Experimental evaluation of ISA 1932 nozzle for differential pressure measurement in air–water two-phase flows

Marek Jaszczur [1*], *Andrzej* Mrowiec[2], *Patryk* Marczak[1]

[1] AGH University of Krakow, Faculty of Energy and Fuels, Al. Mickiewicza 30, 30-059 Kraków, Poland
[2] Calisia University, Pl. Wojciecha Boguslawskiego 2, 62-800 Kalisz, Poland

Abstract. Accurate measurement of multiphase flows remains a significant challenge because of complex phase interactions and flow-regime variability. This study investigates the use of an ISA 1932 nozzle for differential pressure-based measurement of air–water two-phase flows. The test object was an ISA 1932 nozzle compliant with the PN-EN ISO 5167-3:2005 standard. A dedicated experimental test rig was developed to enable precise control of water flow rates and air injection. Tests were conducted with two fixed air mass flow rates (1.0690 kg/h and 0.6485 kg/h) and varying water flow rates up to 35 m³/h. The resulting flow characteristics exhibited strong power-law correlations with R^2 values exceeding 0.999 for both test series. The average discharge coefficient C_{avg} for the two-phase mixture was determined to be 0.9622, remained within a ±1.5% tolerance across a Reynolds number range of 50,000 to 200,000. The findings confirm that the ISA 1932 nozzle is a reliable and accurate device for measuring two-phase air–water flows under controlled conditions, providing a cost-effective alternative to more complex measurement technologies.

1 Introduction

Multiphase flow refers to two or more phases that are immiscible with each other [1]. This phenomenon is widely observed in nature as well as in many industrial applications. In particular, two-phase gas-liquid (air-water) flow attracts significant attention because it frequently occurs in both natural as well as in industrial systems. Multiphase flows, especially those involving chemical reactions, still present major challenges for mathematical modelling. Therefore, experimental studies and the development of measurements methods for multiphase flows remain highly important [2].

Multiphase flows can be analysed using several methods, such as electromagnetic flowmeter, ultrasonic flowmeter, Coriolis flowmeters, magnetic resonance imaging, high-speed cameras, computer tomography, particle image velocimetry, laser Doppler anemometry, and radiometric methods [3,4].

Despite being crucial for heat and mass transfer, this complex phenomenon continues to pose a significant challenge for researchers. Its intricate interactions between phases lead to the creation of multiple structures which are often unstable and transient. Accurate measurement of basic flow parameters, such as individual phase velocities, phase volume fractions, or even the identification of the flow regime, remains particularly difficult.

Typical measurement methods used for single-phase flow may exhibit high uncertainties when applied to multiphase systems. Additionally, dedicated equipment can be costly (e.g. ultrasonic and electromagnetic flowmeters) and difficult to operate or to use for signal analysis.

1.1 Multiphase flow description

Multiphase flow in nature includes rivers, where solid materials are transported by water, clouds which consist of liquid droplets suspended in air, and blood flow, which contains solid components (red and white cells) within a continuous liquid phase.

Industrial examples of multiphase flow include cooling systems in power plants (steam and water), mixing tanks, chemical, oil and gas refineries, and application in energy and environmental engineering. Other important examples commonly discussed in the literature are spray coating, used for corrosion protection, spray drying, metal 3D printing [5], and jet engines, where liquid fuel is sprayed into the combustion chamber [6].

Air-water mixture flows in horizontal channels can be classified into different regimes, commonly referred to in the literature as:

- slug flow,
- bubbly flow
- plug flow [7].

* Corresponding author: jaszczur@agh.edu.pl

Figure 1 shows examples of the aforementioned flow regimes, captured during measurements conducted on the laboratory test rig employed in this study.

