IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Instrumentation Mesure Métrologie
Vol. 23, No. 4, August, 2024, pp. 277-285
Journal homepage: http://iieta.org/journals/i2m

Ultrasonic Spike Signal Analysis for Subcooled Boiling Condensation Measurement

Nguyen Tat Thang

Department of Computer Science, Faculty of Information Technology, Posts and Telecommunications Institute of Technology, Hanoi 10000, Vietnam

Corresponding Author Email: thangnt@ptit.edu.vn

https://doi.org/10.18280/i2m.230403

Received: 10 June 2024
Revised: 6 August 2024
Accepted: 13 August 2024
Available online: 23 August 2024

Keywords:
ultrasonic velocity profile method, UVP, spike signal, condensation, subcooled boiling, measurement uncertainty

ABSTRACT

Condensation is a key factor in subcooled boiling, significantly affecting heat and mass transfer, which are critical in many industrial processes. In a previous study, we successfully obtained the condensation rate - the collapsing speed of vapor bubbles during subcooled boiling using the ultrasonic velocity profile method - UVP method, employing two primary ultrasonic frequencies. The ultrasonic sensor was driven by sinusoidal electrical burst signals, also called tone-bursts, with a specified center frequency. This study examines the application of spike excitation signals within the same method. Spike signals, commonly produced by pulsers, i.e. pulse generators, in the ultrasonic testing field, offer the potential to enhance the accuracy of the UVP method while can reduce the cost of the measurement system. Our investigation involved measuring and analyzing ultrasonic echoes in water under two conditions: ambient temperature and boiling. Subsequently, these signals were applied to measure air-water adiabatic bubbly flow, and the measurement accuracy was validated. Finally, subcooled boiling flow measurements were performed, and the associated uncertainties were thoroughly analyzed.

1. INTRODUCTION

Boiling bubbly flow is a common flow phenomenon in various industrial and engineering systems [1, 2], such as boilers, heat exchangers, and boiling water reactors in nuclear engineering. The two-phase mixture of liquid and vapor bubbles is often employed to efficiently remove generated heat, then to generate power in these systems. Subcooled boiling happens when the bulk liquid temperature remains below the saturation point, while the liquid near the heated surface reaches boiling, leading to the formation of vapor bubbles. These bubbles detach, come into the bulk liquid, where they undergo condensation [3-5]. The rate at which the vapor within bubbles condenses is a crucial parameter in understanding subcooled boiling. For instance, it plays a key role in the analysis of interfacial condensation heat transfer [6]. The condensation rate significantly influences the heat and mass exchange between the vapor and liquid phases, thus directly impacting the distribution of void fraction defined as the proportion of vapor volume relative to the total flow volume in a two-phase flow [7, 8]. Void fraction is particularly important in processes like nuclear reactor operation, where it affects reactor kinetics and, consequently, the power of the reactor core. Given its significance, void fraction is a critical factor in ensuring nuclear reactor safety. Although subcooled boiling and condensation have been extensively studied over the past few decades, much further research is still required due to the complex nature of these phenomena. There is still lack of detailed understanding, and hence accurate prediction/calculation of the phenomenon. Numerical studies depend heavily on experimental data for model validation and the development of closure correlations. Presently, the heat transfer coefficient correlations used in many computational models are based on experimental data obtained under limited flow conditions, such as specific ranges of bubble size, pressure, and temperature. Therefore, the experimental measurement of the condensation rate in subcooled boiling bubbly flows remains a topic of important interest.

Past experimental studies of subcooled boiling have primarily been carried out using optical visualization techniques [9-14]. Additionally, other methods, such as interferometry [11] and wire mesh tomography - WMT [15], have been utilized. However, optical and interferometric approaches necessitate the use of specially-designed viewing windows, which can be particularly challenging to implement under high-temperature or high-pressure conditions. It is tough to apply these methods to measure systems already in operation [10]. Moreover, these techniques often focus on observing either individual bubbles or a small number of bubbles to prevent issues like bubble overlap in the viewing window. Unlike optical methods, WMT does not require optical windows and is suitable for conditions with a high void fraction [15]. However, its sensor, i.e. the wire mesh sensor - WMS, is placed in the flow field. Its effects, such as the noticeable fragmentation of bubbles caused by the wire mesh, require careful consideration. As a result, the development of new measurement techniques that can address these limitations is still of great importance.

The UVP method has become a valuable technique for visualizing the spatio-temporal velocity distribution in fluid mechanics [16]. This approach involves the use of an ultrasonic sensor, i.e. ultrasonic transducer or TDX for short, which emits ultrasound waves and captures the echo signals reflected from the flow field along a specified measurement line or the sound propagation path - the sound path. The received wave data is recorded in a spatio-temporal format, and the velocity distribution is determined by analyzing the stored wave data. Various signal settings and digital processing techniques are applied to perform the analysis, enabling the calculation of instantaneous velocity profiles along the sound path. The conventional UVP systems typically employ repetition pulsed Doppler signal processing [16]. UVP measurements of liquid flows usually require the introduction of seeding micro-particles acting as ultrasonic reflectors into the fluid, especially when natural reflectors are insufficient. The use of the UVP method for measuring two-phase flows has also gained significant research interest.

Aritomi et al. [17] pioneered the use of the UVP method to measure air-water bubbly flow within a vertical channel. In such flows, ultrasound is reflected by both the seeding particles and the surfaces of the bubbles. The velocity profile includes the velocity of bubble surfaces whenever the surfaces intersect the measurement line - the ultrasonic beam and reflect the ultrasound. It's important to note that the velocity of a bubble's surface should coincide with the bubble's velocity, i.e., the bubble centroid velocity, assuming that the bubble's shape and size remain unchanged during motion. The UVP method has also been employed in studies measuring boiling bubbly flows [18-20]. Applications to high-temperature flows have been successfully executed as well [21]. For two-phase flow, beside the conventional UVP method, the multiwave UVP method was developed [22] to measure the velocity profiles of each phase (liquid and bubbles) along a single measurement line. This method involves generating two ultrasonic frequencies simultaneously at the same location, allowing for concurrent measurement of liquid and bubble velocities. Signal processing techniques such as the pulsed Doppler method [22] or the ultrasonic time domain cross-correlation (UTDC) method [23] are utilized in this approach. Experimental studies using the multiwave UVP method to measure air-water bubbly flow have demonstrated its capabilities. The UVP method enables non-intrusive, non-contact measurements without the need for optical windows, as ultrasound can penetrate various materials. It can also measure flows in extreme industrial conditions. Thus, applying the UVP method to determine condensation rates is of great interest.

