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FLUID-VELOCITY MEASUREMENTS AND FLOW-PATTERN IDENTIFICATION BY NOISE-ANALYSIS OF LIGHT-BEAM SIGNALS

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Abstract—For fluid-velocity measurements of the two-phase flow in reactor safety experiments, a new method has been developed. This method is based on cross-correlating the signals of two light-beam detectors, which cross the diameter of the test-section (no flow restriction).

Furthermore, the signals of the two detectors are also used to give a rough estimate of the flow-pattern of the investigated two-phase flow. This flow-pattern identification is performed by comparing several characteristic functions (like the spectra and probability-functions of the signals) of a known flow-pattern recorded in an air–water test-facility, with equivalent functions of the investigated two-phase flow. This flow-pattern identification is performed by comparing several characteristic functions (like the spectra and probability-functions of the signals) of a known flow-pattern recorded in an air–water test-facility, with equivalent functions of the investigated two-phase flow. An important requirement for these comparisons is the appropriate normalization of the abscissa of the characteristic-functions, which is performed with the time-averaged fluid velocity.

As an example, the results of a blow-down experiment are shown. Velocities up to 300 m/s could be measured within a pressure range up to 50 bars and temperatures up to 280°C. Flow-regime changes were observed in three different parts of the blow-down.

1. DESCRIPTION OF THE METHOD

An important requirement for suitable measuring equipment (especially for saturated two-phase flows) is that of minimising the flow-restriction of the spool-piece because of the influence of the pressure-losses on the investigated two-phase flow. The usual spool-pieces, like turbine-flowmeter or drag-body, fulfil this requirement only in a limited manner because they usually change the properties of the flow and influence the results of the experiment. The method proposed in this paper is a non-intrusive optical method (light-beam). It uses the fluid-inherent patterns (in our case the fluctuations of the transparency of the two-phase flow due to the arrangement of the steam (gas)–liquid interfaces along the beam) as a tracer and determines the transit-time of this "tracer" between two detectors by means of cross-correlation technique.

1.1 *Brief description of the cross-correlation technique*

The cross-correlation technique is a statistical method to determine the time-delay between two noise signals. To explain the method, as an example, in figure 1 the time-dependent fluctuations of the amplitudes of the high-pass filtered (1 Hz) signals of two light-beam detectors have been plotted. The measurement was performed in a bubbly-flow. The upper signal is that of the upstream detector; the lower, that of the downstream one.

As can easily be seen, the signal-pattern remains relatively unchanged between the two detectors but a "time-shift" τ_p can be determined, in this special case, even directly from the signals.

Usually, the situation is more complicated and it is not so easy to determine the transit-time "by eye" from the two signal-traces. In these cases, the cross-correlation function R_{xy} can be used which describes the "similarity" of two signals $x(t)$ and $y(t)$ as a function of a time-delay τ between them; expressed mathematically,

$$R_{xy}(\tau) = \lim_{T \to \infty} \left[\frac{1}{T} \int_{-T/2}^{T/2} x(t) * y(t-\tau) * \mathrm{d}t \right]. \qquad [1]$$

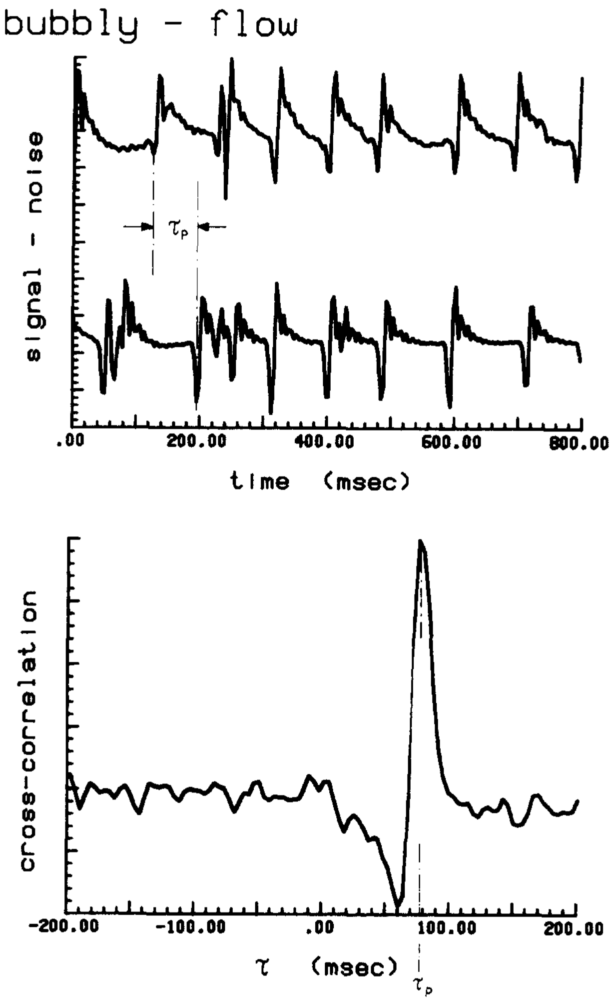

Figure 1. Explanation of cross-correlation technique (bubbly-flow). (a) Trace of the two detector signals; (b) corresponding cross-correlation function.

Obviously, this "similarity" between the two signal-patterns (R_{xy}) has its maximum at the delay-time τ_p (figure 1b). Therefore, the transit-time of the bubbles which have induced these signals to the detectors is related to the maximum of the cross-correlation function, whereas the value of this maximum itself is unimportant.

In principle, the measuring-time for this method should be infinite [1] and within this time, the fluid-velocity is assumed to be stationary. For practical applications in two-phase-flow measurements, depending on the expected fluid-velocities, a few seconds are usually sufficient to get a well-pronounced peak in the cross-correlation function.

For the application of the cross-correlation technique under non-stationary conditions (transient-analysis), one assumes that within a measuring interval Δt, the flow remains quasi-stationary, i.e. its velocity undergoes only small changes (Lübbesmeyer & Crowe 1980).

