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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Spherical probe for liquid flow rate measurement in two phase flows

Experimental investigations of a spherical probe for determination of liquid flow rate in two phase flow are presented. The probe is made of a metal sphere of diameter of a few milimeters connected electrically to a voltage source. The probe is designed for operation in a flow of droplets suspended in gas. The method is based on the measurement of electric current taken by the probe resulting from liquid detached from the probe due to aerodynamic forces. The probe current is proportional to the liquid deposited on the sphere, which depends on the liquid phase content and liquid phase velocity in two phase flow.

1. Introduction

The spherical probe [1-2] is designed for the measurement of the liquid volumetric flow rate in two phase flow of a mixture of gas and liquid droplets. The principle of operation of this method is based on the removal of the electric charge from an electrode (a sphere) immersed in the flow, and maintained at a high electric potential, by the liquid detached from the sphere. The current from the spherical probe is proportional to the charge rate taken off the probe. The charge flowing from the sphere is a function of the liquid mass flow rate, i.e., the liquid content in the gas-liquid mixture, and the velocity of the liquid phase.

The method is principally destined for the measurements in the flow of high velocity that allows a permanent detachment of the liquid from the sphere by aerodynamic forces. The advantage of the spherical form of the probe to the other geometrical shapes is that the deposition process and then the results of the measurement are independent of the flow direction.

Two fundamental hydrodynamic problems are met in the consideration of the measuring characteristics of the spherical probe.

The first one is the deposition of the airborne droplets on the sphere and the

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representation of the mean volume flow rate of the liquid phase by the fraction of the droplets deposited. In the case of high Reynolds and Stokes numbers (Re > 1000 and St > 100) the deposition efficiency can be determined with the assumption of the potential flow around the sphere. In such case the aerosol droplets are deposited then only due to inertial forces and the deposition efficiency is close to the value of 1. It is also assumed that the droplets are not charged, i.e. the aerosol is electrically neutral.

The second problem is the removal of liquid from the sphere due to aerodynamic forces and also the relation between the current and the deposited liquid. There is still a lack of theory on the liquid detachment from an object immersed in two phase flow and therefore only experimental data can be analyzed.

The purpose of this paper is to present the results of theoretical and experimental investigations of the aerosol droplet deposition, detachment of the liquid from a spherical probe immersed in a two-phase flow and the measurements of the spherical probe characteristics.

2. Principle of operation

The method for measurement of the liquid mass flow rate in two phase flow of gas and liquid droplets is based on the removal of the electric charge from the sphere maintained at high electric potential. Liquid is deposited on the sphere mainly due to the inertial forces. The current from the spherical probe is proportional to the rate the charge is taken off the sphere. It is proved that the current is a function of the liquid volumetric flow rate, i.e. the liquid content in the gas-liquid mixture and the velocity of the flow.

A detailed description of the principle of operation of the probe is presented in [1-2]. In the following only fundamental equations of the probe characteristics will be presented.

The charge on a sphere at potential U relative to infinity is

$$Q = 2\pi\varepsilon_0 DU \tag{1}$$

where: D is the diameter of the sphere, ε_0 – the permittivity of the free space.

The current flowing through the spherical probe, caused by the charge taken off by detaching droplets of equal sizes, is:

$$I = q\frac{dn}{dt} \tag{2}$$

where q is the charge of a single droplet. Assuming the droplet is at the same potential as the spherical probe is, at the moment of detachement, the droplet charge can be determined from:

$$q = 2\pi\varepsilon_0 Ud \tag{3}$$

where: d is the diameter of a detached droplet.

Then Eq. (2) becomes

$$I = 2\pi\varepsilon_0 U d \frac{dn}{dt} \tag{4}$$

in which $\frac{dn}{dt} = \dot{n}$ is the rate of the number of droplets detaching from the sphere.