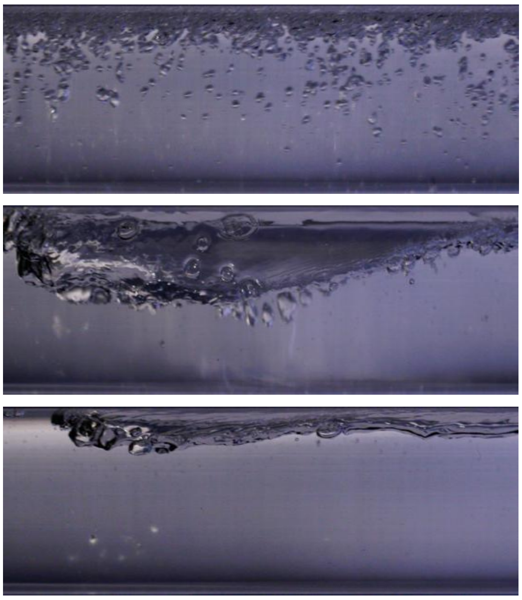

Fig. 1. Different flow regimes of an air-water mixture captured during the measurements: (a) – bubbly flow, (b) – plug flow, (c) – slug flow.

1.2 Common multiphase flow measurement devices

Due to the highly dynamic behaviour of multiphase flows, their description requires more effort than for single-phase flows. The literature describes three main approaches to analysing multiphase flow:

- theoretical – where the flow is described using mathematical equations and models,
- numerical – where dedicated, specialised software is used,
- experimental – where dedicated laboratory setups are constructed and which utilise specialised measurement devices [8].

Since this paper focuses on measurement techniques, some of the most common methods are described below.

1.2.1 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a non-invasive optical technique typically used to obtain velocity fields. Seed particles are introduced into the fluid and follow the flow. A selected plane is illuminated with a laser or LED light, and a camera captures two frames separated by a known time delay. Dedicated software then calculates the particle displacement and determines velocity vectors, allowing researchers to reconstruct the flow field [9].

1.2.2 Radiometric technique

Radiometric measurement is another non-invasive technique used to determine individual phase velocities as well as to identify flow regimes [10]. It is based on the difference in ionizing radiation absorption between phases. Typically, it uses a gamma-ray source, (e.g., Am-241) and scintillation probes. When radiation travels through the mixture, water attenuates the signal more than air (i.e., water has higher absorption), which is observed as a decrease in the scintillation probe signal. With two probes separated by a known distance and applying the cross-correlation function (CCF) it is possible to obtain individual phase velocities from the time lag between corresponding signal peaks [11].

1.2.3 Other measurement devices

Other devices can be used to determine phase velocities. Ultrasonic transducers (UTs) are common non-invasive examples. They utilize the Doppler effect: an ultrasonic signal is emitted into the flow and the frequency shift of the signal reflected from a moving bubble, droplet or solid particle is measured. The shift is proportional to the velocity of the scattering targets (secondary phase). UTs measure the velocity of the continuous or dispersed phase, while phase fraction is often estimated using conductance or impedance sensors; such combined systems can achieve good accuracy [12].

Electromagnetic flowmeters (EMF) are also used to determine velocities in multiphase flow, but their application is restricted to cases where the continuous phase is electrically conductive (for example, water). An EMF measures the voltage inducted by the conductive liquid moving through a magnetic field, which is proportional to liquid-phase velocity. To capture phase distribution, an EMF is often combined with Electrical Resistance Tomography (ERT). Such combined systems have reported flow velocity errors as low as 3% [13].

1.3 Orifice method

The orifice method is widely used for measuring flow rates. It is estimated that in industrial installations approximately 40% of flow measuring devices are based on pressure-drop measurement using orifice plates, nozzles, or Venturi tubes [14]. The fluid flowing through an orifice generate a pressure drop along the pipe. The static pressure measured in the orifice throat is lower than the static pressure before it. This causes an increase in the velocity of the flowing fluid, resulting in an increase in kinetic energy. Theoretically, this behavior can be described by Bernoulli's equation together with the continuity condition. Figure 2 shows a schematic of the theoretical flow through a measuring orifice.

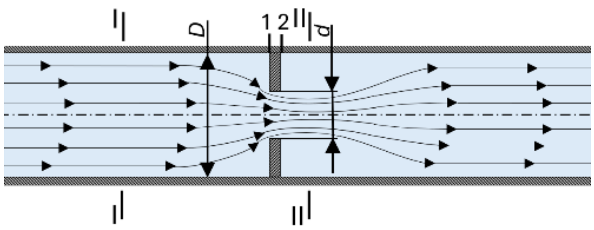

Fig. 2. Schematic of fluid flow through a measuring orifice.