The determination of the delay-time between the two signals may also be performed in the frequency-domain. The equivalent function is then the cross-power spectral density function (CPSD). The transit-time τ_p in this case is given by the linear slope of the phase of this complex function. To obtain an estimate of how the signal-pattern changes between the two detectors, the coherence function is used. If the signals are unchanged (frozen pattern), this function is equal to one for all frequencies; totally uncorrelated signals give zero for all frequencies. For more detail, the reader is referenced to text-books, e.g. Bendat & Piersol (1971) or Otnes & Enochson (1972).

1.2 *The light-beam detector*

For application of noise analysis techniques, one of the main problems is the choice of suitable detectors. They should have the following two important characteristics:

—Sensitivity for one of the fluid-inherent natural noise sources like temperature, conductivity, density or transparency.

—The corner-frequency of the transfer-function of the detectors should be as high as possible. Furthermore, the detectors should

—Introduce minimal flow-restriction.

—Be mechanically and chemically stable at higher pressures and temperatures.

—Be of low cost.

There are some detector-types used up to now which more or less fulfil these requirements. For the detection of natural fluid-inherent temperature-fluctuations, microthermocouples are used. A disadvantage of the thermocouple is the relatively low corner frequency of the transfer-function (Wesser *et al.* 1978), which is of the order of about 10 Hz (maximum). However, thermocouples are local probes (i.e. they measure only at one point of the flow-area), and this could have some disadvantages when measuring averaged fluid velocities in pipes. With respect to the corner frequency, better results can be expected with impedance-probes (detection of conductivity-fluctuations, normally also a local probe) or X-ray (γ-ray) densitometers. The disadvantages, especially of the latter detectors, are their high building costs due to cooling as well as radiation shielding requirements.

The aforementioned disadvantages can be avoided by using a light-beam detector, which was first proposed by Riebold *et al.* (1970) for bubble-velocity measurements in steel tubes with high pressure steam–water flow, but has also been used by other investigators in different flow-regimes, as mentioned by Hewitt (1978).

The measuring method is based on the modulation of two downstream mounted light beams, which cross the diameter of the flow-tube. Therefore, the light-beam measuring section consists of two "window pairs" (each pair with one window for the light-beam transmitter and one for the light-beam receiver) in a steel tube (figure 2). In our case, these windows are Light-Conducting Rods (dia. 6 mm) which are mounted on steel adaptors with a special high-temperature resistant glue. Instead of a very expensive laser and beam-splitting system as proposed by Riebold *et al.* (1970), the EIR light beam system uses two low voltage light-bulbs.

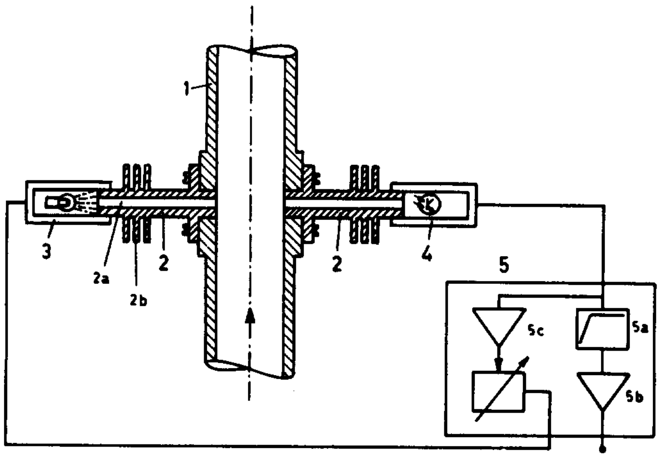

Figure 2. Sketch of one of the two needed light-beam detectors. 1, Stainless steel test-section; 2, window with; 2a, light-conducting rod; 2b, adaptor with "heat-trap"; 3, low-voltage bulb (3.7 V, 0.3 A); 4, photo-transistor; 5, amplifier with; 5a, high-pass (1 Hz); 5b, signal-amplifier (gain 100); 5c, bulb-current regulating amplifier.

The signals from the receivers (phototransistor) are used twice. The d.c.-component controls the light beam intensity. This feature allows the use of the system in experiments where the flow-regime of the investigated fluid may change with time (which also may change the transparency of the fluid). The a.c.-component on the other hand, is recorded on a magnetic tape after high-passing it with a 1-Hz filter and amplifying it with a gain of 100 (maximum); it is then later analyzed off-line. Because of the relatively low gain, the signal-to-noise ratio is high enough to be insensitive to the normal 50-Hz (and higher harmonics) background, which may sometimes disturb the evaluation by noise-techniques.

1.3 *Uncertainties of the measuring technique*

When applying cross-correlation techniques to measurements in two-phase flows some problems occur and these are discussed briefly.

(1) *The physical meaning of the measured velocity.* The main problem of interpreting results of cross-correlation measurements is related to this question because, depending on the type of detector (local detector, e.g. thermocouple or beam-detector, e.g. X-ray or light beam), the result is usually only ONE somehow space- and time-averaged "perturbation velocity".

Most of the authors who have published velocity measurements by employing cross-correlation technique have assumed that the measured perturbation velocity can be associated with the flow-area averaged gas- (steam-) velocity (e.g. neutron-noise in BWRs (Kosály 1980)) or in test-sections (Miyazaki *et al.* 1973)). Recent publications now indicate that this assumption is doubtful, but a definite answer to this question is still missing (Hsu 1982). Leavell & Shahrokhi (1979) found that the measured perturbation-velocity is between the steam and the liquid-velocity. For dispersed flows, Lübbesmeyer (1983) found that the perturbation velocity can be associated with the area-averaged volumetric flux j (this finding would also fit the above mentioned results of Leavell and Shahrokhi). To test this assumption, measurements were performed at the air–water test-loop FREDLI (to be described in due course), where the measured perturbation-velocity was compared with the volumetric flux j and the individual phase-velocities which were determined by measuring the inlet flow-rates of air and water by two turbine flow-meters, and the void-fraction in the test-section by the Quick-Closing Valve technique (Hewitt 1982). The results of these measurements in different flow-regimes are shown in figure 3. The points indicate the volumetric flux (measured outside by turbine-flowmeters), as a function of the perturbation-velocity in five different flow-regimes (different symbols), whereas the thick solid line is the "zero-percent error line". The points are fitted to a straight line and this fit is shown by the thin solid-line. Similar figures are plotted for the gas- and the liquid-velocities. The linear fits of these plots are shown in figure 3 as —·— for the gas and as ---- for the liquid-velocity.