The UVP sensor's piezo-electric cell generates ultrasound when driven by an electrical excitation signal [24]. The Doppler method traditionally employs a sinusoidal tone-burst signal, which is generated by a tone-burst pulser to operate a narrow-band ultrasonic sensor at a specific ultrasonic frequency - the center frequency [25]. These tone-burst pulsers are engineered to produce signals with a defined number of wave cycles and a precise frequency. The design and build of tone-burst pulsers are often complex, and they are primarily used for specialized applications, such as conventional UVP measurements and medical ultrasound systems, making them less commonly available and contributing to the high cost of commercial UVP systems. In contrast, electrical spike signals, commonly used in the non-destructive testing (NDT) industry, have a naturally wideband frequency spectrum. Originally, these signals have been paired with wideband signal processing techniques like the UTDC method rather than the Doppler method. Spike signals are shorter pulses compared to sinusoidal signals, enabling higher spatial-resolution measurements. Moreover, spike pulser circuits are simple to design and can be implemented at a lower cost [26]. Therefore, spike pulsers are relatively inexpensive. The use of spike excitation in Doppler UVP measurements, particularly in Doppler multiwave UVP measurements, is of considerable interest and has been executed.

In a previous study [27], we measured the condensation rate in subcooled boiling using the UVP method, where the electrical excitation signal utilized was of the tone-burst type. The uncertainty of the results obtained was examined, and the newly developed method was established. As highlighted in a recent review of experimental studies on condensation in subcooled boiling [28], besides the widely recognized intrusive WMT method [15], visualization techniques based on UVP [27] have gained significant interest. While non-intrusive optical visualization methods [29] continue to be valuable tools in the experimental study of condensation in subcooled boiling, their industrial application faces challenges due to inherent limitations that includes the requirement of optical windows.

In this study, we explore the application of spike excitation signals [30] to the proposed method [27] for measuring condensation. As indicated in the study [30], the cost of hardware can be optimized when using spike pulser-receivers. Additionally, since spike signals are shorter in duration compared to burst-type signals, the accuracy of condensation measurements can be enhanced. We employed budget spike pulsers from the same system used [30]. The investigation followed this procedure: first, ultrasonic reflected signals, generated using the spike excitation signal, in water at both ambient and boiling temperatures were measured and analyzed. The signal's characteristics were clarified. The spike signal was then adapted for measuring the air-water interface to obtain the condensation rate in adiabatic bubbly flow in a vertical direction. The accuracy of the measurements was experimentally validated, i.e. zero condensation rate was obtained as predicted. Subsequently, we conducted measurements of subcooled boiling in a water column and analyzed the results. The accuracy of the received condensation rate in these measurements was confirmed, and the uncertainty of the measurements was further examined. As a result, the spike measurement system demonstrated high utility in both laboratory settings and industrial applications related to subcooled boiling. Moreover, it can be custom-built at a reasonable cost.

2. BASICS OF UVP METHOD

The UVP method is schematically represented in Figure 1 [31]. The velocity of seeding particles moving within the flow field is determined using the Doppler effect. In this method, the TDX emits a series of ultrasonic pulses into the flow at a pulse repetition frequency F_{prf}. Immediately after each pulse is emitted, the TDX switches to receive mode, capturing echo signals from distances (or depths) increasing with the propagation of the ultrasonic pulse, starting from the TDX surface onward, along the measurement line. The maximum depth from which an echo signal can be captured corresponds to the maximum time allowed for the receiving mode of the pulser/receiver before the next pulse is emitted. As depicted in Figure 1, when the sampling time $t_{sample\text{-}n}$ changes, it determines the specific positions along a velocity profile where fluid velocity is calculated. The echo signals from these positions are extracted from the entire dataset. The Doppler shift frequency f_d for each position is determined by digitally processing the echo signal at that location. This allows for the calculation of fluid velocity at each specified location, resulting in a complete velocity profile of the flow. For a more in-depth understanding of the UVP method, references such as [16, 24-26] are recommended.

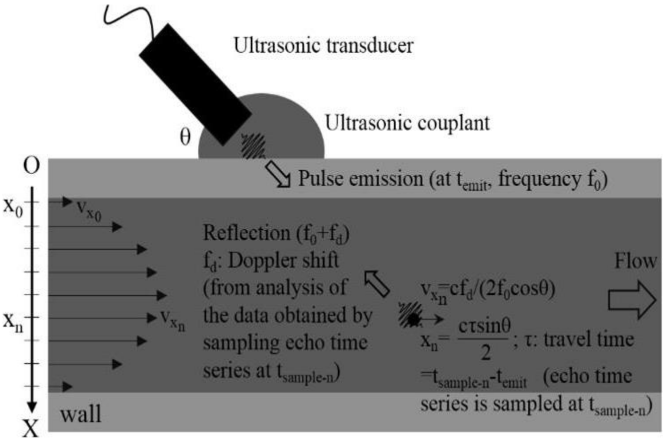


Figure 1. Basics of UVP method [31]

Typically, the electrical signal used to excite the ultrasonic sensor for emitting pulses is of the tone-burst type, characterized by a clearly defined frequency. However, when spike pulser/receivers (P/Rs) are employed, the signal type changes to a spike. The application of spike signals for measuring velocity profiles in both single-phase and two-phase flows at ambient and boiling temperatures has been explored [20, 32]. A key factor influencing the characteristics of the excitation pulse is the signal's damping, which refers to the decrease in pulse amplitude over time. The next chapters will present detailed measurements and analyses of the electrical excitation signal with varying damping parameters of the P/Rs, along with the application of spike signals in measuring condensation during subcooled boiling.