1.4 Measurement method for orifice

In practice it is difficult to place pressure taps exactly at the theoretical cross-sections (I-I upstream of the constriction where the flow is undisturbed, and cross-section II-II at the throat where the stream has the smallest cross-section) for every configuration (orifice plate, nozzle, Venturi tube). Therefore, standardized tap locations are used for measuring the pressure difference before and after the orifice. These are cross-sections 1-1 and 2-2 where the pressure drop $(p_1 - p_2)$ is measured using corner tapings.

For this reason, the discharge coefficient *C* has been introduced for technical calculations. It is determined experimentally for real, incompressible flow. It accounts for all deviations from the theoretical flow, such as the velocity profile distribution in the pipeline, viscous effects, and losses resulting from the formation of vortices in the vicinity of the constriction, where the actual flow behavior significantly deviates from the theoretical one. This coefficient depends only on the type of measuring constriction and the Reynolds number $C = C(Re_D)$. When designing the shape of measuring constrictions and their manufacturing process, the goal is to make the dependence of the discharge coefficient *C* constant and linear over the widest possible range of Reynolds numbers.

The relationship for calculating the volume flow rate for an incompressible fluid is presented by the following formula:

$$q_v = \frac{1}{\sqrt{1-\beta^4}} \cdot C \cdot F_2 \cdot \sqrt{\frac{2}{\rho}(p_1 - p_2)} \qquad (1)$$

where:

- q_v – volume flow rate, m^3/s
- β – constriction ratio, -,
- C – discharge coefficient, -,
- F_2 – cross-section of the constriction opening, m^2,
- ρ – fluid density, kg/m^3,
- p_1 - pressure measured directly before the constriction, Pa,
- p_2 - pressure measured directly after the constriction, Pa,

1.5 Multiphase flow measurement using orifice method

The orifice method (and related techniques) was traditionally used to measure single-phase flows, although over the years, its application to multiphase flow measurement has increased.

Chakrabarti et al. [15] performed a study of liquid-liquid multiphase flow through an orifice. The main goal of this study was to examine how obstruction affects the flow. They concluded that orifice can be recommended as a homogenizer for liquid-liquid flow systems and that it can serve as an effective flow meter, provided appropriate calibration is applied

Venturi meters were investigated by Hall and Reader-Harris [16]. Their research, involving the flow of crude oil, kerosine and water with a magnesium sulphate solution, showed low errors in liquid and gas volumetric flow rates readings.

Pirouzpanah, Çevik and Morrison [17] developed a different setup. An orifice plate was used to create a more homogeneous flow for a swirl flow meter, which showed high accuracy for multiphase mass flow rate measurements.

Campos et al. [18] experimentally tested orifice plate applicability for industrial multiphase flow measurement. By adding Chisholm's correlation to their mathematical model, they accounted for the slip velocity between gas and water. Their model enhanced with the slip formula, provided predictions for oil, gas and water flow rates with an error of less than 3.5%, while a model without the slip correction showed difference exceeding 10%.

Results presented in the literature show that the orifice method might be a reliable instrument for multiphase flow measurement. Although the orifice method has been extensively studied for single-phase flow conditions, its performance in multiphase systems, particularly for air-water mixtures, remains an important research topic that still requires further experimental investigation.

Therefore, this research study aims to contribute to the understanding of orifice-based measurement techniques under two-phase flow conditions and to evaluate their potential for accurate and cost-effective flow rate measurement. The analysis focuses on the applicability of the orifice method to air-water flow measurement, based on a methodology and an experiment specifically designed for this purpose.

2 Experimental setup

In order to verify the applicability of the orifice method for multiphase flow measurement, a dedicated test rig was designed and constructed. This chapter presents a detailed description of the experimental setup, which consists of a closed-loop water circuit and a digital data acquisition and control system. The geometry of the ISA 1932 nozzle used in the analysis is also discussed.

