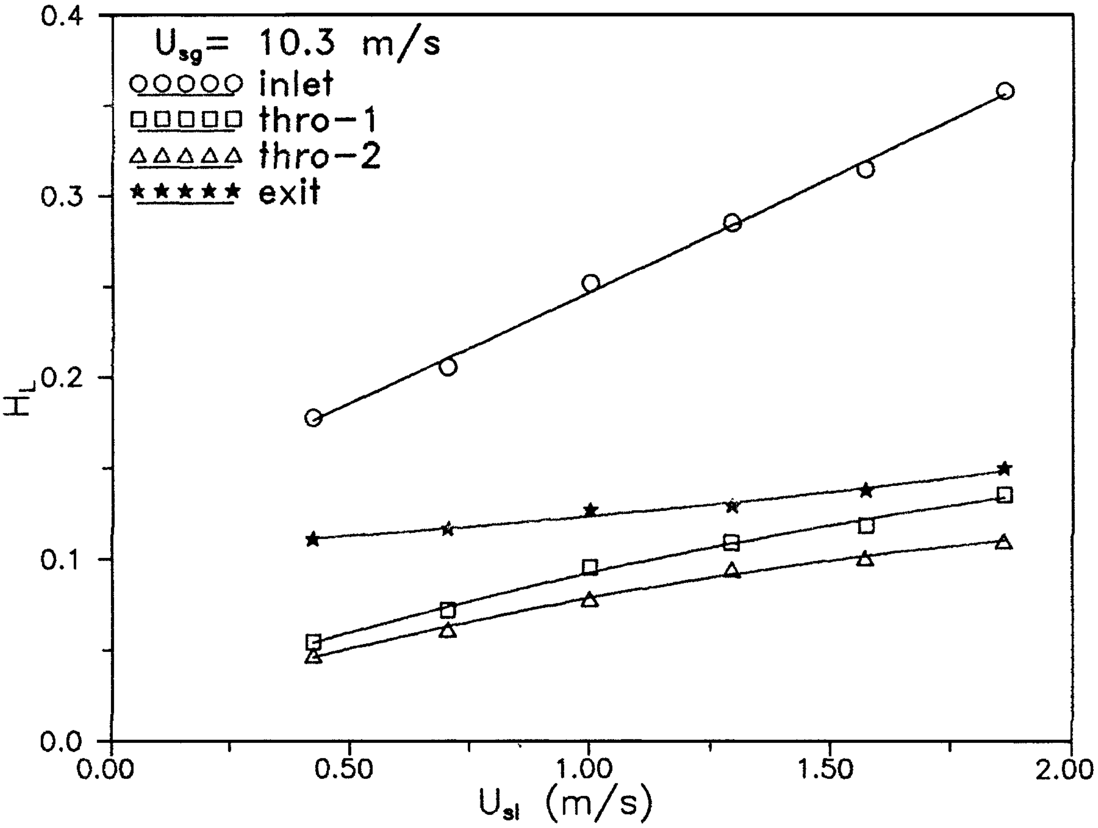


Fig. 7: Hold-up in the Venturi, high velocity

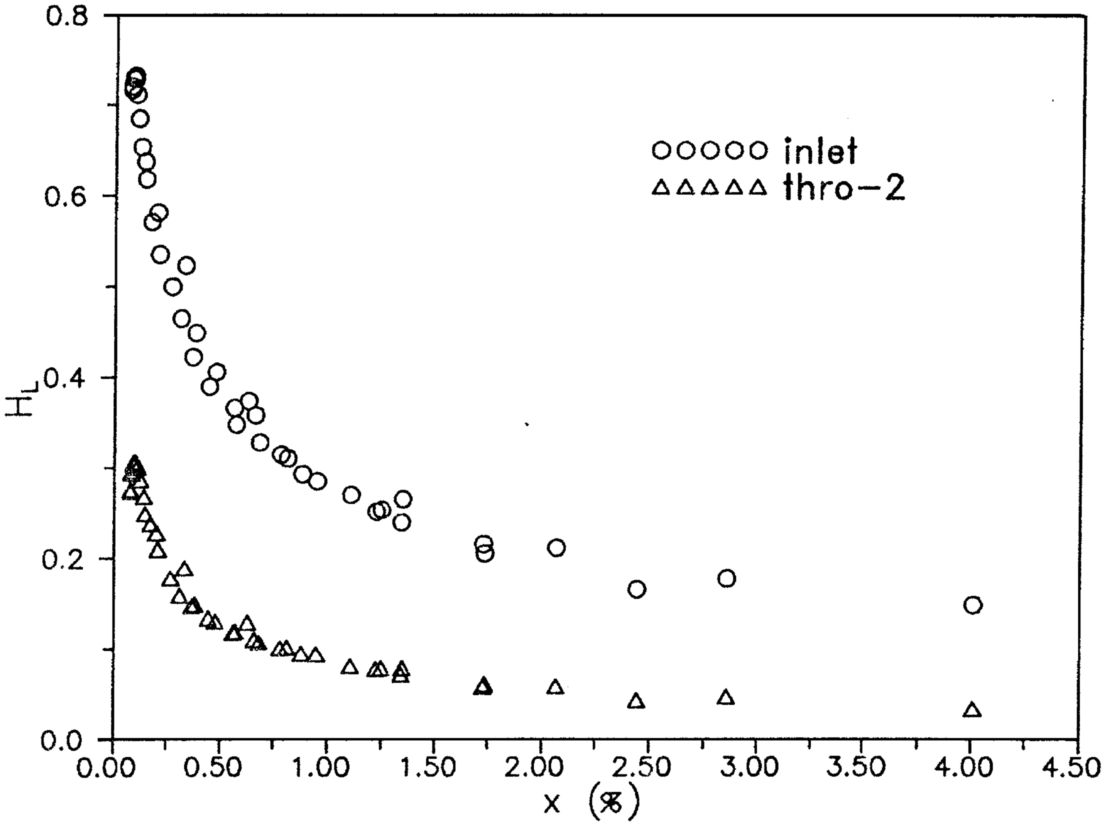


