Journal of Visualization, Vol. 11, No. 2 (2008)143-152

**Regular Paper**

# Local Structure of Two-Phase Flows in Horizontal Ducts

## Effects of Uniform and Suddenly Varying Duct Sections

Arosio, S.*[1] and Guilizzoni, M.*[2]

*1 Department of Energy, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy.
E-mail: sergio.arosio@polimi.it
*2 Department of Energy, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy.
E-mail: manfredo.guilizzoni@polimi.it

Received 20 July 2007
Revised 23 January 2008

***Abstract*** : When considering the flow of a two-phase mixture, the complete characterization of its behavior requires not only the evaluation of its temperature and pressure evolutions, but also the description of the distribution of the phases (the so-called "flow structure"). This is of great importance in problems concerning the analysis of the solicitations undergone by the containing ducts, both from a mechanical point of view and - even more important - when heat transfer at fixed power is involved. In the present paper the description and quantitative visualization of the structure of two-phase flows in horizontal ducts with constant diameter and with section modifications is proposed. The evolution of the flow along the duct is described in local terms by means of section fields of void fraction, flow complexity and local mean temporal length of the gaseous phase. These last are three local, time-averaged quantities which can be easily calculated starting from relatively simple experimental acquisitions of the phase density function.

***Keywords*** : Two-phase flow, Section fields, Horizontal ducts, Void fraction, Flow complexity.

# 1. Introduction

Two-phase flows (both liquid-liquid and liquid-gas) are very common in a broad range of chemical and industrial plants. It is therefore evident the importance that a deep understanding of their behavior has for a good design in all these fields. As rigorously derived constitutive equations have not been formalized up to now to complete the theoretical description of the flow, experimental investigations are fundamental, first of all to describe "what happens" in the flow, which is the first step towards a comprehension of the phenomenon. A great number of studies exists on the volume or cross-sectional averaged behavior of two-phase flows. On the contrary, the local flow structure is much less investigated in literature (except for bubbly flow), despite its importance as a beginning for developing physically-based models, as a core aspect in problems involving duct solicitations and fixed-power heat transfer (first of all to avoid burnout risks), and - more recently - as an input to CFD simulations. In a previous paper (Arosio and Guilizzoni, 2006) some quantities and techniques were presented, which proved very useful to describe in quantitative terms the local structure of gas-liquid flows. In the present paper, the proposed approach is applied to describe the evolution of air-water mixtures flowing in horizontal ducts. The circular duct with uniform diameter was chosen as a reference case. Two-phase flows in ducts with sudden section expansions and in ducts with inserted asymmetrical obstacles (simulating partially closed gate valves) were then studied.

## 2. Experimental Quantities, Set-Up and Procedures

The quantities used in the analysis and the experimental set-up and procedures were described in details in previous works (Arosio and Guilizzoni, 2006), so they will be only briefly resumed here. The flow of a two-phase mixture can be completely characterized by means of six quantities: temperature, pressure, phases velocities and two other quantities able to describe the structure of the flow. These last are the object of this study. The first one is of course the well-known local void fraction $\alpha_P$, which can be defined as the probability for a point inside the flow to be immersed in the gaseous phase (Delhaye, 1968). It can be calculated as the mean of the phase density function df(**p**,t). In discrete terms:

$$\alpha_P(\mathbf{p}) = 1/N \sum_{i=1,N} df(\mathbf{p},i)\ ;\ \ df(\mathbf{p},i) = 0 \text{ if at instant i point } \mathbf{p} \text{ is immersed in the liquid phase}$$
$$= 1 \text{ if at instant i point } \mathbf{p} \text{ is immersed in the gaseous phase}$$

if N is the number of acquired samples. The phase density function can be sampled by means of local probes, of optical or impedance type.

The second quantity should be one able to convey information about how much "complex", rich in changes between the phases, the flow structure is. Such a characteristic can be for example partially expressed by the interfacial area concentration $a_i$, which has the advantage to be useful in the interfacial area transport equation (Kocamustafaogullari and Ishii, 1995), but it can give the effective number of interfaces present in the flow only when the statistical distributions of flow structures shapes and sizes is known. It has also the great disadvantage to be easily measurable only for "stationary" flows: bubbly, annular, annular-mist, … (Kocamustafaogullari and Ishii, 1995; Hazuku et al., 2007). The measurement of $a_i$ for the other flow regimes seems to require further improvements in complex and expensive techniques such as multi-probe measurement and MRI (Kojasoy et al., 1998; Reyes et al., 1998). On the contrary our interest is to apply simple and general techniques for the determination of the number of flow structures, mainly in the field of intermittent (plug/slug) flow. We therefore preferred to focus our attention on another local, time-averaged quantity we named "local flow complexity" $cf_P$:

$cf_P(\mathbf{p})$ = (number of 0-1 and 1-0 transitions in the phase density function sampled in point **p** during the sampling interval from t to t+T) / (maximum number of potential transitions in the same phase density function signal) = $N_T / (N-1) \approx N_T / (f\ T)$

where f is the sampling frequency of the probes and T is the time length of the sampling interval. f must be high enough to capture also the interfaces of the smallest / fastest flow structures; T must be long enough to have a measured value statistically independent from the sampling interval itself.