The results show that only for bubbly-flows is the assumption, that what is measured is the volumetric flux, a good approximation. It should be noted that, also in this flow-regime, the corresponding gas- and liquid-velocities are higher and lower respectively than the measured "perturbation-velocity". For all other flows, the assumption underestimates the real area-average velocities, which is reasonable especially for fully developed annular-flows because, for example, most of the air passes the detectors of the spool-piece without inducing any signal.

(2) *Influence of a radial profile.* For detectors which register the fluctuations of an information carrier crossing the diameter of the flow-area, the radial velocity and void-concentration profile may play an important role on the result of the measurement. To investigate this effect, some numerical simulations were performed recently by Lübbesmeyer (1982) and proved experimentally by Analytis & Lübbesmeyer (1983). Unfortunately, the results showed that one does not measure any mathematically defined average velocity of the profile. Usually, the measured velocity is a velocity near the minimum or maximum velocity of the radial profile and therefore, is lower or higher than the area-average value.

(3) *Measuring-error due to the resolution of the spool-piece.* Apart from the statistical error which mainly influences the scattering of the different noise-analytic functions, the main measuring error is due to the resolution of the spool-piece. It should be noticed that, because the cross-correlation function has to be determined via a digital computer, any "cross-correlation spool-piece" is a digital one, i.e. the results are only given as discrete points whereas the velocities are registered either as the next higher or the next lower velocity point corresponding to the next lower or higher value for the peak of the cross-correlation function on the DISCRETE τ-axis. Therefore, the main error of the measurement is usually due to the resolution R_s of the spool-piece, which may be given approximately by (Lübbesmeyer 1983):

$$R_s \approx \frac{v}{f_s * D}. \qquad [2]$$

The resolution is inversely proportional to the sample-frequency f_s which is the frequency for the analog-digital conversion of the detector signals and to the distance between the detectors D, and directly proportional to the measured velocity itself. Unfortunately, it is not possible to increase either the sample-frequency or the detector-distance to any extent because both are strongly dependent on the "frequency content" of the signals which is related to the investigated flow.

Obviously, the resolution affects only the scattering of the individual measuring points around the "real" velocity curve and not the general trend of the measurement.

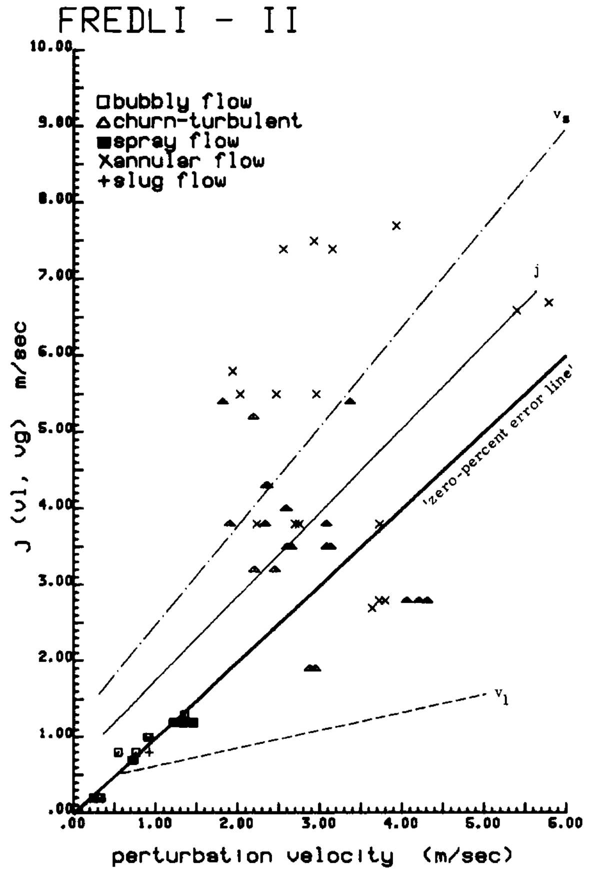

Figure 3. Comparison of the perturbation velocity with the external measured volumetric-flux of the two-phase flow (FREDLI-II measurements).

2. FLUID-VELOCITY MEASUREMENTS DURING BLOW-DOWN'S

With the above described spool-piece, time-dependent fluid-velocity measurements were performed at the blow-down facility of the Inst. f. Kerntechnik of the TU Berlin. Figure 4 illustrates the main parts of this facility. In principle, it consists of two vessels, the boiler (with a volume of 0.26 m^3 and the buffer with 0.38 m^3), a connecting tube (dia. 25 mm, length 1 m) between with the ball-valve and the two spool-pieces (one with horizontal and one with vertical beam arrangement) and a vertical chimney (dia. 100 mm, length 10 m), which connects the buffer vessel with the environment. Except two pressure-transducers for the pressure in the boiler- and buffer-vessel, there was no additional instrumentation available to check the measured velocities by a reference method.

To perform a blow-down, the water of the boiler vessel is heated up to the saturation temperature of the desired pressure. Then, the valve is opened manually. As a result, an expanding two-phase flow is streaming through the test-section, evaporates almost completely in the buffer vessel and is finally blown in the environment through the chimney.

Figure 5 shows the results of the fluid-velocity measurements of such a blow-down at two different locations of the test-section and for a starting pressure of 8.5 bars, as well as the pressure variations in the boiler- and the buffer-vessel. A significant increase of the measured fluid-velocity between the first (horizontal beam) and the second spool-piece (vertical beam) can be observed. This increase can be explained as being due to the evaporation process in the test-section. Due to the decrease of the density of the fluid, the velocity of the fluid increases proportionally to maintain a constant mass flow.