Fig. 8: Hold−up vs. quality, medium throat

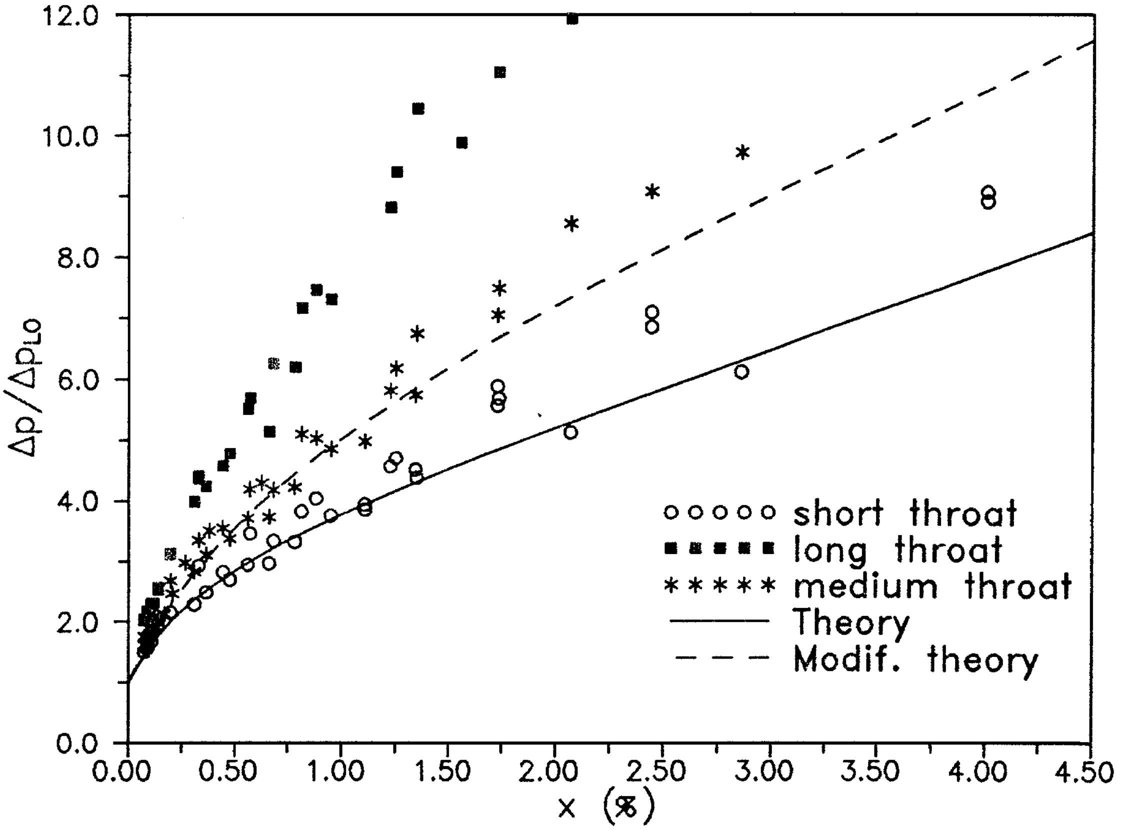


Fig. 9: Two−phase