The mass flow rate of a droplet deposited on the spherical probe, provided a 100% deposition efficiency is:

$$\dot{m}_d = \frac{\pi^2}{24} N w \rho_l D^2 \delta^3 \tag{5}$$

where N is the droplets' concentration, δ – diameter of the droplets in the aerosol, w – droplets' velocity, assumed to be equal to the gas phase velocity, ρ_l is the liquid density.

In stationary conditions, the mass of the liquid detached from the spherical probe equals to the mass of deposited droplets

$$\frac{\pi^2}{24} N w \rho_l \delta^3 D^2 = \frac{\pi}{6} \dot{n} \rho_l d^3 . \tag{6}$$

From this equation, the number of droplets detaching from the sphere in a unit of time is:

$$\dot{n} = \frac{\pi N w D^2 \delta^3}{4 d^3} . \tag{7}$$

Taking into account in Eq. (4) the result (7) one obtains:

$$I = \frac{\pi^2}{2} \varepsilon_0 U N w \delta^3 \left(\frac{D}{d}\right)^2 . \tag{8}$$

Because

$$\dot{V}_l = \frac{\pi^2}{24} N v \delta^3 D_c^2 \tag{9}$$

is the volumetric flow rate of the liquid phase in the test channel of diameter D_c, the current flowing from the spherical probe is:

$$I = 12\varepsilon_0 U \left(\frac{D}{d}\right)^2 \frac{\dot{V}_l}{D_c^2} . \tag{10}$$

Equation (10) is the characteristics of the spherical probe. Current I is a measure of the volume (or mass) flow rate of the liquid phase.

Main shortcomings of this model is that the deposited droplets are not monodisperse and the 100% deposition efficiency occurs only for high Stokes numbers. Also, the droplets detaching from the spherical probe are not regular spheres. These problems are discussed in the following sections. However, despite of this the characteristics of the spherical probe follow quite well the proportionality as predicted by Eq. (10), because of the statistical nature of the deposition/detaching processes. That justifies the assumption that the droplets diameters d and δ can be approximated by mean values of their actual sizes.

3. Droplet deposition on the sphere

One of the most important problem of the measurement with the spherical probe is the efficiency of the deposition of droplets on the sphere. The deposition efficiency is principally governed by the kinetic energy of the droplet, i.e. by its mass and velocity, and also by the viscosity of the gas. The droplets will flow around the collector if their velocity or mass are too low. There is, therefore, a limiting value of the Stokes number below which the deposition efficiency decreases, and the correction factor has to be used. The equations of motion of a droplet around the collector have to be solved to determine this limiting value.

In the following, the procedure presented in papers [3-4] will be adopted for the determination of the deposition efficiency. The Stokes, inertial and gravitational forces acting upon the droplet were taken into consideration in the equations of motion. It is also assumed that the flow field near the sphere is resulting from the Navier-Stokes equations in the free space, regardless of the pipe walls and the flow field in the vicinity of the collector is not disturbed by the droplets. The electrical forces: both Coulomb and image on the droplet will be set to zero.

The trajectory of a droplet of mass m in the vicinity of the spherical probe, in the system of coordinates placed in the center of the sphere, is given by the following vector differential equation:

$$m_d \cdot \frac{d\vec{w}}{dt} = \frac{C_d Re_d}{24}\vec{F}_s + m_d\vec{g} \tag{11}$$

in which w is the droplet velocity and F_s is the Stokes drag force on the droplet:

$$\vec{F}_s = 3\pi\eta_g\delta(\vec{u} - \vec{w})/C_c \tag{12}$$

where δ is the diameter of the aerosol droplet, u – the gas velocity, η_g – gas viscosity, r – the distance between the droplet and the spherical probe centres. C_c is the Cunningham slip correction factor [5-6] and C_d – the non-Stokesian drag coefficient, which for the Reynolds number based on the droplet $\mathrm{Re}_d < 2 \cdot 10^5$ is given by the Brauer and Sucker relation [7-8]:

$$C_d = 24\,\mathrm{Re}_d^{-1} + 3.73\mathrm{Re}_d^{-1/2} - \frac{4.83 \cdot 10^{-3}\mathrm{Re}_d^{1/2}}{1 + 3 \cdot 10^{-6}\mathrm{Re}_d^{3/2}} + 0.49. \tag{13}$$

To generalize the problem, the vector of the position of the droplet is normalized by the spherical probe radius R, i.e. $\bar{r} = r/R$, time can be converted into dimensionless from by $\bar{t} = tu_0/R$, while the vector of the local gas velocity u, and droplet velocity w are normalized by the gas velocity u_0 in the undisturbed region.