Unfortunately, it was impossible to perform a reference-measurement to check the applicability of the proposed spool-piece. The only way to do this is via a semi-experimental route, i.e. by comparing the measurements with the results of a computer-code, in our case with SLIP (Covelli 1981).

The resulting time behaviour of the volumetric fluxes at the positions of the two spool-pieces as well as of the boiler-pressure for the blow-down case are shown in figure 6. The total

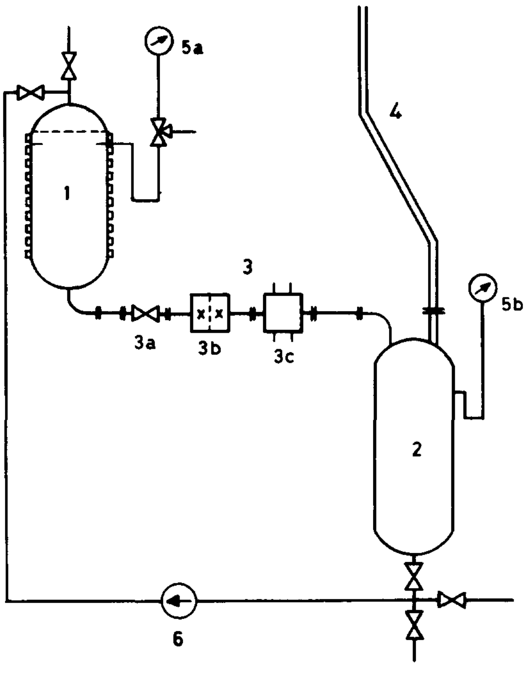

Figure 4. Sketch of the IKT blow-down facility. 1. Boiler vessel (0.26 m^3); 2. buffer vessel (0.38 m^3); 3. test-section; 3a. ball-valve; 3b. EIR spool-piece (horizontal light-beam); 3c. EIR spool-piece (vertical light-beam); 4. chimney (NW-100, 10 m long); 5. pressure-transducers; 5a. range 0–60 bar; 5b. range 0–8 bar; 6. feed-pump.

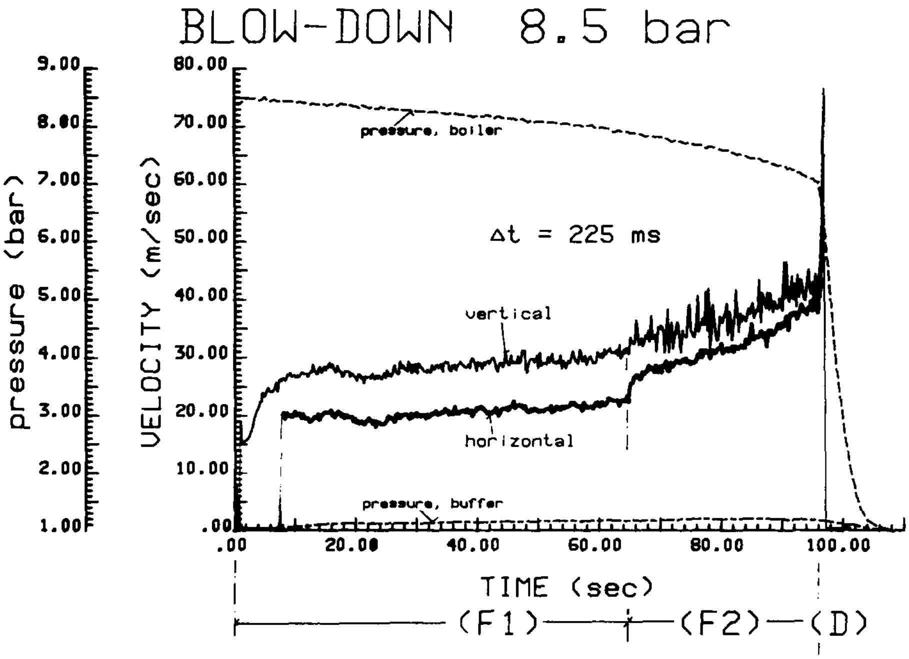

Figure 5. Result of a measurement at 8.5 bar starting pressure.

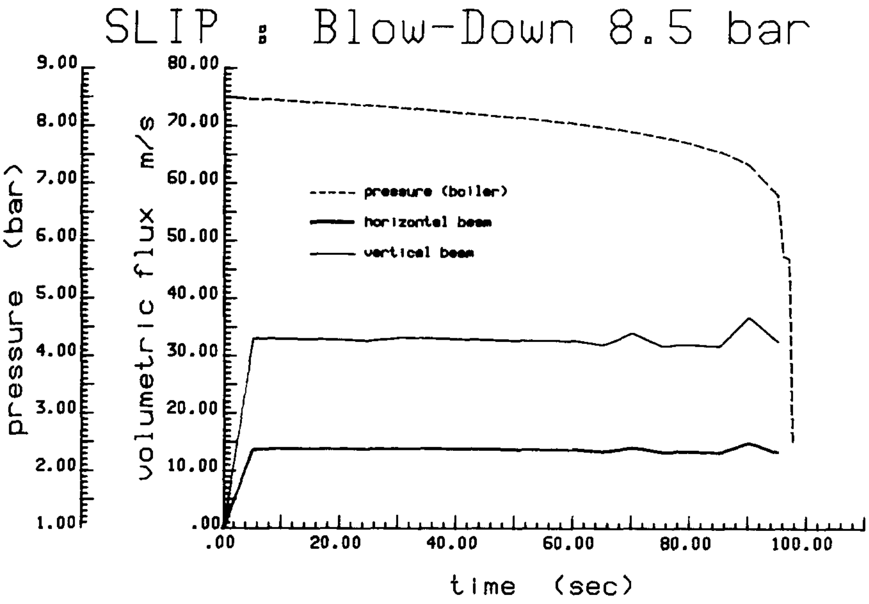

Figure 6. Results of SLIP-code for the blow-down experiment 8.5 bar.

blow-down time is given very accurately by the code. Also, the time dependence of the boiler-pressure is in perfect agreement. The agreement between the measurement shown in figure 5 and the resulting volumetric fluxes is relatively poor, although one can say that for both cases, the measured velocities and the corresponding volumetric fluxes are much closer to the measured velocities than the corresponding liquid- and steam-velocities, predicted by the code (e.g. for the case of vertical beam: $v_l = 6.3$ m/s, $v_G = 35$ m/s; for the case of horizontal beam: $v_l = 7.9$ m/s, $v_G = 69$ m/s). It can be seen that for the vertical beam spool-piece, the measured velocity is closer to the volumetric flux than it is for the case of the horizontal beam spool-piece. The reason for this difference remains an open question.