2.1 Test rig scheme

The test rig comprises a closed-loop channel through which water circulates continuously. A schematic diagram of the setup is presented in Figure 3. The water loop begin in the water tank (1) which is equipped with a degasser, to remove excess gas from the returning fluid and a thermometer (8) to monitor the water temperature. A centrifugal pump (not shown in the figure), circulates water through the loop.

Single-phase water are first measured by an orifice flow meter (3). At location (4) air is introduced into the water flow. The compressor (5) supplies pressurized air, and its flow rate is measured by a gas flow meter before being injected into the water. The resulting air-water mixture is measured by another orifice plate (7) and returns to the mixing tank (1), thereby completing the closed loop. The entire setup is controlled by dedicated, in-house software, which allowing real-time acquisition and recording of sensors data as well as adjustment of pump speed and gas injection parameters.

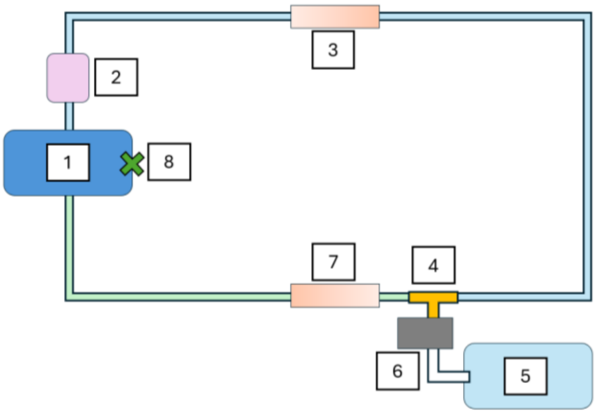

Fig. 3. Experimental setup scheme. (1) water tank, (2) degasser, (3) orifice for water measurement, (4) gas nozzle, (5) compressor, (6) gas flow meter, (7) orifice for air-water mixture measurement, (8) thermometer.

2.2 Orifice description

For the experimental tests, an ISA 1932 nozzle made of stainless steel, compliant with the PN-EN ISO 5167-3:2005 standard, was used. It was welded into a thick-walled pipe housing with an internal diameter of 50 mm and a length of 300 mm, equipped with DN50 mounting flanges, thus forming an integrated measurement module (Fig. 4).

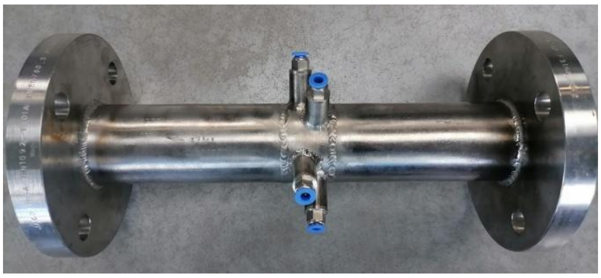

Fig. 4. View of the measurement module with the welded ISA 1932 nozzle.

The module includes, two pairs of corner pressure tapping holes, each with a diameter of 3 mm, offset from each other by an angle of 90°. For design and manufacturing reasons, for each pair, there is an angular offset of 20° between the impulse holes (on the inlet and outlet side). To measure the differential pressure before and after the nozzle, the holes were connected in pairs, allowing the determination of an average pressure from two points (on the positive and negative pressure side) located 90° apart.

2.3 Data acquisition and instrumentation

To record and archive the experimental results, a computer-based data acquisition system was built, allowing the collection of measurement signals from the flow meter and the differential pressure transmitter connected to the tested ISA 1932 nozzle, installed in the test rig.

The differential pressure across the nozzle was measured using an intelligent differential pressure transmitter (model APR-2000/ALW), programmed for a measurement range of Δp = 200 kPa with a 4–20 mA current output signal, at a time constant of t = 4s. The transmitter is characterized by a maximum measurement error of 0.075% within the specified in the experiment range.