The Stokes number is introduced to characterize the deposition process, in the dimensionless form:

$$St = \frac{C_c \delta^2 \rho_d u_0}{18 \eta_g D} \tag{14}$$

where ρ_d is the droplet density.

The equation of motion of the droplet in dimensionless form reads

$$\frac{d^2\vec{r}}{d\bar{t}^2} = \frac{1}{St}\frac{C_d \mathrm{Re}_d}{24}\left(\vec{u} - \frac{d\vec{r}}{dt}\right) + \vec{g}\frac{R}{u_0^2}\,. \tag{15}$$

In Fig. 1 the results of numerical simulation of the collection of droplets on

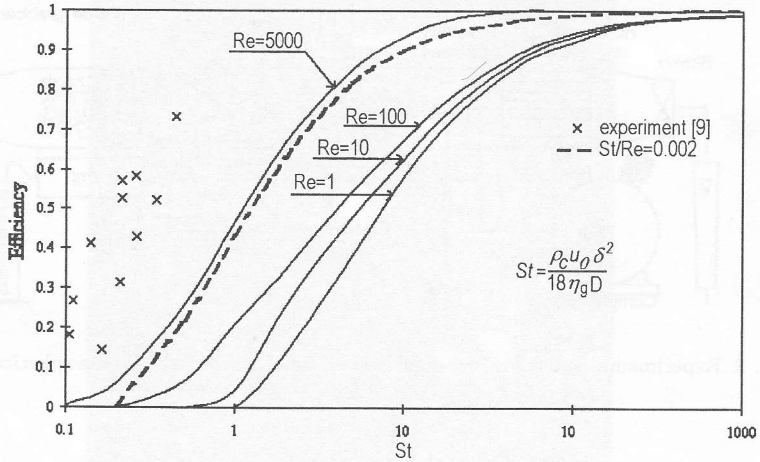

Fig. 1. The results of numerical simulation of the collection efficiency of the droplets on the spherical collector.

the spherical probe for different values of the Stokes and Reynolds numbers are presented. For Reynolds number, Re < 130, the flow field around the collector was determined by solving the Navier-Stokes equations using the finite element method. For higher values of Re the solutions were unstable and the potential flow was assumed. There is a lack of experimental data confirming or denying this theory. A few experimental points taken from the literature [9-10] suffer from the lack of specification of the experimental conditions.

From the obtained results it can be concluded that for low values of the Reynolds number (Re < 100) the Stokes number should be higher than 1000. For the Reynolds number Re > 1000 and St > 100 at least 95% of the aerosol droplets are deposited on the spherical probe.

However, it should be noticed that under specified conditions both these dimensionless numbers cannot vary separately and remain in the relation:

$$\frac{\mathrm{St}}{\mathrm{Re}} = \frac{1}{9}\frac{\rho_d}{\rho_g}\left(\frac{\delta}{D}\right)^2 \tag{16}$$

that in fact is independent of the gas velocity and gas viscosity. The actual value of the Reynolds number for a given Stokes number is determined only by the droplet to gas density ratio and the cross section of the droplet normalized to the collector. That leads to the conclusion that the collection efficiency changes according to the thick solid line in Fig. 1.