The velocity-history can be divided into three different intervals. During the first, F1, the velocity is more or less constant at around 20 m/s for the first spool-piece and 29 m/s for the second. During the second interval, F2, the velocity increases with a gradient of about 0.5 m/s^2 for both spool-pieces. In these first two time-intervals, the boiler-pressure is nearly constant and the increase in the buffer-pressure remains low (0.3 bar). Finally, during the third part, the blow-out (*D*) lasts only for a few seconds and is characterized by a sharp decrease of the boiler-pressure while the fluid-velocity increases to values above the range of the spool piece.

Therefore, the "range of the spool-piece" was changed by changing the sample-frequency of the analysis. The results of some blow-outs for different starting-pressures (6, 11, 20 and 50 bar) are given in figure 7. The observed fluid-velocities are slightly lower than the sound velocity of the steam flow at that pressure.

It should be noted that up to now, measurements in the first two intervals of a blow-down were only successful with boiler-pressures lower than or equal to 12 bar. With higher pressures, there was, roughly speaking, not enough "noise" in the signals to perform an analysis.

3. FLOW-PATTERN IDENTIFICATION

3.1 *Description of the method*

Flow-pattern identification by analysing the detector-signals by statistical methods is an approach which has been proposed by some authors before, e.g. Jones & Zuber (1975), Crowe *et al.* (1977) and Vince & Lahey Jr. (1982). These authors showed that different flow-patterns influence the detector-signals in different ways which is expressed by different shapes of the signal-spectra and the probability-functions. The most significant changes have been observed (and therefore extensively discussed) for the probability functions of the signals between slug-flows and bubbly-flows, where for slug-flows, a typical "two-hump" shape (camel-shape) exist which disappears completely for most of the other flows.

The aforementioned investigations are only the first step towards a general flow-pattern identification method, because up to now they can only be used in the same channel where the "calibration" was performed with KNOWN flow-patterns. Therefore, the next step would be to develop a method which allows the flow-pattern identification to be made for other channels, where a visual identification is impossible. As a first approach, the following method is proposed. It consists of a comparison of selected noise-analytic functions obtained from a

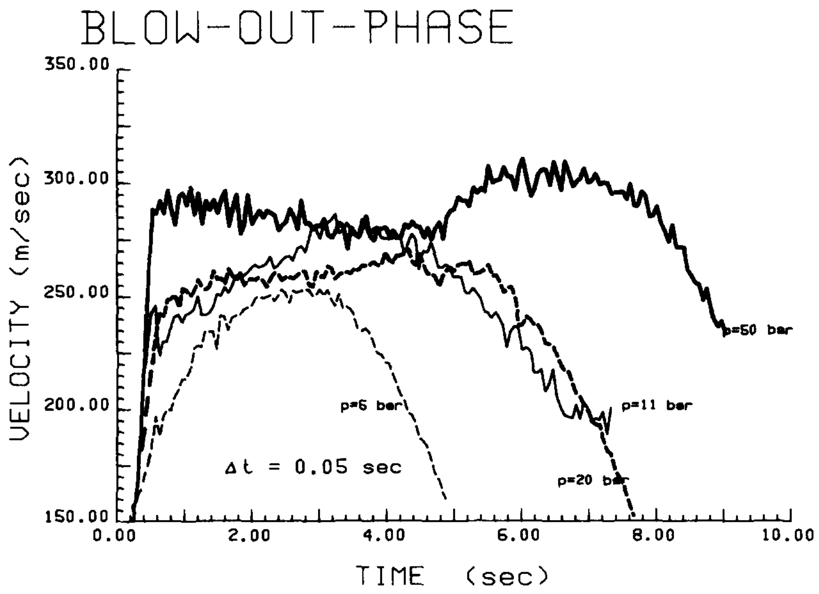

Figure 7. Velocity measurement in the blow-out part of the blow-down.

simple test-loop with known flow-patterns, with the equivalent functions of the investigated two-phase flow measured in an other facility. In the time-domain, these functions (called CHARACTERISTIC-FUNCTIONS, (CHAF)) are:

—The signals themselves.
—Probability functions.
—Coincidence-probability functions.
—Cross-correlation functions (CCF).

In the frequency-domain:
—Auto-power-density functions (APSD).
—Cross-power-density function (CPSD).

The coincidence-probability function focusses on the common part of the two signals because only the probability of the two signal amplitudes coincident within certain limits at a certain time t are of interest. It is the probability-function of a signal $xy(t)$ which may be defined as follows:

$$xy(t) = \begin{cases} [x(t) + y(t)]/2 & \text{if:} |x(t) - y(t)| < \epsilon \\ \text{not existing.} & \end{cases} \qquad [3]$$

Obviously, for two similar signals the coincident-probability function is equal to the probability function of the signal, whereas two completely different signals have no coincident probability function.

Note that when applying the coincidence-probability function, the time-delay between the two signals must be zero to make the two signals comparable at the same time-point t.

Finally, although the coherence function is not suitable to be used as a CHAF due to its strong dependence on the distance between the detectors (which may be different between the investigated and the reference cases), this function is also determined in order to get an estimate of the accuracy of the measurement.