Flow parameters (signals from the flow meter and the differential pressure transmitter) were recorded using SANWA 5000 multimeters connected to the PC-based acquisition system via an RS232 interface. The computer was equipped with PC Link Plus software, which, allowed acquisition of measurement data with a sampling interval of Δt = 3 s

On the described test rig, measurements were performed for each tested constriction and nozzle at selected volumetric flow rates q_v up to approximately 35 m³/h. The measurements were performed for a stabilized water flow, recording series of observations. Each series was averaged over approximately 100 individual samples. The volumetric flow rate in the measurement system was determined using a Promag 400 electromagnetic flow meter, operating over the range q_v = 0…40.0 m³/h with a measurement error limit of 0.5%, a time constant of t = 3 s, and a 4-20 mA current output signal. To supply air for generating the air-water mixture, a BROOKS Instrument 4800 series adjustable mass flow meter was used.

3 Results and discussion

In the conducted tests, the characteristics of two-phase (air-water) flow were measured at two predefined air flow levels. Specifically, two test series were designated: P = 100% (full reference air flow) and P = 50% (half of that reference flow). For series P = 100% the average air mass flow rate was q_{air} = 1.0690 kg/h whereas for P = 50% it was q_{air} = 0.6485 kg/h. In each test series, the air flow was kept constant while the water flow was varied to generate different total mixture flow rates. The results of these experiments are presented in the Figures 5-7.

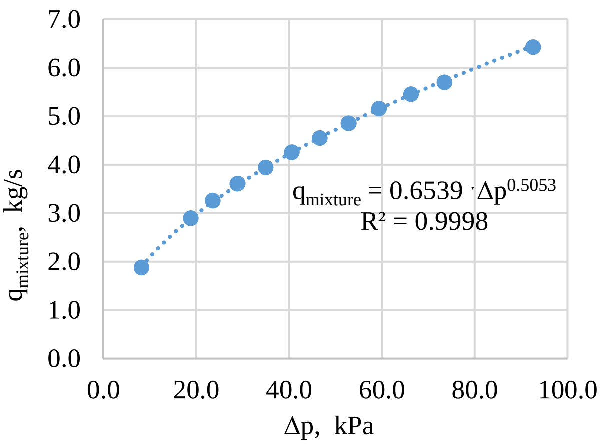

Fig. 5. Flow characteristic $q_{mixture}$ = f(Δp) of the analysed ISA1932 nozzle for two-phase flow (q_{air} = 1.0690 kg/h).

Figure 5 shows the measured flow characteristic of the analyzed ISA 1932 nozzle for the two-phase (air-water) mixture at P = 100%. The volumetric flow rate $q_{mixture}$ of the mixture was varied up to approximately 24 m³/h, while the air mass flow was fixed at q_{air} = 1.0690 kg/h. A power-law fit equation (2) where Δ*p* denotes the pressure difference ($p_1 - p_2$), in kPa is shown in Figure 5 and was drawn through the measured points. The fitted exponent equal to 0.5053, is very close to 0.5, which is consistent with the theoretical square-root dependence of flow rate on pressure drop.

$$q_{mixture} = 0{,}6539 \cdot \Delta p^{0{,}5053} \qquad (2)$$

The fitted curve exhibits a very high coefficient of determination, R^2 = 0.9998, indicating excellent agreement with the experimental data.

Figure 6 shows the corresponding flow characteristic for the case P = 50% (the supplied air flow rate q_{air} = 0.6485 kg/h). The mixture volumetric flow rate $q_{mixture}$ was varied in similar manner. The fitted trend curve described by equation (3) was drawn through the measurement points in Figure 6, where again Δ*p* denotes the pressure difference ($p_1 - p_2$).

$$q_{mixture} = 0{,}6603 \cdot \Delta p^{0{,}5058} \qquad (3)$$

This fit has a coefficient of determination R^2 = 0.9999. The exponent remains essentially unchanged (0.5058 vs. 0.5053), indicating the same underlying flow behaviour. The slightly higher coefficient (0.6603 vs. 0.6539) suggests a marginally higher volumetric flow rate for a given Δp when the air content is lower, possibly due to the higher effective density of the mixture.