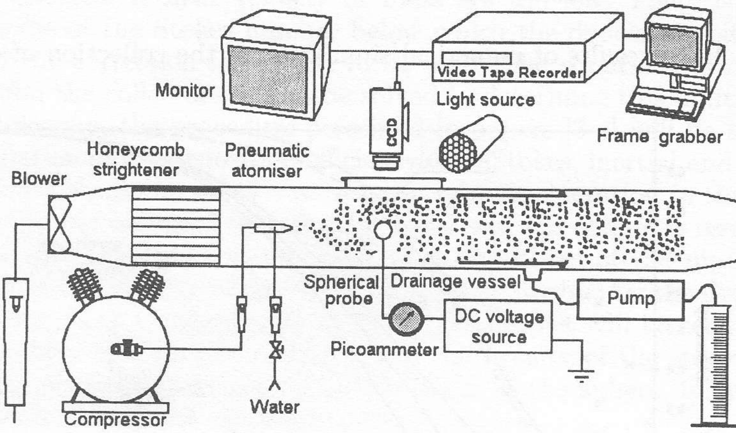

Fig. 2. Experimental stand for investigations of the characteristics of the spherical probe.

4. Experimental stand

Experimental stand for the investigation of the characteristics of the spherical probe is presented in Fig. 2. It is made of a duct of circular cross-section of internal diameter of 72 mm. The droplets are generated by means of a pneumatic atomizer and conveyed by air forced by a fan mounted at the inlet of the duct. A honeycomb straightener is installed at the inlet of the duct to remove vortices in the flow. The atomizer is placed at a distance of about 300 mm upstream of the spherical probe.

The probe is made as a stainless steel sphere of diameter of 11 mm and placed in the axis of the pipe. The sphere was mounted on a circular bar of 1 mm diameter, which was covered with an isolation pipe made of a metaplex. A special mounting of the probe situated outside the pipe was designed to minimize the leakage current.

A drainage vessel was placed few centimeters downstream from the spherical probe, in order to determine the volume of the liquid separated at the channel walls. The separated liquid was pumped to a graduated cylinder during the measurements.

The air velocity in the duct, averaged over the cross section of the duct, was determined from the volumetric flow rate of air forced by the fan and the air supplying the atomizer. The mean velocity of the gas in the duct was estimated to be about 13 m/s, for the volumetric flow rate of 185 m^3/h. The local value of air velocity was determined from the traces of greater droplets flowing near the collector. The traces remaining on the recorded pictures within the time interval of 1/10000 s, i.e. the time the electronic shutter was opened, are shown in Fig. 3. The air velocity determined from these measurements was estimated to be 26.8 m/s, with a standard deviation of about 1.356.

The process of the liquid detachment from the sphere was recorded by means

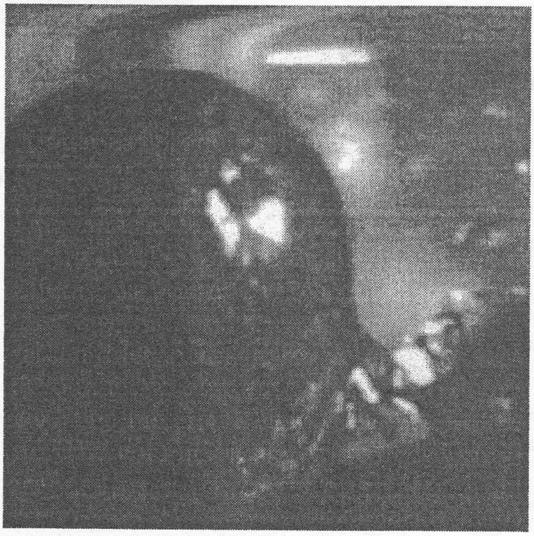

Fig. 3. An example of the traces of the aerosol droplets in the vicinity of the spherical probe.

of a CCD camera coupled to a video tape recorder. A special transparent-glass mounted in the pipe wall was used for these observations. Continuous light and light pulses of 3 μs duration, generated by a stroboscopic lamp were used for illumination of the sphere and detached liquid. The electronic shutter of the CCD camera was set either to 1/10000 s or 1/500 s to record the liquid detachment by continuous light illumination. The shutter 1/50 s was also used, but in this case the frequency of light pulses generated by the stroboscopic lamp was set to 106 Hz (maximum available for the type of the lamp used), that allowed us to record two consecutive positions of the jet or droplets within one frame, and obtain more information on the jet development.