It is possible to demonstrate that for each value of $cf_P$, $\alpha_P$ can vary only in the interval between:

$\alpha_{Pmin}$ = the nearest superior integer $[cf_P\ (N-1)/2]\ /\ N \approx cf_P / 2$
$\alpha_{Pmax}$ = 1 – the nearest superior integer $[cf_P\ (N-1)/2]\ /\ N \approx 1 - cf_P / 2$

Along with the above given definition, $cf_P$ is not able to tell if the number of interfaces seen by the probe is due to the dimensions of the flow structures or to their velocity. To discriminate between the spatial and the cinematic aspects, another quantity called "spatial flow complexity" $scf_P$ can be defined:

$$scf_P(\mathbf{p}) = cf_P(\mathbf{p})\ w_r / w_t$$

where $w_r$ is a "reference" flow velocity (which can be arbitrarily chosen; for the present study its value was fixed to 1 m/s) and, in order to adopt easy-to-measure quantities, $w_t$ is the cross-sectional averaged transport velocity of the gaseous phase $V°/(\alpha A)$. $V°$ is the volume flow rate of the gaseous phase, $\alpha$ is the cross-sectional averaged void fraction and A is the area of the duct section. A relationship exists between $a_i$ and $cf_P$. In fact, considering the above given expression of $cf_P$ and the definition of the local interfacial area concentration given by Delhaye (2001):

$$a_i(\mathbf{p}) = 1/T \sum_{j=1, N_T} [\, 1 / |\mathbf{w} \cdot \mathbf{n}|_j \,] \quad \text{it results} \quad a_i(\mathbf{p}) = f \sum_{j=1, N_T} [\, 1 / |\mathbf{w} \cdot \mathbf{n}|_j \,] / N_T \, cf_P = f\, \overline{(1 / w_n)}\, cf_P$$

where $\mathbf{w}$ is the velocity of the $i^{th}$ interface passing through point $\mathbf{p}$ and $\mathbf{n}$ is the unit vector normal to the interface at the same point, so that $w_n$ is the average of the speeds of displacement of the interfaces at point $\mathbf{p}$. Concerning $a_i$ and $scf_P$, the first is the derived local quantity of the global volumetric interfacial area $\Gamma = A_i / V$ (where $A_i$ is the interface area in the volume V). $\Gamma$ gives an indication about the complexity of the flow structure even if, as already said, it can give information on the number of structures only for flows whose statistical distributions (of velocities, shapes, sizes) are known. On the contrary, $scf_P$ is born as a local quantity giving an approximation (due to the fact that an approximate velocity of the phases is used) of the number of flow structures and it cannot by itself give information about the interfacial area. The velocity vectors distribution would be necessary to convert the local $scf_P$ into $a_i$ information or the shape and size distributions would be necessary to convert the volume-averaged spatial flow complexity $scf_V$ into $\Gamma$ information.

Finally, the "local mean temporal length" (in seconds) of the gaseous phase structures $\tau_{aP}$, can be defined as:

$$\tau_{aP}(\mathbf{p}) = \alpha_P N / \{ f [\, cf_P (N-1) / 2 + 1 \,] \}$$

As $\alpha_P$ N gives the number of samples in which the probe detected gaseous structures and $cf_P(N+1)/2$ ($\pm$ 1) is the number of flow structures seen by the probe, $\alpha_P N/[cf_P (N-1)/2 \pm 1]$ would give the local mean length of the gaseous phase structures in terms of samples; dividing it by the sampling frequency in Hertz, the corresponding quantity in seconds is obtained. If $cf_P = 0$, $\tau_{aP}$ is equal to 0 too if $\alpha_P = 0$ (no gaseous phase structures seen by the probe) while it is otherwise equal to the sampling interval length if $\alpha_P = 1$ (only gaseous phase seen by the probe).

For all the three quantities, it is possible to draw 2D and 3D graphs on the duct, thus creating surfaces able to visualize the distribution of each quantity in the different sections of interest. The synergic use of $\alpha_P$ and $cf_P$ allows a detailed description of the local time-averaged structure of a two-phase flow and of its modifications. As a derived quantity, $\tau_{aP}$ gives in effect no further information than the couple $\alpha_P$-$cf_P$, but it appears to convey visual information in a very efficient way.