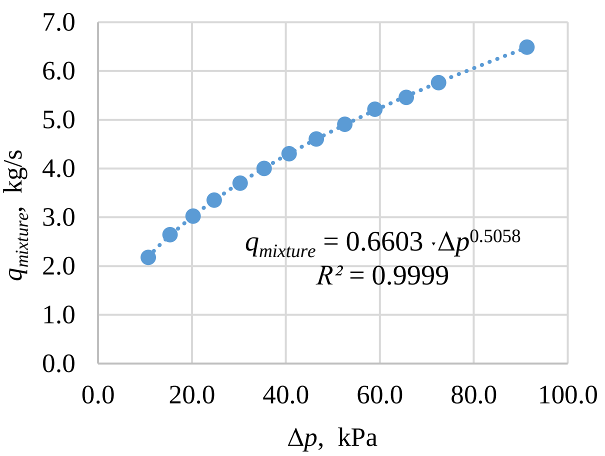

Fig. 6. Flow characteristic $q_{mixture}$ = f(Δ*p*) of the tested ISA1932 nozzle for two-phase flow (q_{air} = 0.6485 kg/h).

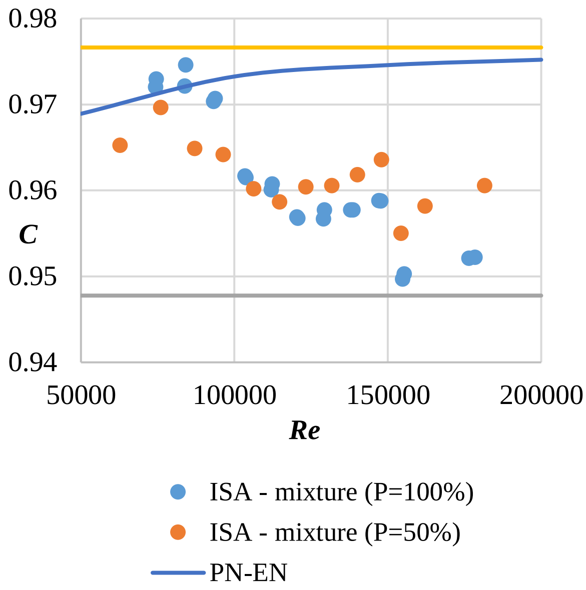

Fig. 7. Discharge coefficient *C* = *f*(*Re*) for the tested ISA1932 nozzle under two analyzed test series P=100% and P=50%.

Figure 7 presents the discharge coefficient *C* as a function of the Reynolds number (Re) for the two-phase mixture under both test series conditions (P = 100% and P = 50%) with the range 50000 ≤ Re ≤ 200000. The experimental *C* values are plotted as points. Two horizontal lines define a tolerance band of ± 1.5% around the mean discharge coefficient C_{avg} = 0.9622, determined over the tested Reynolds number range. For the reference, the standard discharge coefficient curve for a single phase water case *C* = f(*Re*) through an ISA 1932 nozzle, according to PN-EN ISO 5167-3 standard is plotted in Figure 7 as a continuous curve. The measured two-phase data lie very close to the standard single-phase curve with all points falling within the ±1.5% tolerance band, implying that entrained air has little effect on the discharge coefficient. The average coefficient C_{avg} = 0.9622 is slightly below the nominal value 0.975 often reported for this nozzle type, reflecting minor two-phase effects and experimental uncertainty. The near-constant *C* value across the examined Reynolds number range indicates a stable, fully turbulent flow regime. These results demonstrate that, under the tested conditions, the two-phase air–water mixtures behaves essentially identically to single-phase water flow in terms of its passage through the nozzle.

4 Conclusions

ISA1932 nozzles are more difficult to manufacture and install in a pipeline compared to other standardized differential-pressure elements. However, they provide higher measurement accuracy, especially for small constriction ratios, because the influence of pipe roughness is negligible and concerns about the sharpness of the inlet edge are eliminated.

The ISA1932 nozzle profile, owing to its gradual cross-section taper, prevents flow separation from the wall. Consequently, for the same throat diameter and the same volumetric flow rate of the analysed fluid, the permanent pressure loss introduced by the nozzle is lower than that observed with a standard orifice plate. Under operating conditions the ISA1932 nozzle is therefore a more robust measuring device than an orifice plate, since contamination of the nozzle typically has a less adverse effect on measurement accuracy.