The detection-mechanism by light-beam detectors proposed in this paper is complex. In contrast to, for example, X- or γ-ray densitometers, conductivity dependent or neutron sensitive systems, the signal-properties of the light-beam detectors are independent of the density of the fluid (or void-fraction) and only functions of the configuration of the liquid-steam interfaces traversed by the light beam. The "configuration" of the interfaces is somehow dependent on the flow-pattern of the investigated two-phase flow. Because the fluid-velocity plays an important role for the detection mechanism (e.g. the corner-frequency of the signal-spectra is affected (Vince & Lahey 1982), this effect should in principle be eliminated. Also, an influence of the beam-length may be significant. Therefore, as a first approach, a very simple normalization of the abszissae was introduced. It is assumed that in the frequency-domain the frequency-range is directly proportional to the fluid-velocity, v, and inversely proportional to the "path travelled by the light-beam" in the fluid, d, (in our case, the tube-diameter). Therefore, the simple normalization gives the dimensionless frequency f':

$$f' = f * d/v. \qquad [4]$$

By analogy the normalization in the time-domain gives the dimensionless time t':

$$t' = t * v/d. \qquad [5]$$

Since we are only interested in the shapes of the CHAFs, all curves are normalized to their maximum value.

3.2 *Measurement of the CHAF* (*reference curves*)

To obtain the "reference-curves", measurements were made at a simple air–water loop in different flow-regimes.

Figure 8 shows a sketch of the test-loop FREDLI-II. In principle, it consists of a 25-mm-dia. glass tube and a valve-system for water and pressurized air. One valve-pair is connected to a jet-pump. The jet-pump generates all kinds of bubbly-flows including the "inverse cases" of mist-flow. The second valve-pair is connected to an outer mixer-chamber, where different kinds of annular-flows may be generated. By varying the settings of the four valves, a wide range of two-phase flow patterns can be generated in the vicinity of the measuring section, which is located only a few centimeters above the jet-pump nozzle. Downstream, the different flow-patterns normally collapse to bubbly flow. This in no way affects our results since only the influence of a certain flow pattern on the light-beam signal is of interest.

For different flow-regimes, the CHAFs normalized by using [4] and [5] are shown in figure 9. In the time-domain, the abzissa for all curves ranges from $t' = 0$ to $t' = 30$ and in the frequency-domain from $f' = 0$ to $f' = 2$. Note that for the APSD's and for the probability-functions the curves of channel B are plotted in the negative direction. Furthermore, as already stated before, in order to obtain the coincidence-probability function, one of the signals was delayed by a digital delay-line (Crowe & Phildius 1980) so that the peak of the CCF is always at zero.

Bubbly-flow. For bubbly-flow, three different cases have been investigated, two with nearly the same large bubble-diameter but different fluid-velocities, and one with a much smaller bubble-diameter and also with different fluid velocities. The bubbles for the first two cases were

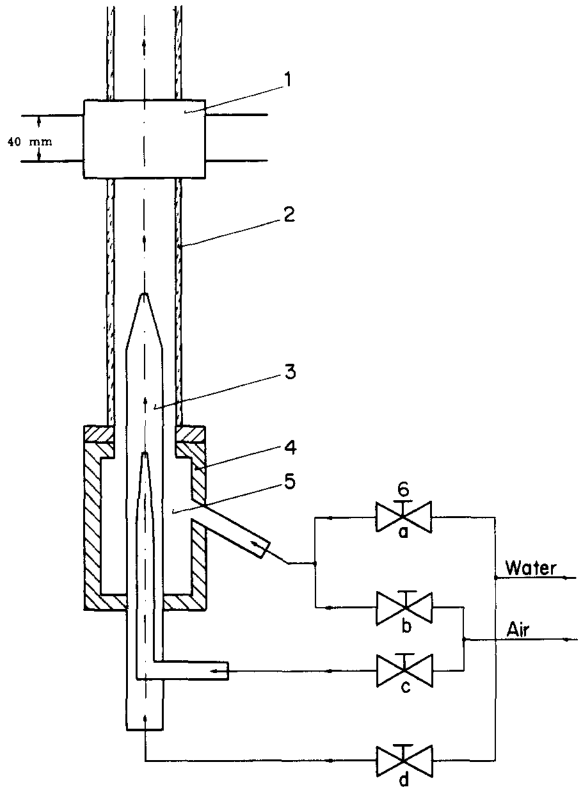

Figure 8. Sketch of the FREDLI-II test-facility. 1, light-beam spool-piece; 2, glass tube; 3, jet-pump; 4, mixer; 5, outer mixer-chamber; 6, needle valves for (a) outer water, (b) outer air, (c) jet-pump air, (d) jet-pump water.