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The experimental acquisitions were taken on the plant available in the Thermo-fluid dynamics Laboratory of the Department of Energy of the Politecnico of Milan, which consists in two loops: a closed loop for the liquid phase (water) and an open loop for the gaseous phase (air), which share a portion (approximately 12 m long and made of Plexiglas® to allow visual and photographic observation of the flow) where the two-phase flow sets up. At the beginning of the test section, air is added to the water current by means of three metallic mesh introducers, placed at 120° from each other. Previous analyses indicated such a solution as the best one to minimize the length of development of the flow. On the test section, a series of local optical or impedance probes are placed, to sample the phase density function in each point of interest. A sketch of the experimental set-up and of the experimental points placing on each duct section of interest is shown in Fig. 1. Further details, together with the details on data acquisition and processing can be found in (Arosio and Guilizzoni, 2006).

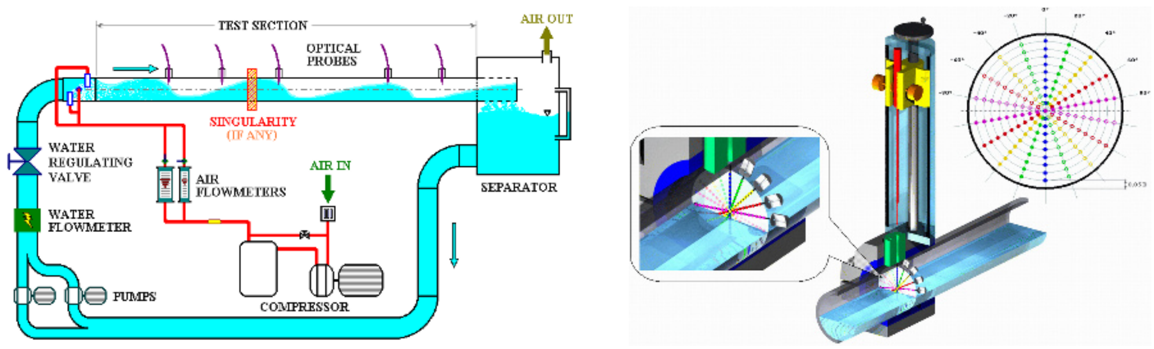


Fig. 1. Sketches of the test set-up and placing of the experimental points on each duct section of interest.

The test section can be easily modified to test different configurations. In the present paper, results referring to four different configurations of practical interest are presented:

- duct with uniform diameter, 60 mm i.d.;
- duct with sudden section expansions, from 40 to 60 mm i.d. (expansion ratio $A_{downstream}$ / $A_{upstream}$ = 2.25) and from 60 to 80 mm i.d. (expansion ratio $A_{downstream}$ / $A_{upstream}$ = 1.78);
- duct with uniform diameter (60 mm i.d.) including an asymmetrical obstacle simulating a partially closed gate valve. This obstacle (clogging: 50 %) was inserted from the top, the bottom and sideways to verify its effects in the different cases.

The singularities were positioned at more than 100 diameters from the mixing section, where previous investigations showed that the flow, in the range of the analyzed flow regimes, is almost fully "developed". In Fig. 2, two sketches of the configurations with singularities are presented. The investigated duct sections for each duct configuration are indicated in Figs. 3, 6, 7 and 8.

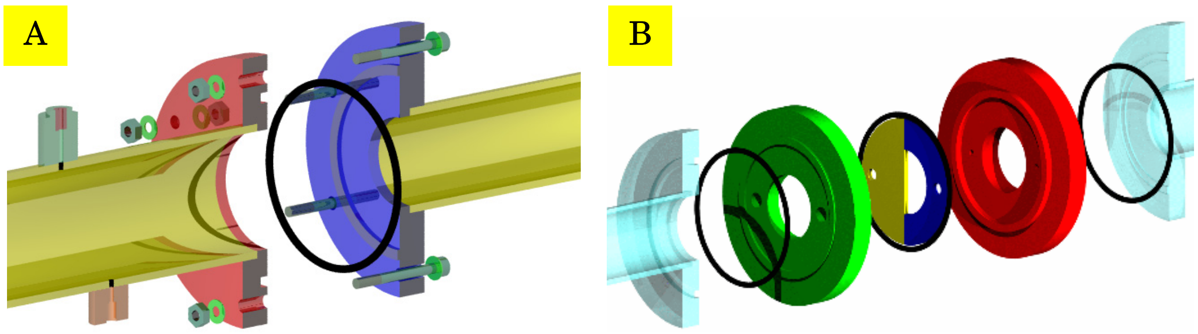


Fig. 2. Sketches of two investigated singularities (flow direction: from right to left): A) 60 to 80 mm i.d. sudden expansion, B) gate valve simulator (inserted from the right side of the duct).