Based on the flow measurements conducted on the test rig it can be concluded that the tested ISA1932 nozzle can serve as an effective measuring device for two-phase (water-air) flows within the investigated Reynolds number range ($50000 \le Re \le 200000$), provided an asymmetric tolerance band around the standardized discharge coefficient $C_{PN\text{-}EN}$ (+0,5% / -2,5%) with a mass flow rate $q_{air} \le 1$ kg/h of air supplied to the water flow.

Acknowledgements
The scientific research presented in this paper was carried out under the grant ‘Methodology for assessing the suitability of selected differential pressure flowmeters for two-phase liquid-gas measurements’, obtained in the Polish Metrology programme (PM/SP/0020/2021/). This work was also co-financed by the Ministry of Science and Higher Education (AGH grant No. 16.16.210.476).

References

1. P. Dziubiński, J. Prywer, Mechanika Płynów Wielofazowych, (Wydawnictwo WNT, Warszawa, 2018)
2. G. Falcone, G. F. Hewitt, C. Alimonti, Multiphase flow metering: principles and applications (Elsevier, Amsterdam, 2009)
3. E. J. Mohamad, et al., Measurement and analysis of water/oil multiphase flow using Electrical Capacitance Tomography sensor, Flow Meas. Instrum. 47 62–70, (2016)
4. R. L. Powell, Experimental techniques for multiphase flows, Phys. Fluids. 20 (2008)
5. C.T. Crowe, & C.T. Crowe (Eds.)., Multiphase Flow Handbook (1st ed.). (CRC Press, 2005)
6. Rolls-Royce, The Jet Engine. 5th Edition, (Rolls-Royce, Derby, 2005)
7. H. Pineda-Pérez, T. Kim, E. Pereyra, N. Ratkovich, CFD modeling of air and highly viscous liquid two-phase slug flow in horizontal pipes, Chemical Engineering Research and Design, Volume 136, (2018)
8. C. E Brennen., Fundamentals of Multiphase Flow, (Cambridge University Press, Cambridge, 2013)
9. A. Neogi, H. K. Mohanta, P. C. Sande, Particle image velocimetry investigations on multiphase flow in fluidized beds: A review, Flow Measurement and Instrumentation, Volume 89, (2023)
10. E. Åbro, G.A. Johansen, Improved void fraction determination by means of multibeam gamma-ray attenuation measurements. Flow Measurement and Instrumentation 10, (1999)
11. R. Hanus, M. Zych, V. Mosorov, A. Golijanek-Jędrzejczyk, M. Jaszczur, A. Andrusziewicz, Metrology and Measurement Systems, Vol. 28 (2021)
12. C. Tan, Y. Yuan, X. Dong, F. Dong,. Oil–water two-phase flow measurement with combined ultrasonic transducer and electrical sensors. Measurement Science and Technology 27, (2016)
13. Y. Faraj, M. Wang, J. Jia, Q. Wang, C. G. Xie, G. Oddie and C. Qiu 2015 Measurement of vertical oil-in-water two-phase flow using dual-modality ERT–EMF system Flow Meas. Instrum. 46 255–61
14. M. Reader-Harris, Introduction and History. In: Orifice Plates and Venturi Tubes. Experimental Fluid Mechanics. (Springer, Cham, 2015).
15. D.P. Chakrabarti, G. Das, P.K. Das, LIQUID-LIQUID TWO-PHASE FLOW THROUGH AN ORIFICE. Chemical Engineering Communications 196, 1117–1129 (2009)
16. A.R.W. Hall, M.J. Reader-Harris Use of Venturi meters in multiphase flow measurement. (Proceedings of 17th North Sea Flow Meas Workshop, Norway, 1999)
17. S. Pirouzpanah, M. Çevik, G.L. Morrison Multiphase flow measurements using coupled slotted orifice plate and swirl flow meter. Flow Measurement and Instrumentation 40, 157–161, (2014)
18. Campos, S.R.V., Baliño, J.L., Slobodcicov, I., Filho, D.F., Paz, E.F., Orifice plate meter field performance: Formulation and validation in multiphase flow conditions. Experimental Thermal and Fluid Science 58, 93–104 (2014)