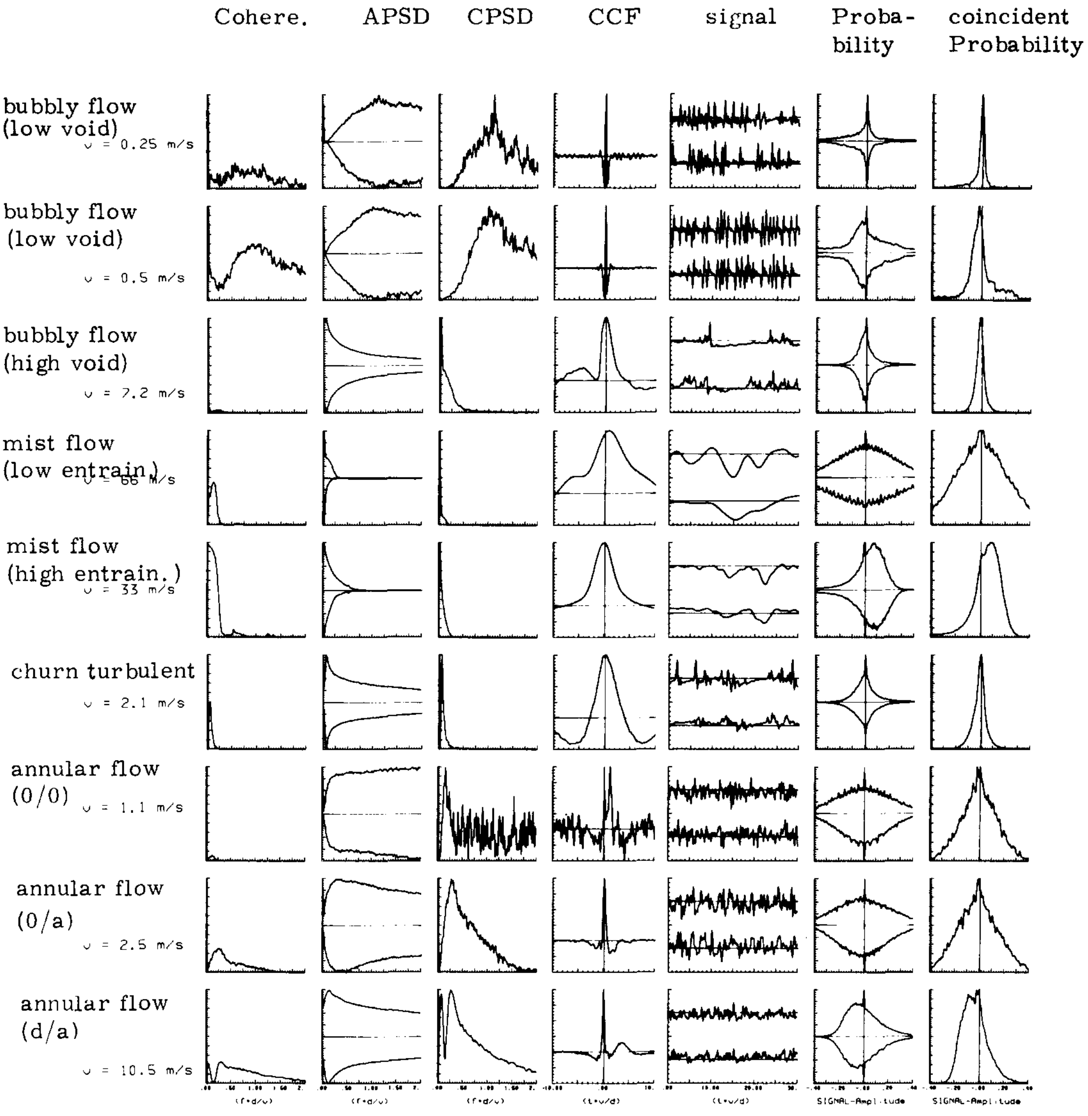

Figure 9. Characteristic functions for the reference-case.

ellipsoids of 7 * 16 mm; this was measured by photographic techniques. As a test of the normalization procedure, two cases with the same bubble-shapes but different fluid-velocities were chosen, the first with half the fluid-velocity of the second. The shapes of the CHAFs were similar even when the fluid-velocity was doubled. This seems to be a good verification of the applicability of the normalization procedure.

In the third case, the bubble-diameters were much smaller than in the previous case, and the shapes of the CHAFs change significantly. In particular, in the frequency domain, the main part of the energy is shifted to lower, dimensionless frequencies. Note that the second peak on the left handside of the main-peak of the CCF is due to the poor coherence of the measurement and means that the transit-time is zero.

Mist-flow. Similarly to the case of bubbly-flow, mist-flow also produces different shapes of the CHAFs for different droplet-diameters. This is demonstrated with two kinds of mist-flow, the first with small droplets (low entrainment) and the second with larger ones (higher entrainment). In the frequency-domain, the main spectral energy is now in the first 10 percent of the total dimensionless frequency range and is shifted to even lower values if the average diameter of the droplets decreases.

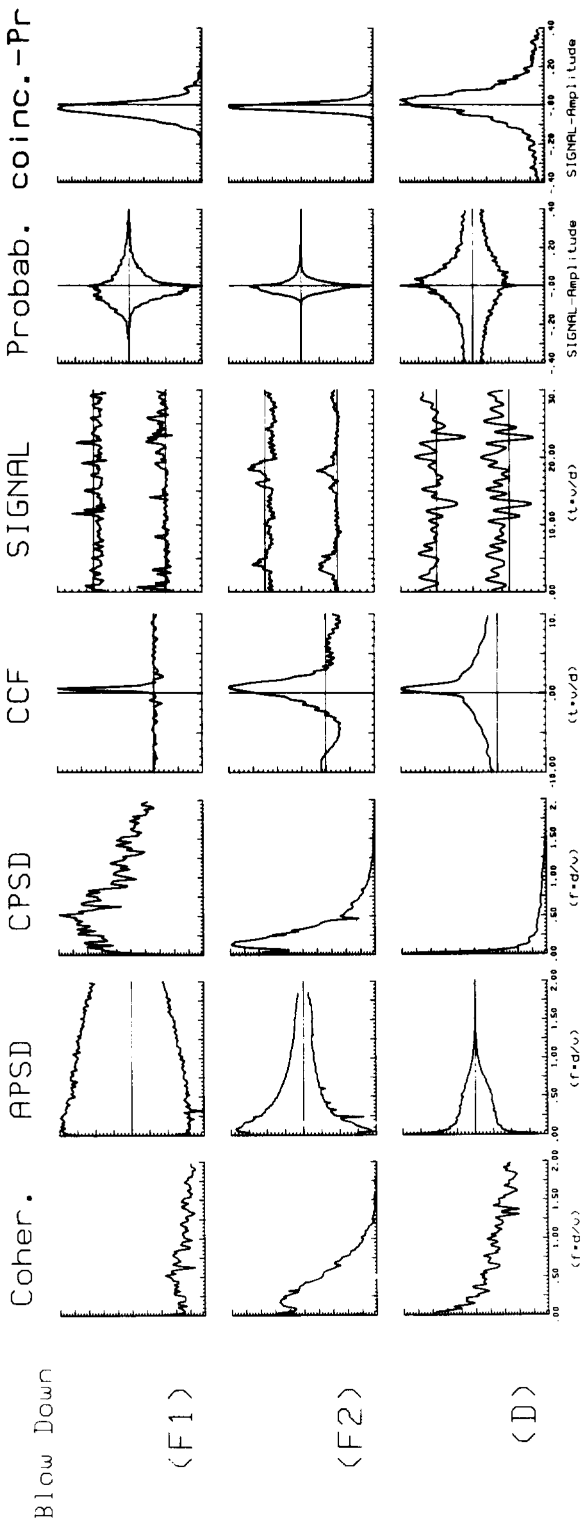

Figure 10. Characteristic functions for three time-intervals of the 8.5bar blow-down (vertical beam).