## 3. Duct with Uniform Diameter

A smooth 60 mm i.d. duct was chosen as the reference case for the comparison with ducts including section singularities. For horizontal, circular ducts with uniform diameter many results are available in literature concerning the flow description and void fraction measurement and correlation with the flow governing parameters (in particular mass flow rates and gas volume flow ratio). Data were acquired to have an accurate term of comparison, evaluated on the same experimental set-up and by means of the same experimental techniques. Among the most important results, such a campaign gave information about the flow development after the mixing of the phases. Figure 3 presents the local void fraction section fields and some point-to-point differences between them. Five sections along the duct axial coordinate were investigated, for 20 flow regimes resulting from the combination of 5 liquid mass flow rates Gl and 4 gas volume flow ratio xv. All the investigated flow regimes are in the intermittent flow region. The regularity of the flow structure evolution when moving along each "coordinate" z/D (dimensionless axial coordinate), Gl, xv is evident. Point-to-point differences between the fields easily allow to quantify each modification. As a particularly significant example, point-to-point differences (represented in the lower part of the figure) between the field for each section and the most far from the mixing zone ("developed" flow) evidence the long evolution of the two-phase flow after its "birth" at the beginning of the test section.

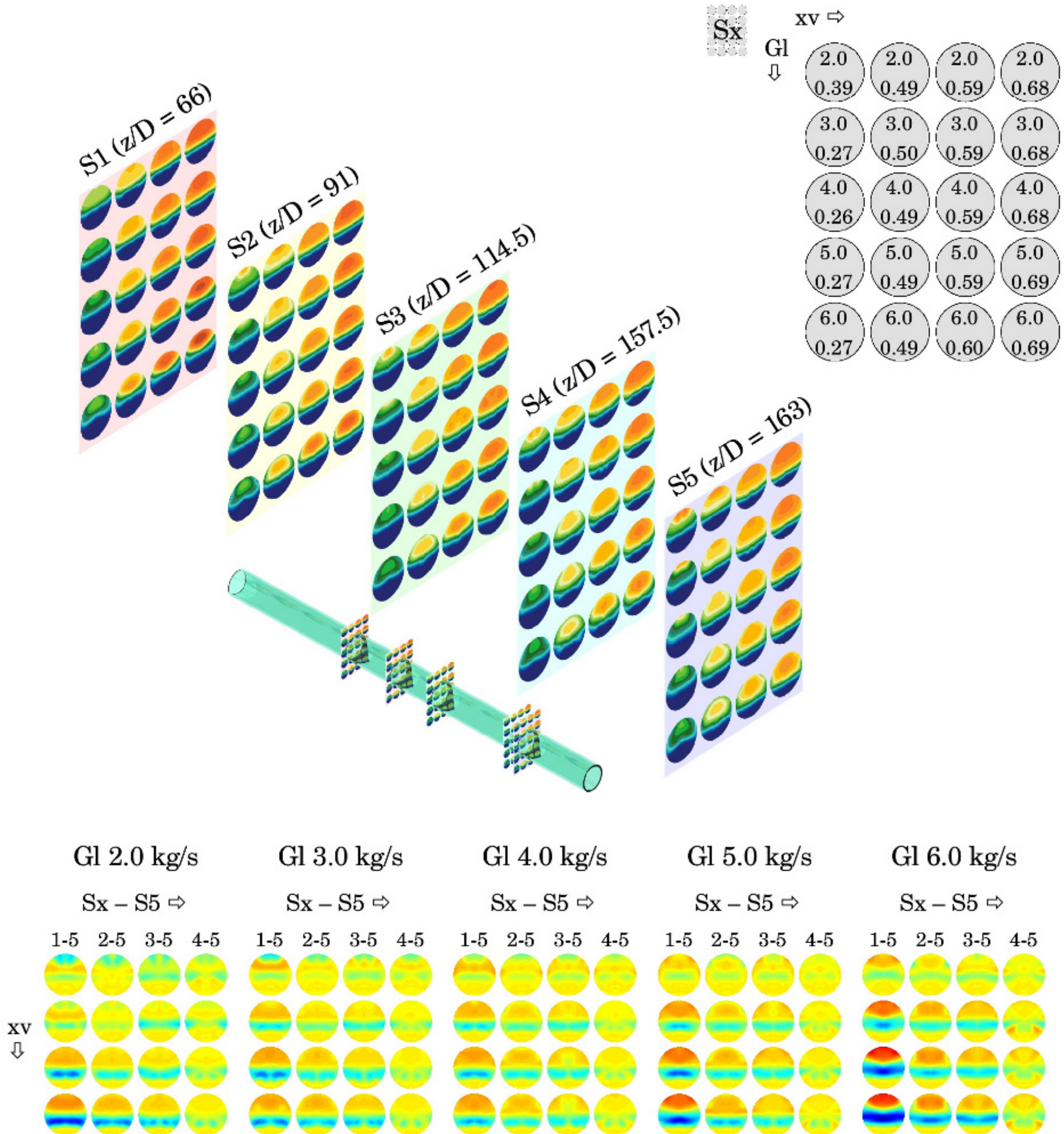


Fig. 3. $\alpha_P$ section fields for the 60 mm i.d. duct: 5 axial positions (z = 3955, 5468, 6855, 9455, 9785 mm; z/D = 66, 91, 114.5, 157.5, 163) and 20 flow regimes (Gl = 2, 3, 4, 5, 6 kg/s; xv from 0.26 to 0.69). In the upper part of the figure, $\alpha_P$ section fields are presented (with their legend in term of Gl and xv). The color scale is uniformly spaced from 0 (deep blue) to 1 (red) (see Fig. 6 for further details). In the lower part of the figure, point-to-point differences between the section fields are presented. The color scale is uniformly spaced from -0.5 (deep blue) to 0.3 (red).