3. CHARACTERISTICS OF SPIKE SIGNAL IN WATER AT AMBIENT TEMPERATURE AND SUBCOOLED BOILING CONDITIONS

3.1 Theoretical spike

A theoretical (negative) spike can be presented by a voltage $V_i(t)$ varying with time as described in Eq. (1) below [30]:

$$V_i(t)=\begin{cases} 0 & t\le 0 \\ -V_\infty\left[1-\exp(-\alpha_1 t)\right] & 0\le t\le t_0 \\ -V_0\exp\left[-\alpha_2(t-t_0)\right] & t\ge t_0 \end{cases} \quad (1)$$

where, $V_\infty = V_0/(1-e^{-\alpha_1 t_0})$. The parameters t_0, α_1, α_2 and V_0 show the amplitude, rise and fall characteristics of the spike. An example of a spike, negative in this case, is depicted in Figure 2.

Additional information on spike signals can be found, for example, in reference [30].

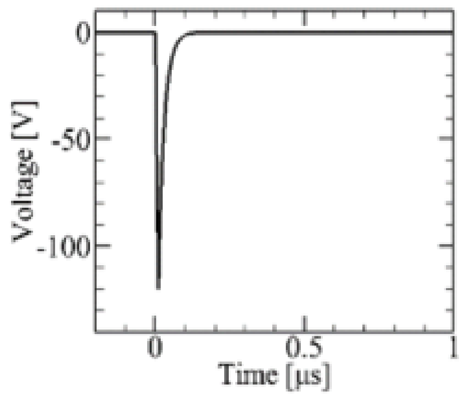


Figure 2. A negative spike calculated using Eq. (1) [31]

3.2 Characteristics of reflected ultrasonic signal

Numerical simulations can be utilized to assess the correlation between the excitation signals and the resulting reflected ultrasonic signals [33, 34]. In this study, experimental measurements were conducted at two frequencies: 2 MHz and 8 MHz. The 2 MHz frequency is commonly employed for measuring the bubbles, while the 8 MHz frequency is used for the liquid. Figure 3 [30] presents a schematic diagram of the experimental setup used to measure the electrical excitation spike and the corresponding ultrasonic signal reflected from seeding particles in water.

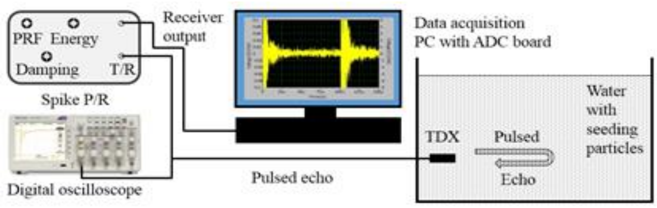


Figure 3. A schematic diagram of the experimental setup used to measure excitation spikes and ultrasound reflected from seeding particles in water [30]

As illustrated in Figure 3, a spike pulser/receiver DPR300 from JSR Ultrasonics Co. Ltd. is utilized, operating in pulsed echo mode in which the cycle pulse emission/echo reception is periodically repeated. In this configuration, TDXs from Japan Probe Co. Ltd., with center frequencies of 2 MHz and 8 MHz, are employed to emit ultrasonic pulses. The same TDXs are responsible for receiving the reflected signal for each emitted pulse. Both the PRF - Pulse Repetition Frequency and Energy controls are kept constant, while the damping parameter is adjusted to examine its impact. The excitation spikes are captured using a digital oscilloscope from HAMEG Instrument Co. Ltd. as shown in Figure 3. Due to the challenges of operating the oscilloscope and TDX simultaneously, the excitation spike from the P/R was measured in advance by the oscilloscope. Subsequently, the oscilloscope was disconnected, allowing the TDX to be controlled by the P/R to emit and receive ultrasound. The received reflected ultrasonic signals are transmitted from the P/R output to a computer via an ADC board from National Instrument Co. Ltd. and recorded using a LabView package for the acquisition of digitized signal. The measurement conditions are summarized in Table 1.

Table 1. Experimental conditions and setup for recording spike-excitation reflected ultrasonic signals at room temperature

Parameters and Units	Value
PRF [Hz]	5000
Damping resistance R_d [Ω]	331 (max.), 59 (moderate) and 30 (min.)
Sampling rate (oscilloscope) [GHz]	2
Sampling rate (ADC board) [MHz]	100
Center frequencies of the multiwave TDX [MHz]	2 and 8
Water temperature [℃]	23

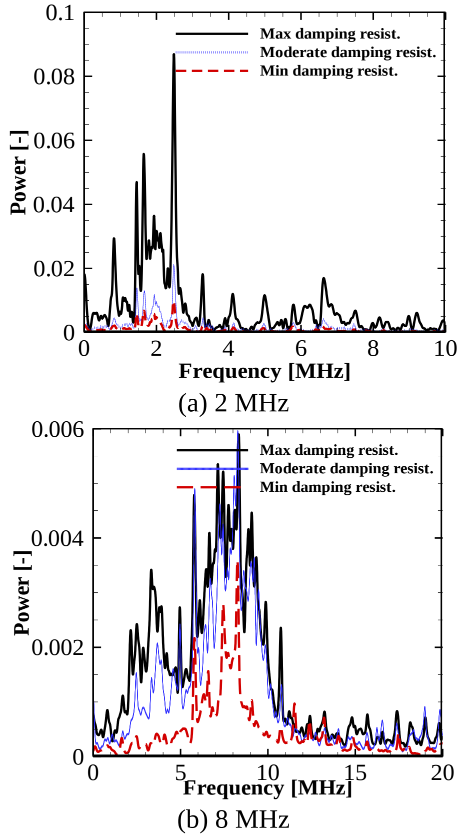


Figure 4. Frequency spectral of the reflected ultrasonic signal in water at room temperature

It is well established [30] that the behavior of a spike is primarily determined by the damping, specifically i.e. how fast the spike's amplitude decreases. Consequently, the reflected ultrasonic sound was analyzed under varying R_d of the damping resistor of the pulser (maximum, moderate, and minimum) to identify the optimal damping setting, as demonstrated below.

