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Fundamental investigation of natural convection induced by vertical heated rod using ultrasound velocity profiler

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Abstract: Natural convection is a fundamental phenomenon observed in various industrial, nuclear energy, power generation, and electronics cooling applications. In nuclear reactors, natural convection plays a crucial role in residual decay heat removal following reactor shutdown incidents or accidents. The design of fuel elements and fuel assemblies significantly influences flow rates, impacting natural circulation. Understanding natural convection requires analysis of the spatiotemporal velocity profile, which provides valuable insights into flow behavior. Therefore, the Ultrasonic Velocity Profiler (UVP) emerges as a suitable tool for observing natural convection flow behavior. However, since sound velocity in a fluid is temperature-dependent, it might affect the accuracy of velocity measurements. Hence, confirming the applicability of UVP becomes essential. In this study, a vertical heated rod with a diameter of 12 mm and a length of 225 mm is immersed at the center of a vertical acrylic pipe with a diameter of 144 mm and a height of 500 mm. The ultrasonic transducer is positioned outside the pipe to enable long-term flow behavior measurement. Utilizing the UVP technique, one-dimensional velocity profile behavior inside the pipe is measured and validated using Particle Image Velocimetry (PIV). Consequently, the spatiotemporal velocity profile is depicted in color scale to comprehend the natural flow behavior induced by a single heater rod.

Keywords: *Natural convection flow, UVP, PIV, heated rod.*

I. INTRODUCTION

The study of natural convection flow holds significant importance across various fields including geophysics, astrophysics, and nuclear engineering, particularly in scenarios such as residual decay heat removal from nuclear fuel during incidents or accidents. Conventionally, natural convection flow arises due to temperature differences and is propelled by buoyancy forces. In nuclear reactors, sufficient distances are maintained between fuel elements to facilitate residual heat removal. Moreover, advanced nuclear power plants incorporate various types of passive cooling systems, such as utilizing cooled water placed atop reactor buildings to remove heat from steam

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generators. Therefore, understanding the efficiency of natural convection flow is crucial for optimizing and verifying safety design systems, with particular interest in the velocity profile of such flows.

Choi et al. [1] reviewed passive heat removal systems in advanced nuclear reactor designs, emphasizing the need to clarify several characteristics of natural convection. Park et al. [2] conduct experiments using a single horizontal heater rod to elucidate large vortex behavior and energy dissipation employing LIF/PIV techniques. Bazoz et al. [3] and Foroozani [4] provided simulations of natural convection incorporating temperature-dependent physical variables. However, these studies focus on short-term observations of natural convection. Furthermore, Computational Fluid Dynamics (CFD) simulations, including turbulence models, require validation using experimental data.

Various measurement techniques such as PIV (Particle Image Velocimetry), PTV (Particle Tracking Velocimetry), and LDA (Laser Doppler Anemometry) have been developed for velocity field measurement based on optical techniques. However, the optical methods require a measurement window. The UVP (Ultrasound Velocity Profiler) method is particularly suitable for flow in narrow gaps compared to optical methods [5-8], as it does not require optical windows for light or laser passage. The UVP system consists of an ultrasonic transducer emitting ultrasound pulses, a pulser/receiver with a high-speed digitizer, and a signal processing algorithm developed using LabVIEW. The transducer diameter can be designed for specific narrow gap distances (e.g., 2 mm). Understanding the spatial and temporal distribution of flow and fluctuations is crucial for investigating local energy transfer in convective heat transfer flows, often referred to as spatiotemporal velocity profiles.

However, the UVP technique faces challenges, such as the dependency of sound speed on the medium's temperature. Therefore, the applicability of UVP for natural convection measurements requires confirmation using alternative methods. In this context, the PIV method is a suitable choice for providing two-dimensional velocity distributions and conducting non-intrusive measurements.

II. EXPERIMENTAL SETUP

1. Experimental apparatus of natural convection

The main test section is the vertical heated rod with a diameter of 12 mm and a length of 225 mm. The heated rod is immersed at the center of a vertical pipe made of transparent acrylic with an inner diameter of 144 mm and a height of 500 mm. The transparent acrylic has a thickness of 3 mm for illumination and image acquisition. The ultrasonic transducer is placed outside of the pipe to measure the long-term flow behavior. The working fluid is water, and its initial temperature is kept at room temperature (27 ^{o}C) with a constant heat flux of 11864 W/m^2. The UVP measurements require the suspension of ultrasonic wave-reflecting particles in the fluid. Nylon powder (d = 80 μm; ρ = 1020 kg/m^3) is dispersed in the working fluid as reflector particles for both UVP and PIV measurements (Fig. 1 and Fig. 2). A high-speed camera records the movement of particles illuminated by a laser sheet. This data allows the analysis of the two-dimensional velocity distribution using the PIV method.