Such an evolution is always smooth, but in particular for the lower gas flow rates it seems not to be monotone: oscillations occur, in the central part of the duct, near the liquid carpet surface between two consecutive plugs/slugs (see for example the 2nd row in the Gl 2.0 kg/s, Gl 3.0 kg/s and Gl 4.0 kg/s section fields of point-to-point differences). Analogous oscillations can be observed in flows past a sudden expansions (see the following section and Arosio and Guilizzoni, 2004) and they seem therefore to be a characteristic behavior in the response to disturbances induced in horizontal two-phase flows (the mixing section in the case of uniform diameter ducts).

## 4. Duct with a Sudden Section Expansion

When a two-phase flow encounters a sudden expansion in the duct, different behaviors are possible. For very low phase velocities (resulting in pure plug flow upstream the singularity), the liquid phase splashes in the larger downstream duct and then recreates plugs. This behavior is qualitatively depicted in Fig. 4 which shows some photographs of such flows together with the results of a simulation created using the Lattice Boltzmann simulator included in the Blender® 3D modeling software. Such a simulator is based on a single- phase, free-surface LB model developed by N. Thürey (2007).

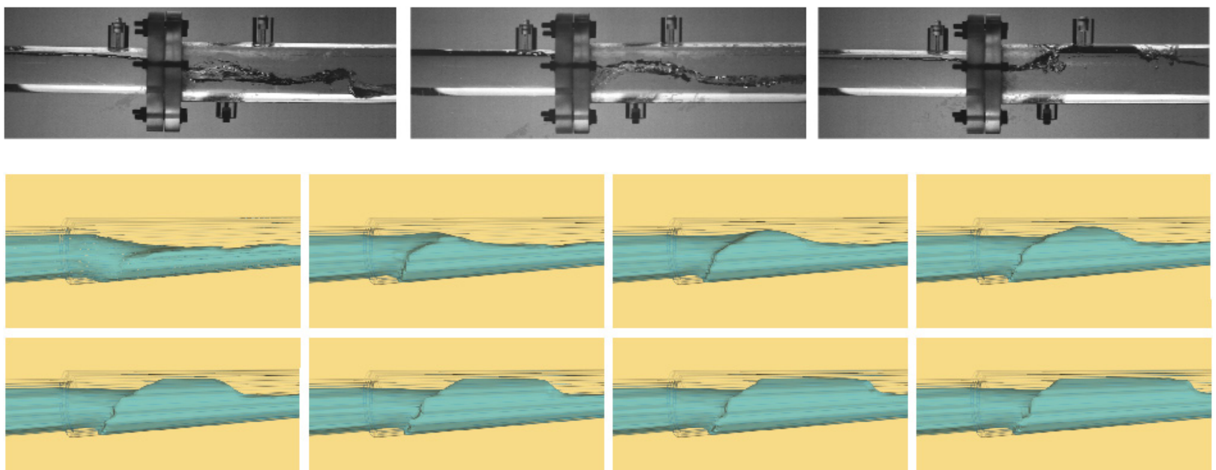

Fig. 4. Reformation of a plug just after a sudden section expansion, for very low phases velocities. Photographs (exposure time 1/2000 s) and sequence obtained using the Lattice Boltzmann simulator included in the Blender® 3D modeling software.

Default data for the density and viscosity of water and no-slip boundary conditions at the duct wall were used. Water is inserted from the left end of the duct with an initial axial velocity of 0.75 m/s. The aim was not to obtain quantitative agreement with experimental data, but only to create a qualitative image of the time evolution of the flow at the singularity when the superficial velocities of the phases and consequently the phase interactions are very low.

When the velocities of the phases increase, the behavior of the flow downstream the singularity changes firstly to the "wings" and then (for higher velocities) to the "jet" behaviors. They are shown in Fig. 5. For further details on such flow configurations see (Arosio and Guilizzoni, 2006). Figure 6 shows section distribution of local void fraction and spatial flow complexity just after the 60 to 80 mm i.d. sudden expansion (z/D = 1.8), for different flow regimes.