Figure 4 illustrates the analysis results of the measured reflected ultrasonic signal for 2 MHz (a) and 8 MHz (b) frequencies. The figure shows that with low damping (i.e., high R_d at the pulser circuit's resistor [30]), the Signal-to-Noise Ratio - SNR of the reflected signals at 2 MHz and 8 MHz frequencies improves significantly. As a result, it becomes feasible to measure bubble interface velocity and liquid velocity using the UVP method with spike excitation. Initial tests to measure interface velocity to calculate the condensation rate will be conducted on air-water bubbly flow, and the accuracy of these measurements will be evaluated based on the velocity profiles of the bubbles' top and bottom interfaces. This evaluation will be discussed in the following section.

Similarly, we conducted measurement and analysis of the reflected ultrasonic signal under subcooled boiling conditions. The experimental conditions are detailed in Table 2.

Table 2. Experimental conditions and setup for measuring spike-excitation reflected ultrasonic signals under subcooled boiling conditions

Parameters and Units	Value
PRF [Hz]	5000
Damping resistance R_d [Ω]	331 (max.), 59 (moderate) and 30 (min.)
Sampling rate (oscilloscope) [GHz]	2
Sampling rate (ADC board) [MHz]	100
Center frequencies of the multiwave TDX [MHz]	2 and 8
Subcooling temperature [℃]	1
Water temperature at the measurement section [℃]	100

The results of the analysis of the measured reflected ultrasonic signal are presented in Figure 5 for 2 MHz (a) and 8 MHz (b) frequencies. As illustrated, it is clearly confirmed that under low damping conditions of the pulser (i.e., high R_d of the pulser circuit's resistor), the SNR of the echo signals at 2 MHz and 8 MHz frequencies increases considerably in subcooled boiling conditions. Consequently, measuring the velocity of the bubble interface using the UVP method with spike excitation is also feasible in subcooled boiling. Therefore, test measurements will be conducted for subcooled boiling with condensing vapor bubbles, and the accuracy of these measurements will be assessed based on the velocity profiles of the top and bottom interfaces of the condensing bubbles. This evaluation will be discussed in the next section.

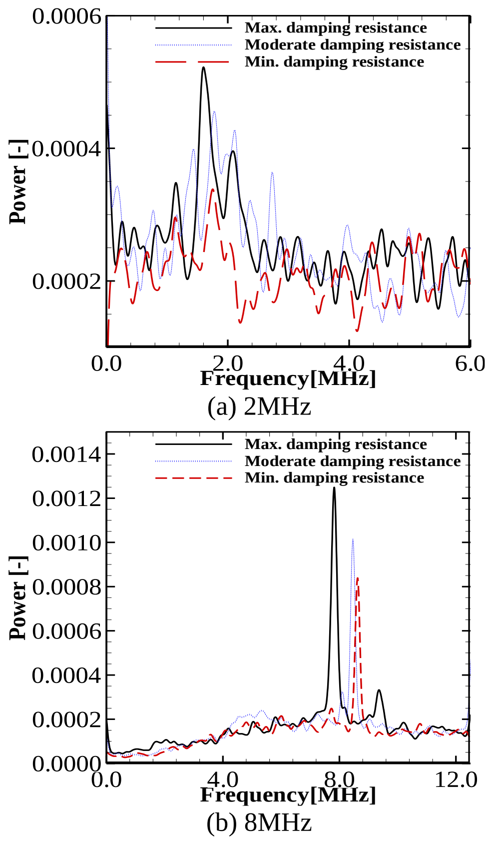


Figure 5. Frequency spectral of the reflected ultrasonic signal under subcooled boiling conditions

4. INTERFACE VELOCITY MEASUREMENT OF AIR BUBBLES IN BUBBLY FLOW AT ROOM TEMPERATURE

The experimental setup for the measurement of bubble interface in air-water two-phase bubbly flow is shown in Figure 6.

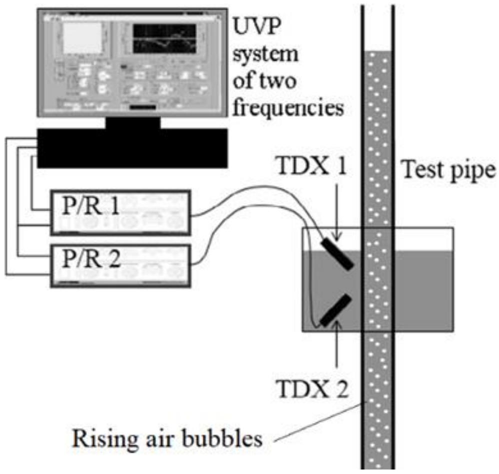


Figure 6. Experimental setup of air-water two-phase bubbly flow measurement

The experimental setup is depicted in Figure 6. The measurement section and the arrangement of the TDXs are shown Figure 7. Air-water bubbly flow was produced within a vertical pipe with an inner diameter (I.D.) of 50 mm. Air bubbles were generated at the bottom of the pipe. Based on the analysis of the bubble images, the bubbles had an average diameter of approximately 5 mm, approximating a spherical shape. The measurement section was enclosed within a water box, with two ultrasonic sensors placed inside, as shown in Figure 6. The water served as an ultrasonic couplant between the sensors and the pipe wall and was also used to remove the distortion in the bubble images caused by the curved shape of the pipe wall. Proper images of the flow field were checked carefully and confirmed.

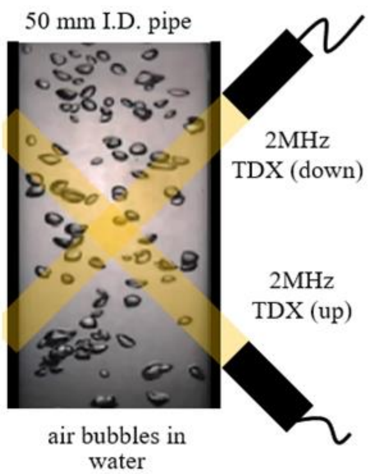


Figure 7. A schematic diagram illustrating the arrangement of the TDXs for measuring air-water bubbly flow in a vertical round tube

Measurements were conducted at atmospheric pressure and room temperature. As illustrated in the figures, two 2 MHz TDXs were utilized in the proposed method to measure condensation rate [27]. The higher sensor looks downward to measure the velocity of the top interface of the air bubbles, while the lower one looks upward to measure the velocity of the bottom interface of bubbles.