The recorded pictures were next reviewed frame-by-frame with the aid of a frame grabber. From the recorded pictures the mechanisms of the jet development were reconstructed and also the size of the droplets could be determined.

5. Experiments

The observations of the jet detaching from the spherical probe have been carried out by means of an image processing system. The size of the droplet detached from the spherical probe was measured by the frame grabber system, directly from the image recordings, taken by the stroboscopic illumination of the $3\mu s$ time duration. A typical histogram of the droplet size distribution at the distance of about 20 mm downstream from the sphere is shown in Fig. 4a, for the volumetric flow rate of the gas of 185 m^3/s (mean gas velocity 13 m/s), and in Fig. 4b for 100 m^3/s (mean gas velocity of 7 m/s). About 1000 droplets were measured to determine the histograms. It was established that the droplets detached from the spherical probe are of diameters in the range from 0.4 to 1.2 mm. Only the droplets of the diameter greater than 0.2 mm can be classified with the optical method used, because smaller droplets are difficult to be distinguished.

It was observed first that a short jet is usually formed in the lower part of the sphere, which subsequently shifts downstream and is accelerated upwards, disintegrating next into droplets. Three types of the liquid detachments from the sphere can be distinguished from the observations:

- Vast droplets, usually greater than 1 mm in diameter, detaching directly from the sphere (Fig. 5).
- Elongated jets stretching out from the sphere and disintegrating into droplets due to aerodynamic forces (Fig. 6).
- Blowings originating at the sphere surface and next disintegrating into small droplets, of diameter usually smaller than $100\mu m$ (Fig. 7).

For lower gas velocities (7 m/s) it was possible to record two phases of the droplet formation with the aid of double flash. The process of droplet formation is illustrated in Fig. 8. The time interval between two flashes is 9.43 ms. From the double flash recordings the initial velocity of the detaching droplets can be estimated to 0.5 m/s. For higher velocities (13 m/s)with the available time interval between two consecutive flashes only a single droplet could be recorded in a frame.

The mean diameter of the detached droplet was estimated to be 0.86 mm, median diameter of 0.8 mm and a modal diameter of 0.6 mm for the mean gas velocity of 13 m/s. For the mean gas velocity of 7 m/s, mean diameter of the droplet was estimated to be 1.56 mm, median diameter – 1.4 mm and modal diameter – about 1 mm.