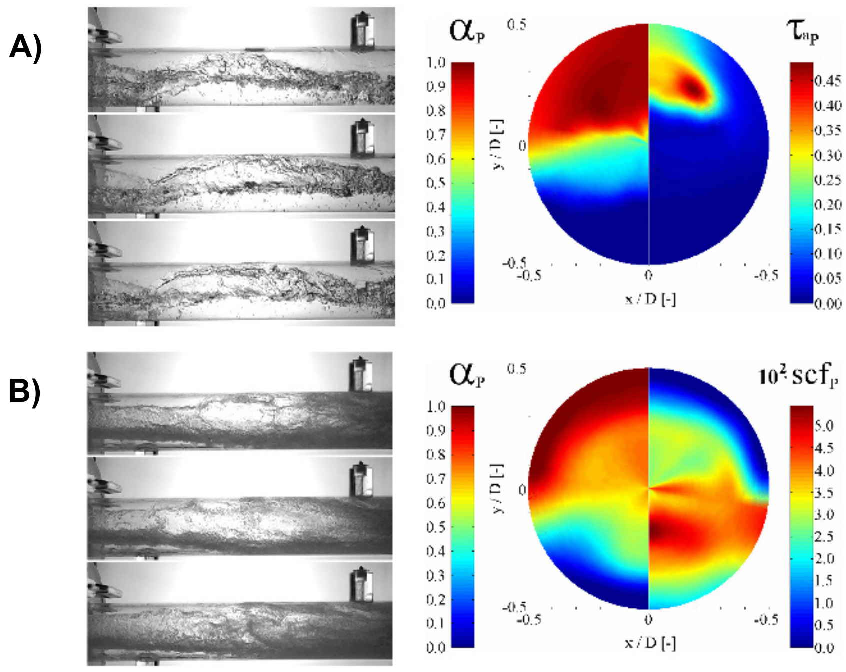


Fig. 5. Flow configurations 1.8 diameters after a sudden expansion in the duct section (60 i.d. to 80 mm i.d., 2827 $mm^2$ to 5027 $mm^2$ ): section distributions of local quantities compared with photographic shots of the flow (exposure time 1/2000 s). A) "wings" behavior, liquid mass flow rate Gl = 4.5 kg/s and gas volumic fraction xv = 0.26; B) "jet" behavior, liquid mass flow rate Gl = 7.0 kg/s and gas volumic fraction xv = 0.48.

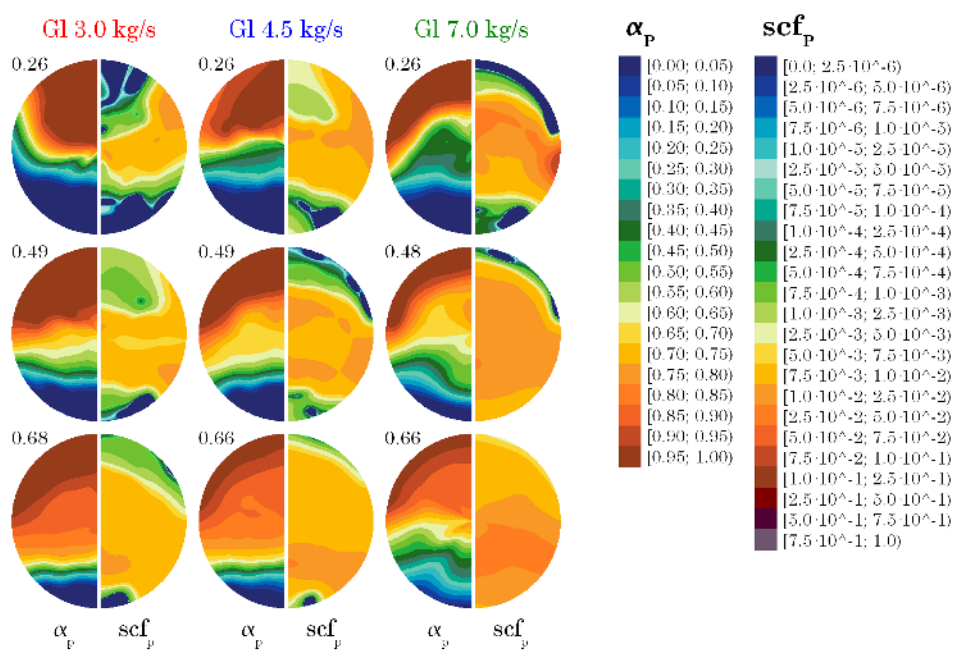


Fig. 6. Section distributions of local void fraction (left half of the field) and local spatial flow complexity (right half of the field) 1.8 D downstream the 60 to 80 mm i.d. sudden expansion, for different flow regimes: Gl 3.0, 4.5, 7.0 kg/s; xv from 0.26 to 0.68.

The flow regimes having Gl 3.0 – xv 0.26 and Gl 4.5 – xv 0.26 are in the plug flow region, the others are in the plug-to-slug transition field or pure slug flows. Gl 7.0 – xv 0.66 give a very frothy flow. In these cases too, the regularities in the flow evolution passing from one couple of mass flow rates to the following are evident. As it can be easily observed in Fig. 6, the combined use of $\alpha_P$ and $scf_P$ clearly evidences the "wings" or "jet" behaviors.