Velocity profiles were simultaneously collected by the two sensors using the UVP system with two TDXs (Figure 6). They are then analyzed for the calculation of the condensation rate, which is 0, in this type of flow. The averaged velocity profiles measured by both sensors were calculated and shown in Figure 8. As presented, except for the near-wall region (right) where the data were influenced by the wall, and in some areas where data were insufficient, the average interface velocities measured by the two TDXs are consistent and the same. Consequently, the condensation rate, determined by the difference between the velocities of the upper and lower interfaces of the bubbles [27], is confirmed to be 0. Therefore, in the first case of adiabatic air-water bubbly flow, the validity of the measurement of the condensation rate using the spike signal is well established.

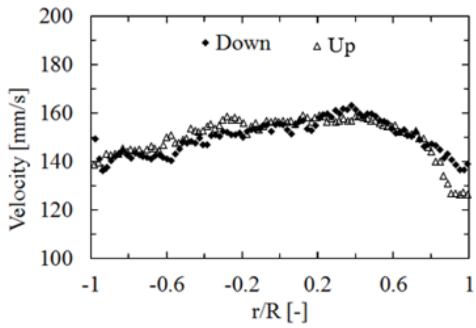


Figure 8. Velocity profiles measured at the top and bottom interfaces of air bubbles in adiabatic bubbly flow of air and water in a vertical round tube

5. INTERFACE VELOCITY MEASUREMENT OF VAPOR BUBBLES IN SUBCOOLED BOILING

The experimental setup for the measurement of bubble interface velocity in subcooled boiling flow is shown in Figure 9.

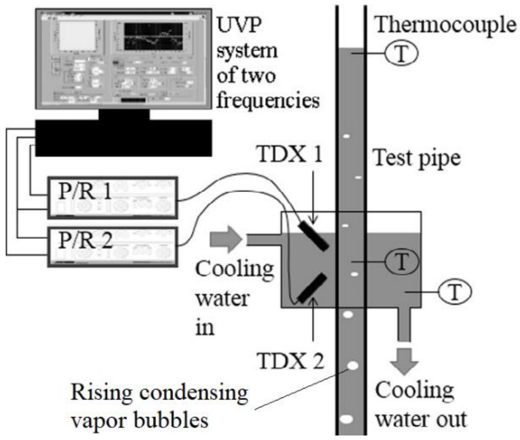


Figure 9. Experimental setup of subcooled boiling measurement

The test section and sensor arrangement used for these measurements in this experiment are identical to those of the adiabatic air-water bubbly flow. And they are shown in Figure 10. Vapor bubbles formed at the bottom of the pipe rise and undergo condensation as they move upward. In this experiment, the liquid was subcooled by 4.6℃. At the measurement position, typically there is single bubble at a time and the average bubble size was approximately 6 mm. The bubbles condense relatively rapidly as they ascend through the subcooled water. This flow condition is well-suited for capturing the condensation rate using either UVP or optical visualization methods.

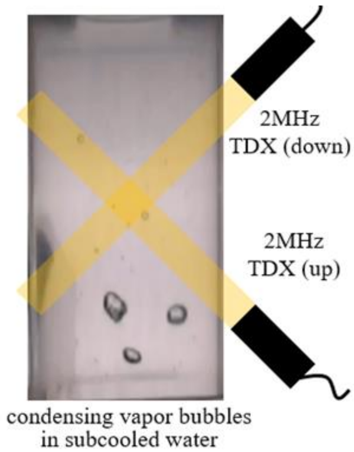


Figure 10. A schematic diagram showing the arrangement of the TDXs for measuring the condensation rate in subcooled boiling

Velocity profiles along the two ultrasonic sound paths were recorded and analyzed. The averaged velocity profiles obtained from the two sensors were computed. Figure 11 displays these profiles. Areas near the wall were excluded from the profiles because the ultrasonic measurement volumes were affected by the pipe wall in these regions. The accuracy of the measured velocity at these volumes was decreased and needs a particular investigation.

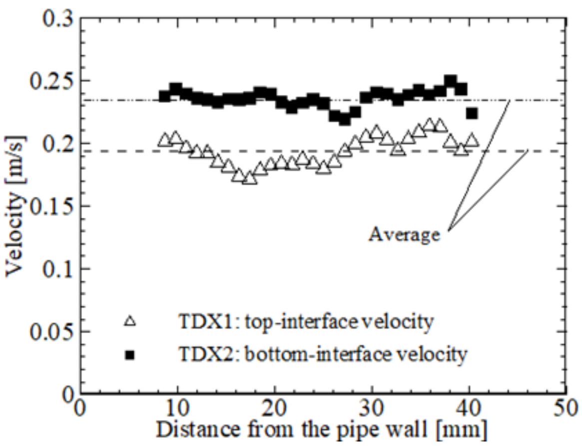


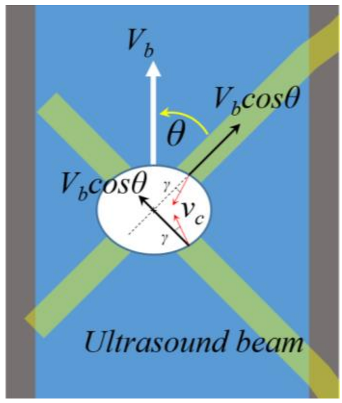
Figure 11. Average velocity profiles for the top and bottom interfaces of condensing bubbles at the measurement position

As shown in Figure 11, the two averaged profiles differ noticeably due to the condensation effect on the velocity of the bubble interface in the sound path. It is straightforward that condensation, i.e. the collapse of vapor bubbles, causes an increase in the velocity of the bottom surface of the bubbles while decreasing the velocity of the top surface. Because the number of bubbles in this experiment is quite small, the average velocity profiles are not perfectly uniform across the pipe cross-section.