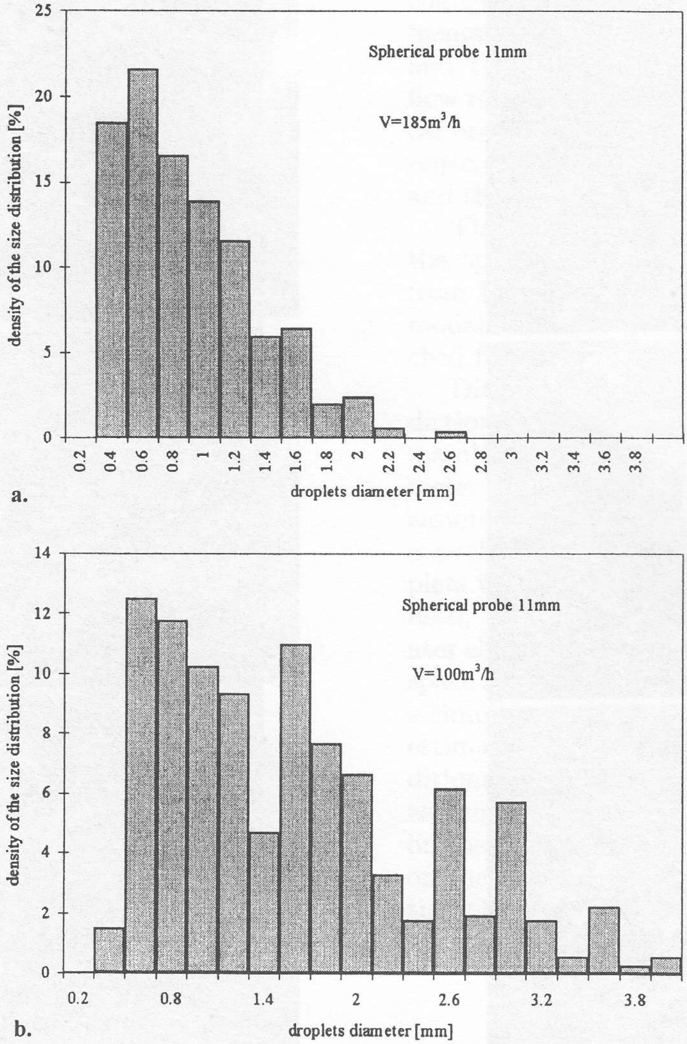

Fig. 4. A histogram of the size distribution of the droplets detached from the spherical probe, for 13.5 m/s (a) and 7 m/s (b).

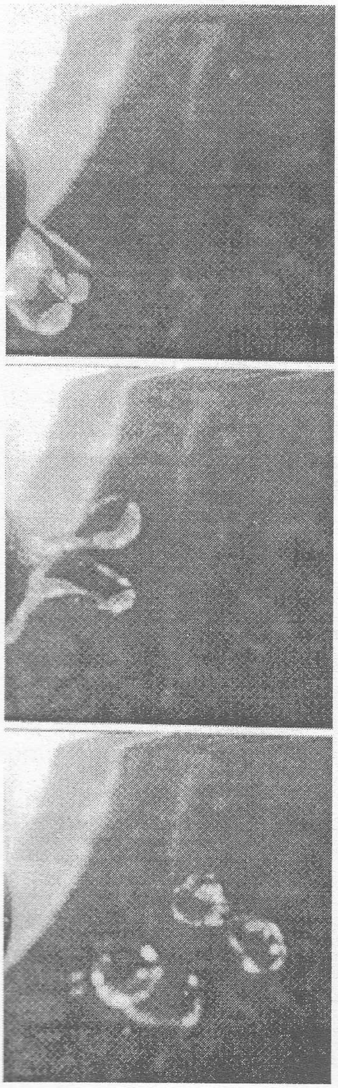

Fig. 5. Liquid detachment from the sphere in the form of vast droplets. Illumination: double flash, 3 μs duration, 9.43 ms time interval between the flashes.

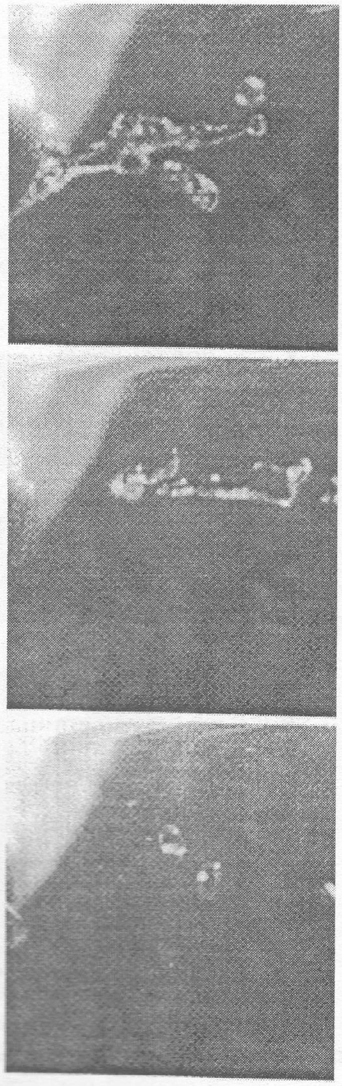

Fig. 6. Liquid detachment from the sphere in the form of elongated jets. Illumination: single flash, 3 μs duration.