multiplier, all air−water data

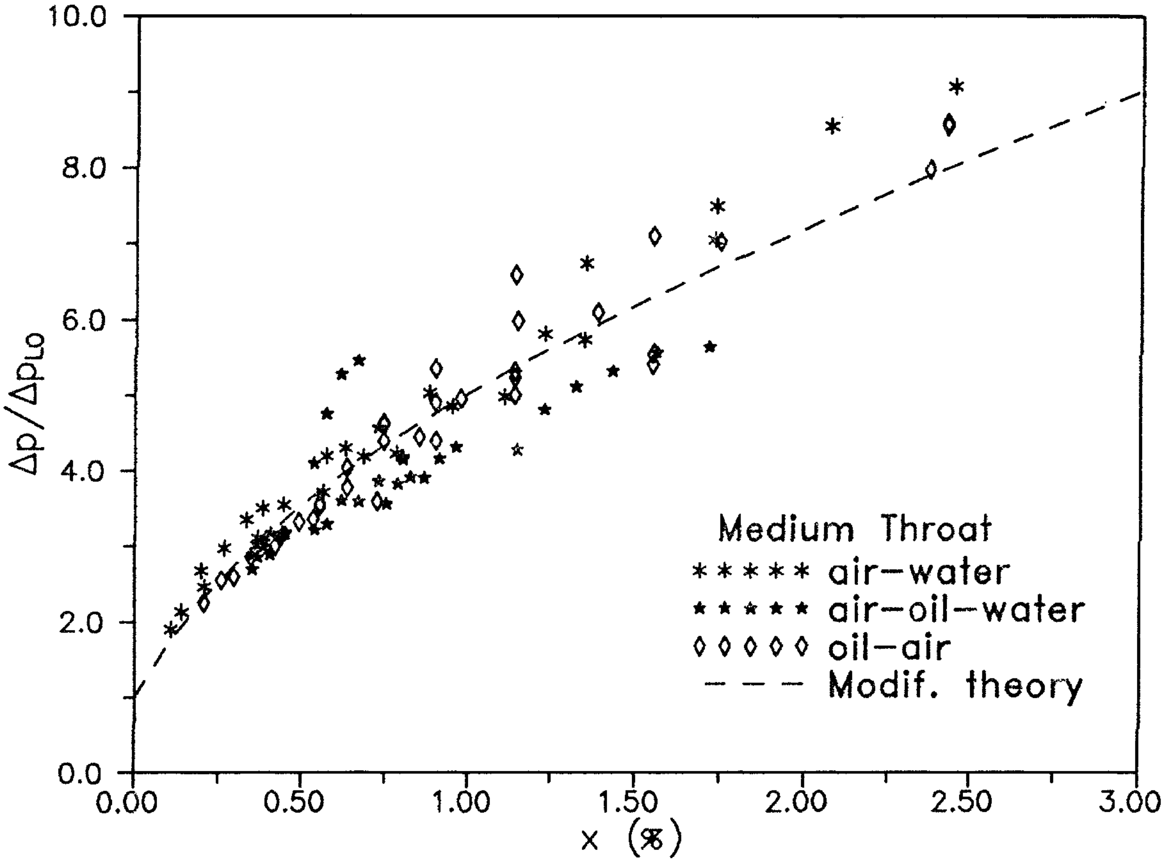


Fig. 10: Two-phase multiplier, all experimental data