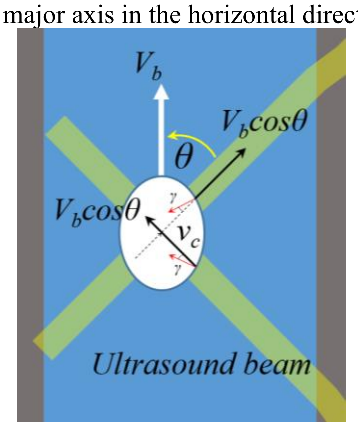
Qualitatively, the results are consistent with those obtained using a sinusoidal excitation signal – tone-burst signal. Consequently, the averaged condensation rate can be derived based on the difference between the two averaged measured velocity profiles as shown in the study [27]. Optical visualization and analysis of digital bubble images, similar to those in the study [27], were also performed. The accuracy of the UVP method was confirmed to be within 5%. Thus, the proposed method for measuring condensation rate using spike excitation signals is initially validated for this flow configuration.

6. THEORETICAL ANALYSIS OF MEASUREMENT UNCERTAINTY

The principle of the proposed method to measure the condensation rate of condensing vapor bubbles in subcooled liquid [27, 35] requires that bubbles have spherical shape. In practice, the bubble shape may deviate from the spherical shape depending on the subcooled boiling conditions etc. In such cases, an additional error will be included in the measured data of the condensation rate by the proposed method. In the original paper [35], measurement error was estimated by comparison with optical method. In this study, an effort to extend the estimation of the error caused by the deviation from the spherical shape has been carried out. In this section, the evaluation of the error is conducted for the general case of the ellipsoidal bubble shape. In fact, in published research of subcooled boiling at industrial conditions, bubble shape can be usually well approximated with ellipsoid.



(a) major axis in the horizontal direction



(b) major axis in the vertical direction

Figure 12. Measurement of the condensation rate of ellipsoidal bubbles using two ultrasonic frequencies

Figure 12 shows the two tendencies of the deviations of vapor bubbles from the spherical shape. Based on Figure 12, the original equations, which are Eqs. (2) and (3) below (or Eqs. (4) and (5) [27]), of the top and bottom velocity of condensing vapor bubbles can be modified as shown in Eqs. (4) and (5) below, respectively.

$$V_{TDX1} = V_b cos\theta - v_c \quad (2)$$

$$V_{TDX2} = -(V_b cos\theta + v_c) \quad (3)$$

$$V_{TDX1} = V_b cos\theta - cos\gamma v_c \quad (4)$$

$$V_{TDX2} = -(V_b cos\theta - cos\gamma v_c) \quad (5)$$

where, V_{TDX1} and V_{TDX2} are the velocities of the top and bottom interfaces of bubbles measured by the two *TDXs*: *TDX1* (downward-looking) and *TDX2* (upward-looking), respectively; V_b is the ascending velocity of the bubble center; v_c is the condensation rate, i.e. the speed of the collapsing of the bubble surface to the bubble center; γ is the angle between the ultrasonic sound path and the normal vector to the bubble interface at the point where the sound path meets the interface as shown in Figure 12. It is obvious that, in the case of spherical bubbles assumed in the study [27], γ reduces to 0 and Eqs. (4) and (5) reduce exactly back to Eqs. (2) and (3) above.

Consequently, from Eqs. (4) and (5), the enhanced equations to calculate the condensation rate v_c in the general case of the vapor bubble shape can be derived as shown in Eq. (6). Eq. (7) below presents the possible range of the variation of the angle γ.

$$vc = \frac{|V_{TDX2}| - |V_{TDX1}|}{2cos\gamma} \quad (6)$$

$$-\pi/4 < \gamma < \pi/4 \quad (7)$$

As the result, compared with the ideal case of assumed spherical bubbles, the relative error caused by the assumption of spherical bubbles can be estimated as shown in Eq. (8).

$$Relative\ error = \frac{(1 - cos\gamma)}{2(1 + cos\gamma)} \times 100\% \quad (8)$$

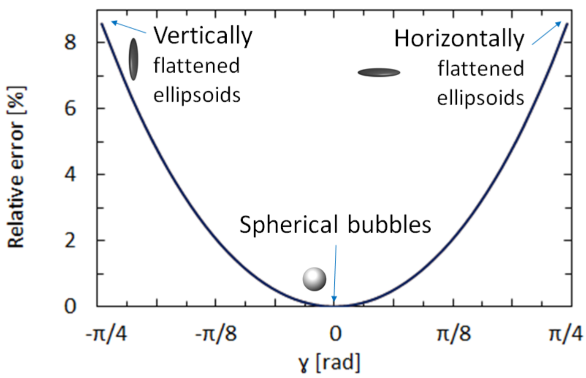


Figure 13. Estimated error caused by the deviation from the assumed spherical shape, i.e. the ellipsoidal shape of condensing vapor bubbles

The error is calculated and plotted in Figure 13. As shown in the figure, the error caused by the deviation from the assumed spherical shape is zero when the angle γ is 0 radian which implies the spherical bubble. There are two limits with a maximum error less than 9% corresponding to the vertically flattened ellipsoids and the horizontally flattened ellipsoids.

7. DISCUSSIONS

Comprehensive experimental investigations of the reflected ultrasonic signal were conducted using spike excitation instead of a tone-burst one, under two conditions of room temperature and subcooled boiling. The results confirm that in both scenarios, the frequency content of the reflected ultrasonic signal significantly increases near the center frequencies of the sensors. This enhancement facilitates the measurement of velocity profiles of fluid flows using the UVP method. The accuracy of the UVP method with spike signal has been thoroughly validated. These additional studies and analyses of the ultrasonic signal generated with spike excitation at both ambient and subcooled boiling temperatures, further confirm the effectiveness of spike excitation signals for various UVP measurements [20, 27, 30, 32].