Concerning the flow evolution downstream the singularity to the end of the test section, Fig. 7 shows a mesh of $\alpha_P$ section fields created joining the ones from the 40 to 60 mm i.d. and the ones from the 60 to 80 mm i.d experimental campaigns. Such a figure was created to evidence how the evolutions of the two flows are similar even if the geometry and phase velocities are different. At the same Gl and xv, the section distributions of the local quantities (for example $\alpha_P$ as shown in the figure) can be put together in a single row using the duct dimensionless axial coordinate z/D as an independent quantity. The resulting sequence of images is coherent to the point that it can seem to be referring to the same flow. Upstream the singularity, the flow can be considered undisturbed at least until very near the same. Then in all cases the flow is completely destroyed in its structure by the singularity (with a "jet" or "wings" structure depending on Gl and xv) and then progressively re-develops. Limiting the analysis to the 60 to 80 mm i.d. fields, it would seem that at z/D = 50 the flow is well realigned, but when considering also the additional section distributions acquired in the 40 to 60 mm i.d campaign (which are at higher z/D) it appears that the flow continues to evolve, returning away from a "developed" condition. On the contrary of what was expected (and seemed confirmed by the SE 60/80 campaign, which had a shorter downstream dimensionless length), the flow does not align asymptotically. Further investigations suggested that this behavior could not be due to experimental errors or to the perturbations at the outlet from the test section. As already noticed for the uniform diameter duct after the mixing zone, the perturbation induced by the singularity seems to be reabsorbed by the flow only after some oscillations. Point-to-point differences between the fields and cross-sectional averaged analysis along the z/D coordinate (Arosio and Guilizzoni, 2004) evidence this behavior even more clearly. At present it is not possible to quantify the number, amplitude and period of these oscillations: extensions of the experimental campaign is required before being able to describe the phenomenon, in particular campaigns on much longer test sections are mandatory. Nevertheless, this indication seems to be clear and reliable, and in the end it is not so surprising, as the two-phase flow system is surely non-linear and probably chaotic (Sæther et al., 1990; Franca et al., 1991).

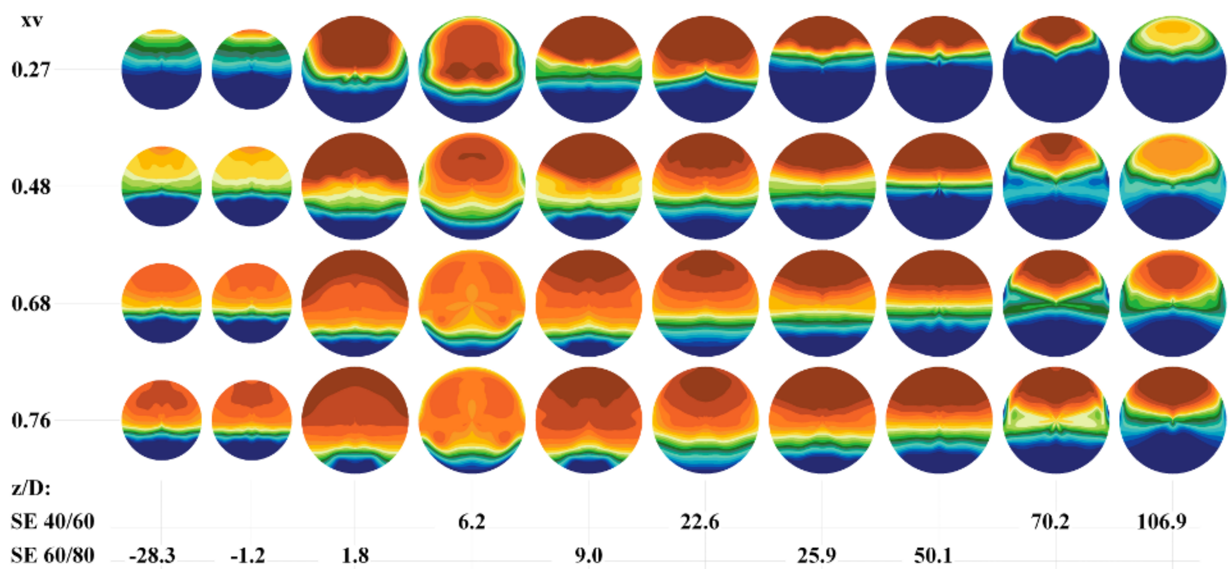


Fig. 7. Mesh of section distributions of local void fraction downstream the 40 to 60 mm i.d. and 60 to 80 mm i.d sudden section expansions, as a function of xv and z/D. Gl = 3.0 kg/s for all flow regimes. See Fig. 6 for the color scale legend.