Fig. 7. Liquid detachment from the sphere in the form of blowing. Illumination: single flash, 3 μs duration.

The current from the spherical probe, as a function of volume flow rate, is presented in Fig. 5. Two parameters were changed in the course of the measurements: the flow rate of the liquid sprayed and the gas velocity. The volumetric flow rate of the aerosol near the spherical probe was estimated from the difference of the flow rate of liquid sprayed and that separated at the duct walls.

The slope of the characteristics of the spherical probe can be estimated from Eq. (10), when substituting the modal diameter of the droplets detached from the sphere.

Difference between theoretical predictions and the measurements can be mainly caused by the value of the diameter of the detached droplet, which is assumed to be too high compatred to a probable actual value. Smaller droplets were not recorded by the method used, but they take off relatively greater charge. The assumption of the free space around the spherical probe is also a simplification, causing an error in the estimation of the droplet deposition. Additionally, the duct walls are grounded as they are wet and the effective field on the sphere, and the resulting charge on the detaching droplets are substantially higher than in the free space.

6. Conclusions

The characteristics of the spherical probe for determination of the liquid flow rate in two phase flows were investigated and compared with theoretical predictions. The experiments were carried out in a duct and not in a free space. The conclusion is, that in two phase flows in a duct the general proportionality of the current from the spherical probe to the volumetric flow rate is still conformed, as

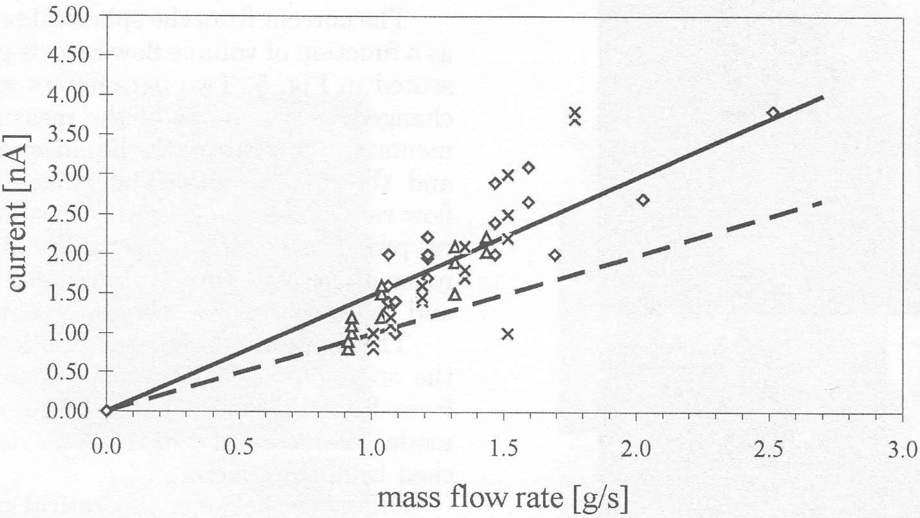

Fig. 8. The current from the spherical probe as a function of volumetric flow rate.

predicted by the theory. However, the actual current is higher than that resulting from the theory, because of the difficulties in determination of the diameter of the detached droplets.

Experimental results confirmed the practical usefulness of the measuring method and also the distributions of the probe characteristics.

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Sonda kulowa do pomiaru natężenia przepływu fazy ciekłej w przepływie dwufazowym

Streszczenie

Przedstawiono wyniki badań doświadczalnych sondy kulowej do pomiaru natężenia przepływu fazy ciekłej w przepływie dwufazowym: gaz + krople cieczy. Sonda wykonana jest w postaci kuli metalowej o średnicy kilkunastu mm podłączonej do zasilacza napięciowego. Pomiar polega na wyznaczeniu natężenia prądu unoszonego z sondy przez ciecz odrywaną z powierzchni przez siły aerodynamiczne. Prąd sondy jest proporcjonalny do objętości cieczy osadzonej na niej, która zależy od zawartości fazy ciekłej i prędkości czynnika dwufazowego.