This study further validates the accuracy of the measurement method by synchronizing the measurement of the top and bottom velocities of air bubbles in adiabatic bubbly flow within a vertical pipe. The velocity of uniformly sized rising air bubbles in ambient temperature bubbly flow was precisely measured using two TDXs positioned in upward and downward directions. The consistency of the measurements in the two directions has significant implications: it confirms that spike excitation is effective with the proposed condensation measurement method; the accuracy of the measurements was strengthened by comparing the velocity of the top surface and that of the bottom surface of air bubbles; and it verifies that the condensation of bubbles in adiabatic bubbly flow is correctly measured as zero. This step is essential to validate the condensation measurement method for adiabatic two-phase flow using spike signals, consistent with the approach using tone-burst signal originally proposed in the study [27].

The measurement of the condensation rate v_c of vapor bubbles in subcooled boiling further indicates that the spike signal is well-suited for the proposed method [27]. In theory, spike signals offer advantages over tone-burst signals, including increased resolution, broader availability, and more cost-effective hardware. The accuracy of the measured condensation rate using spike excitation has been thoroughly validated for the configuration and settings of the subcooled boiling experiment in this study. The error of the measurements is limited to within 5% when compared to methods based on optical visualization and analysis of digital images. This result aligns with flow conditions similar to those investigated in the study [27]. It is conclusively confirmed that using spike signal with the proposed method to measure condensation rate v_c can be effectively applied to subcooled boiling conditions. Moreover, the measurement uncertainty for the condensation rate v_c [27] is comparable to that achieved using a tone-burst signal.

It should be noted that the original proposed condensation measurement method [27] assumes that condensing vapor bubbles have spherical shape. In reality, the bubble shape deviates from the assumed shape, an additional measurement error is included. In this study, we have further proposed an evaluation of the measurement error incurred when the bubble shape is not spherical. A theoretical formular to evaluate this error has been successfully derived. It is highly significant to realize that the added error is just less than 9%. As the result, further evaluation and analysis of the theoretical background of the proposed condensation measurement method has been successfully addressed.

8. CONCLUSIONS

The proposed method for measuring the condensation rate in subcooled boiling using spike signal has been thoroughly investigated and reported. The following analyses and conclusions have been established:

- The condensation rate of adiabatic air-water bubbly flow, known in advance to be zero, was accurately measured.
- The measured condensation rate in subcooled boiling was compared with results obtained through optical visualization and analysis of bubble images, confirming the high accuracy of the measurements.
- The developed spike excitation UVP method for condensation measurement combines the strengths of both spike excitation techniques and the auto-correlation pulsed Doppler method. The shorter length of the ultrasonic pulses enhances spatial resolution. Compared to the conventional UVP method, which uses a tone-burst signal typically lasting several wave cycles, the spike signal method offers improved measurement accuracy.
- The error caused by deviations from a spherical shape was theoretically effectively evaluated for ellipsoidal bubbles.
- The advantages of the method have been highlighted, and potential issues related to its application have been discussed.
- This new method holds practical value for studying and monitoring the condensation rate in subcooled flow boiling.

Additionally, using spike excitation can reduce the cost of UVP measurement systems, potentially increasing the popularity of the condensation rate measurement method.

Based on this work, future studies will focus on collecting datasets for various subcooled boiling conditions and flow configurations. The extensive availability of measured data is crucial for contributing to theoretical and numerical studies of subcooled boiling bubbly flow, which is of immense importance in both theoretical research and industrial applications of subcooled boiling flow.

REFERENCES

[1] Ginoux, J.J. (1978). Two-Phase Flows and Heat Transfer with Application to Nuclear Reactor Design Problems. Hemisphere.

[2] Ishii, M., Hibiki, T. (2006). Thermo-Fluid Dynamics of Two-Phase Flow. Springer Science & Business Media.

[3] Lahey, R.T. (1992). Boiling Heat Transfer: Modern Developments and Advances. Elsevier.

[4] Zeitoun, O.M. (1994). Subcooled flow boiling and condensation. Doctoral Dissertation, McMaster University.

[5] Kolev, N.I. (2007). Multiphase Flow Dynamics 2: Thermal and Mechanical Interactions. Springer.

[6] Pan, L.M., Tan, Z.W., Chen, D.Q., Xue, L.C. (2002). Numerical investigation of vapor bubble condensation characteristics of subcooled flow boiling in vertical rectangular channel. Nuclear Engineering and Design, 248: 126-136. https://doi.org/10.1016/j.nucengdes.2012.04.001

[7] Hai, D.N., Khabeev, N.S. (1983). An approach to the thermal problem for a vapor-liquid medium with a bubble structure. Journal of High Temperature, 21: 137-145. http://mi.mathnet.ru/tvt5882.

[8] Nigmatulin, R.I., Khabeev, N.S., Hai, D.N. (1988). Waves in liquids with vapour bubbles. Journal of Fluid Mechanics, 186: 85-117. https://doi.org/10.1017/S0022112088000059

[9] Isenberg, J., Sideman, S. (1970). Direct contact heat transfer with change of phase: Bubble condensation in immiscible liquids. International Journal of Heat and Mass Transfer, 13: 997-1011. https://doi.org/10.1016/0017-9310(70)90166-3

[10] Brucker, G.G., Sparrow, E.M. (1977). Direct contact condensation of steam bubbles in water at high pressure. International Journal of Heat and Mass Transfer, 20: 371-381. https://doi.org/10.1016/0017-9310(77)90158-2

[11] Chen, Y.M., Mayinger, F. (1992). Measurement of heat transfer at the phase interface of condensing bubbles. International Journal of Multiphase Flow, 18: 877-890. https://doi.org/10.1016/0301-9322(92)90065-O

[12] Zeitoun, O., Shoukri, M., Chatoorgoon, V. (1995). Interfacial heat transfer between steam bubbles and subcooled water in vertical upward flow. Journal of Heat Transfer, 117: 402-407. https://doi.org/10.1115/1.2822536

[13] Okawa, T., Kubota, H., Ishida, T. (2007). Simultaneous measurement of void fraction and fundamental bubble parameters in subcooled flow boiling. Nuclear Engineering and Design, 237: 1016-1024. https://doi.org/10.1016/j.nucengdes.2006.12.010