## 5. Duct with a "Gate Valve"

Gate valves were simulated partially occluding the duct section with a half-moon shaped obstacle (made of Plexiglas® too). Such an obstacle was inserted occluding firstly the bottom half section of the duct, then the top half and finally sideways to evaluate its different effects on the flow. The experimental campaign are still under completion (including the analysis of different clogging ratios) and only a few data are available up to now. At present, the most interesting case seems to be the sideway insertion, as it destroys the flow axisymmetry. Figure 8 presents the $\alpha_P$, $cf_P$ and of $\tau_{aP}$ section distributions respectively 2.5 D and 11 D downstream such a singularity.

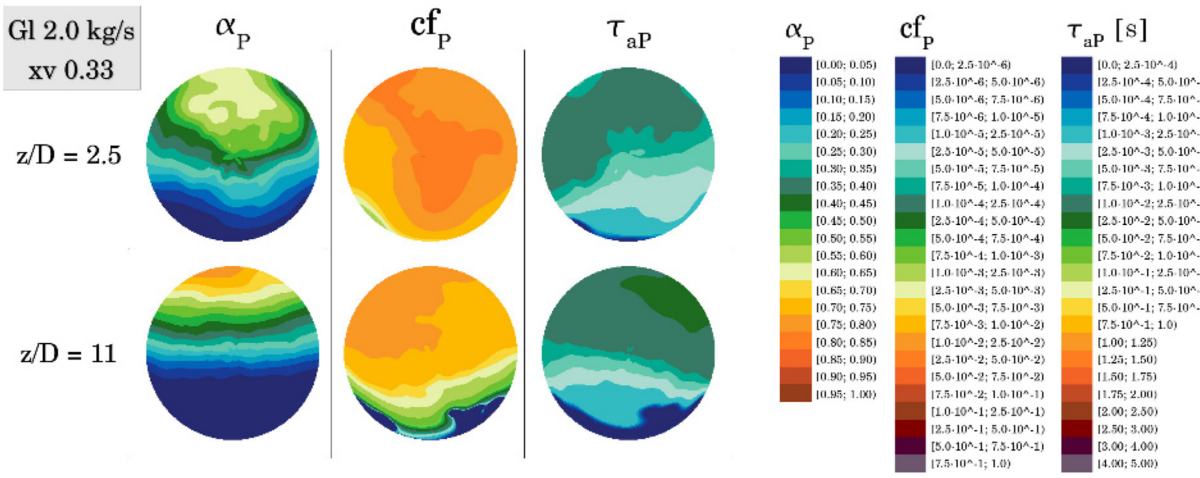


Fig. 8. Section distributions of $\alpha_P$, $cf_P$ and $\tau_{aP}$ 2.5 D and 11 D downstream a gate valve simulator inserted sideways (occluding the right half of the duct).

With reference to the flow direction, the singularity occludes the right part of the duct. It is evident the disturbance it exerts on the flow, even if for all flow regimes it is much lower than the impact of the sudden expansions. A characteristic effect is the swirl given to the flow (see for example the first $cf_P$ field in Fig. 8, where the circulation is very evident), which gradually disappears when proceeding downstream. Even if no upstream section fields are shown in the figure, it can also be indirectly noticed the mixing effect of the singularity (on the contrary of sudden expansions which tend to separate the phases – see Fig. 7, where single-phase regions are clearly visible in the fields downstream the singularity): comparing the 2.5 D and the 11 D section fields, it is evident how in the first ones $\alpha_P$ is lower, $cf_P$ is higher and both of them are more uniform. Then the flow re-develops with a partial phase separation and $\alpha_P$ grows, $cf_P$ decreases and their variances over the section become higher.

## 6. Conclusion

Some techniques to analyze the local structure of liquid-gas flows by means of simple experimental quantities were applied to the description of the evolutions of such flows in ducts both with uniform diameter and with sudden section modifications (sudden expansions, gate valves).

The quantities used are the well-known local void fraction together with the local flow complexity and mean temporal length of the gas structures which are able to describe how "mixed" is the flow in the points of interest. The presented analysis confirmed that the synergic use of the cited quantities allows a very detailed description of the local time-averaged structure of the flow, giving very interesting results about the flow in presence of the cited singularities.

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## Author Profile

Sergio Arosio: He is a full professor of Thermodynamics - Heat and Mass Transfer at Politecnico di Milano (Italy). He graduated in Mechanical Engineering at Politecnico di Milano in 1971. Research area: he has been carrying out researches in the fluid dynamics and energy field with a special attention to: heat exchange in condensation / evaporation in microfin tubes, two-phase flow fluid dynamics in adiabatic contour and non-conventional energy conversion systems. Scientific publications: he is the author of over 100 research papers on the above mentioned fields.

Manfredo Guilizzoni: He received his M.Sc. (Eng.) degree in Industrial Engineering in 1999 from Politecnico di Milano and his Ph.D. in Energy Engineering in 2002 from the same university. He currently is an assistant professor at Politecnico di Milano. His research interests are multiphase fluid dynamics, drop-surface interactions, technical and economic analysis of thermodynamic cycles and computer graphics.