Churn-turbulent. As far as the shapes of the CHAF are concerned, churn-turbulent flow lies between the different forms of bubbly-flow mentioned above, and the annular-flows to which we shall refer shortly. They look similar to those of the small bubble bubbly-flow.

Annular-flow. In the case of annular-flow we want to distinguish between three different cases, the ANNULAR-FLOW (0/0), i.e. a flow with a pure liquid a pure gas phase (interface-waves), ANNULAR-FLOW (0/*a*), which means an annular-flow without entrained water in the centre-flow but gas-bubbles in the water-ring and ANNULAR-FLOW (*d*/*a*), the annular-flow with entrained water droplets in the gas-phase and gas-bubbles in the water ring. While interface-waves have a very poor CCF, which means that the detection of a transport-effect of interface-waves by light-beam techniques is very uncertain, the two other types of annular-flow give good results. It is worth mentioning that the CCF of the annular-flow *d*/*a* gives two transit-times which can be interpreted as the velocity of the entrained droplets (main peak of the CCF and the velocity of the gas-bubbles in the water-ring (smaller peak in the CCF). There are also differences in the CHAF of the two types of annular flow, especially the probability and coincident-probability.

As expected, for different flow-regimes, the shapes of the CHAFs differ since they are somehow dependent on the flow-pattern of the investigated two-phase flow. Unfortunately, in certain cases different flow-patterns have similar CHAFs (e.g. high-void bubbly and churn-turbulent flow) while in other cases, similar flow-patterns result in different ones (like the two bubbly-flow with different bubble-sizes).

3.3 *Flow-pattern identification for the three blow-down intervals*

For the three time-intervals of the blow-down, (F1), (F2) and (D), (see figure 5), the CHAFs were computed and plotted in the same f'- and t'-intervals as the reference CHAFs and they are shown in figure 10. Because of the short measuring-time, the statistical error is high. This explains why these curves are more scattered than the reference functions; this makes a comparison even more uncertain. Although the blow-down was for the case of horizontal two-phase flow, for the comparison, the reference functions for vertical upward flow were used (figure 9). This seemed to be possible because the fluid-velocity was high enough and the length of the test-section small enough to prevent any separation due to gravity. This was verified by determining the CHAFs both for the horizontal and vertical light-beam spool-pieces; no significant differences were observed. This is an indication that the flow was almost radially symmetric.

The flow-pattern-identification for the blow-down part (F1) gives an indication of the presence of annular-flow (*d*/*a*). This is supported by the good agreement between the (reference and measured) APSDs, the signal-amplitudes, the probability-functions and the CPSDs. The agreement between the CCF's and the coincidence-probabilities is poorer, probably because the number and the diameters of the bubbles or entrained droplets are different.

For the blow-down interval (F2), small-bubble bubbly-flow (a kind of foam) can be assumed because of the good agreement between the reference and measured signal-amplitudes, the probability-functions, the APSDs the CCFs and the coincidence-probabilities. Only the agreement between the CPSDs is poorer.

Finally, for the blow-out (interval (D)), mist-flow can be assumed. Here, only a poor agreement between blow-down and reference-functions can be observed for the APSDs, the CPSDs and, under certain conditions, also for the CCFs. This is mainly due to the poor statistics in the evaluations of the functions in the blow-out case.

4. CONCLUSIONS

Transient-analysis (short-time-average cross-correlation technique) by light-beam detector signals for determining the time-dependent fluid-velocity of a transparent two-phase flow seems to be a useful technique. Since the light-detectors in no way obstruct the flow, the method has some advantages over other techniques, especially in experiments with small tube-diameters (in the region of 10–50 mm) in which the transparency of the two-phase flow is usually sufficient. The method is suitable for all kinds of transparent two-phase flows (a more or less transparent water particle-mixture is also a suitable medium).

The measured "perturbation velocity" in dispersed flows like bubbly- or mist-flows can be approximated by the volumetric flux j. For other kind of two-phase flows, the measured "perturbation velocities" are usually lower than the actual value of the volumetric flux j.

The proposed method of flow-pattern identification by comparing normalized CHAFs (those obtained from a test-loop with equivalent ones of the investigated flow) has to be regarded only as a first step. The method cannot clearly distinguish between different flow-regimes as represented in flow-maps, because it is sensitive only to the distribution of the gas–liquid interfaces along the light-beam. Though, it can probably be used for distinguishing between the extremes. This is sometimes sufficient for interpreting the results of fluid-velocity and also density measurements (by means of, for example, γ-densitometers).

NOMENCLATURE

A	flow area
d	equivalent tube diameter (beam-length)
D	detector distance
f	frequency
f'	dimensionless frequency
f_s	sample-frequency for AD-conversion of the signals
j	volumetric flux $[=(Q_1+Q_s)/A]$
Q_l	volume flow of the liquid
Q_s	volume flow of the gas (steam)
R_s	resolution of the "spool-piece"
$R_{xy}(\tau)$	cross-correlation function
t	time
t'	dimensionless time
Δt	length of a measuring interval of one individual cross-correlation measurement in transient-analysis
v	measured "perturbation velocity"
v_l	velocity of the liquid $[=Q_1/((1-\alpha)*A)]$
v_G	velocity of the gas–stream $[=Q_G/(\alpha*A)]$
$x(t)$	signal amplitude of detector A (upstream detector)
$y(t)$	signal amplitude of detector B (downstream detector)
$xy(t)$	coincident amplitude
α	void fraction
ϵ	limit for coincident amplitude
τ	time-shift (abscissa of cross-correlation function)
τ_p	transit-time, determined by the peak of the cross-correlation function

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