[14] Inaba, N., Watanabe, N., Aritomi, M. (2013). Interfacial heat transfer of condensation bubble with consideration of bubble number distribution in subcooled flow boiling. Journal of Thermal Science and Technology, 8: 74-90. https://doi.org/10.1299/jtst.8.74

[15] Pietruske, H., Prasser, H.M. (2007). Wire-mesh sensors for high-resolving two-phase flow studies at high pressures and temperatures. Flow Measurement and Instrumentation, 18: 87-94. https://doi.org/10.1016/j.flowmeasinst.2007.01.004

[16] Takeda, Y. (1986). Velocity profile measurement by ultrasound Doppler shift method. International Journal of Heat and Fluid Flow, 7: 313-318. https://doi.org/10.1016/0142-727X(86)90011-1

[17] Aritomi, M., Zhou, S., Nakajima, M., Takeda, Y., Mori, M., Yoshioka, Y. (1996). Measurement system of bubbly flow using ultrasonic velocity profile monitor and video data processing unit. Journal of Nuclear Science and Technology, 33: 915-923. https://doi.org/10.1080/18811248.1996.9732033

[18] Ito, D., Kikura, H., Aritomi, M. (2006). Characteristics of echo signal of pulse ultrasound on boiling two-phase flow. In Proceedings of the 5th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, Tokyo, Japan, pp. 35-38.

[19] Ito, D., Kikura, H., Aritomi, M., Mori, M. (2008). Study on ultrasonic velocity profile measurement in vapor-water two-phase flow. In Proceedings of the 6th International Symposium on Ultrasonic Doppler

Methods for Fluid Mechanics and Fluid Engineering, Prague, Czech Republic, pp. 77-80.
[20] Nguyen, T.T., Kikura, H., Murakawa, H., Tsuzuki, N. (2014). Measurement of bubbly two-phase flow in vertical pipe using multiwave ultrasonic pulsed Doppler method and wire mesh tomography. Energy Procedia, 71: 337-351. https://doi.org/10.1016/j.egypro.2014.11.887
[21] Eckert, S., Gerbeth, G., Melnikov, V.I. (2003). Velocity measurements at high temperatures by ultrasound Doppler velocimetry using an acoustic wave guide. Experiments in Fluids, 35: 381-388. https://doi.org/10.1007/s00348-003-0606-0
[22] Murakawa, H., Kikura, H., Aritomi, M. (2005). Application of ultrasonic Doppler method for bubbly flow measurement using two ultrasonic frequencies. Experimental Thermal and Fluid Science, 29: 843-850. https://doi.org/10.1016/j.expthermflusci.2005.03.002
[23] Murakawa, H., Kikura, H., Aritomi, M. (2008). Application of ultrasonic multi-wave method for two-phase bubbly and slug flows. Flow Measurement and Instrumentation, 19: 205-213. https://doi.org/10.1016/j.flowmeasinst.2007.06.010
[24] Takeda, Y. (2012). Ultrasonic Doppler Velocity Profiler for Fluid Flow. Springer.
[25] Evans, D.H., McDicken, W.N. (2000). Doppler Ultrasound: Physics, Instrumentation, and Signal Processing. New York: Wiley, 2nd ed. https://lccn.loc.gov/99033585.
[26] Povey, J.W.M. (1997). Ultrasonic Techniques for Fluids Characterization. Academic Press.
[27] Nguyen, T.T., Tsuzuki, N., Murakawa, H., Duong, N.H., Kikura, H. (2016). Measurement of the condensation rate of vapor bubbles rising upward in subcooled water by using two ultrasonic frequencies. International Journal of Heat and Mass Transfer, 99: 159-169. https://doi.org/10.1016/j.ijheatmasstransfer.2016.03.109
[28] Tang, J., Sun, L., Liu, H., Liu, H., Mo, Z. (2021). Review on direct contact condensation of vapor bubbles in a subcooled liquid. Experimental and Computational Multiphase Flow, 4: 91-112. https://doi:10.1007/s42757-020-0100-4
[29] Wei, M., Li, H., Li, S., Tian, M. (2023). Experimental study on the air-steam bubble condensation characteristics in subcooled water. International Communications in Heat and Mass Transfer, 141: 106570. https://doi.org/10.1016/j.icheatmasstransfer.2022.106570
[30] Nguyen, T.T., Murakawa, H., Tsuzuki, N., Duong, H.N., Kikura, H. (2016). Ultrasonic Doppler velocity profile measurement of single-and two-phase flows using spike excitation. Experimental Techniques, 40: 1235-1248. https://doi.org/10.1007/s40799-016-0123-8
[31] Thang, N.T. (2023). Measurement of bubbly two-phase flow in a vertical pipe using ultrasonic velocity profiler and digital optical imaging. Instrumentation Mesure Métrologie, 22(4): 153-160. https://doi.org/10.18280/i2m.220403
[32] Nguyen, T.T., Murakawa, H., Tsuzuki, N., Kikura, H. (2013). Development of multiwave method using ultrasonic pulse Doppler method for measuring two-phase flow. Journal of the Japanese Society for Experimental Mechanics, 13(3): 277-284. https://doi.org/10.11395/jjsem.13.277
[33] Arnau, A. (2008). Piezoelectric Transducers and Applications. Springer.
[34] San Emeterio, J.L., Ramos, A., Sanz, P.T., Ruíz, A. Azbaid, A. (2004). Modeling NDT piezoelectric ultrasonic transmitters. Ultrasonics, 42(1): 277-281. https://doi.org/10.1016/j.ultras.2004.01.021
[35] Nguyen, T.T. (2016). Study of ultrasonic velocity profiling method on boiling two-phase flow. PhD Thesis, Tokyo Institute of Technology.

NOMENCLATURE

V, v	Velocity, m.s^{-1}
TDX	Transducer (ultrasonic sensor)

Greek symbols

θ	Ultrasonic measurement angle (angle of the ultrasonic sound path measured from the vertical direction), radian or º
γ	Angle between the ultrasonic sound path the normal vector of the interface where the sound path meets the interface, radian or º

Subscripts

1, 2	Two sensors of the condensation rate measurement method
b	bubble
c	condensation