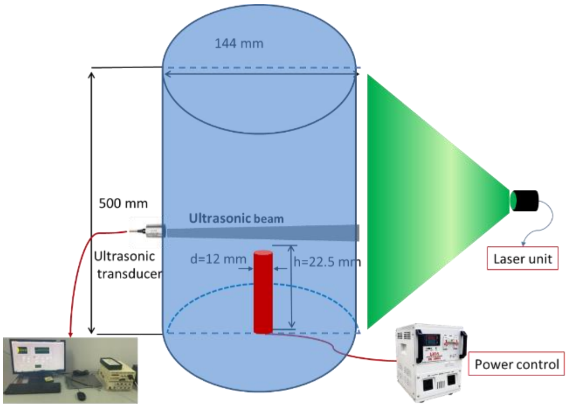

Fig. 1. Sketch of vertical heated rod natural convection and test section for measurement.

2. Rayleigh number

In natural convection, the Rayleigh number is used to be estimate the flow regime. Since the convective flow relates to the heat transfer from the heater rod to the water, the modified Rayleigh number (Ra*) is used to identify the flow regime based on the heat flux density [3]. The heater rod was supplied with power, and the corresponding Rayleigh number typically falls within the range of 10^5-10^9 similar to the conditions of research reactors. The Ra* is calculated as follows:

$$Ra^* = \frac{g\beta q L^4}{\kappa \nu \alpha} \tag{1}$$

Where g is the acceleration due to gravity, β is the thermal coefficient of expansion, q is the heat flux density, L is the characteristic length of the heater rod in the direction of gravity, κ is the thermal conductivity, ν is the kinematic viscosity, α is the thermal diffusivity. Thus, the modified Rayleigh number in our current experiment condition is 1.025×10^8.

3. Principle of UVP technique

The flow behavior in the container is observed using the ultrasound technique. The principle of the UVP method is based on the echography of ultrasound [5, 6]. The ultrasonic pulse is emitted from a transducer and reflected by solid particles suspended in fluids and received with the same transducer. For deriving instantaneous velocity profile, position information is given by a time delay between pulse emission and reception of the echo. The velocity information can be obtained from an instantaneous frequency of the echo at each time instant. The transducer for the velocity measurements was mounted on the outside of the sidewall, and the ultrasonic waves passed through the container wall.

The information of position in each channel is extracted from the time delay T_{PRF} or pulse repetition frequency f_{PRF} $=1/T_{PRF}$ as follows:

$$x = \frac{c \times T_{PRF}}{2} \tag{2}$$

where c is sound speed in the medium.

By analyzing the echo signal such that the instantaneous frequencies at various instants after the emission was computed (called Doppler frequency). The instantaneous local velocity, V(x) is derived from Doppler shift frequency (f_D) at the time and position as:

$$V(x) = \frac{cf_d}{2f_0\cos(\theta)} \tag{3}$$

where f_0 is the basic ultrasonic frequency, θ is inclined angle between ultrasonic sensor and pipe.

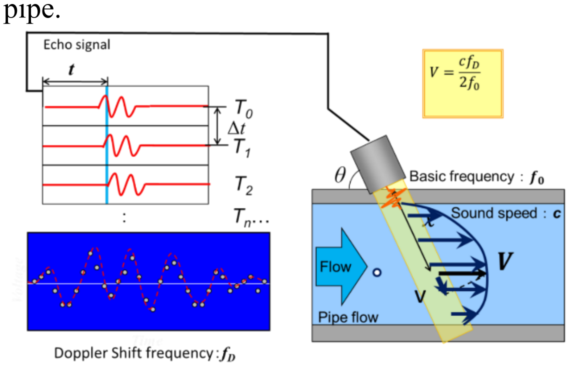

Fig. 2. Principle of Ultrasonic Velocity Profile (UVP)

The UVP utilizes the ultrasonic Doppler frequency reflected on tracer particles for obtaining the velocity. However, it is difficult to compute the Doppler frequency directly by transmitting and receiving of ultrasonic pulses at one time, because the Doppler frequency is much smaller than the basic frequency. Therefore, the UVP requires multiple ultrasonic emissions for obtaining the Doppler shift frequency as shown in Fig. 3. If a tracer particle is moved into the measurement volume at a time, ultrasonic reflected signal is recorded. At the next time step, if the particle moves to Δx in this direction during the time, reflected signal is also recorded, but in different time. These are the signals continuously recorded. If the signals are sampled at this point (red line), the phase change of the signal is recorded as shown in Fig. 3. This frequency is identical to the Doppler frequency. So, Doppler frequency is calculated by the frequency analysis of this wave, and multiple ultrasonic reflected signals are required for analyzing the frequency.

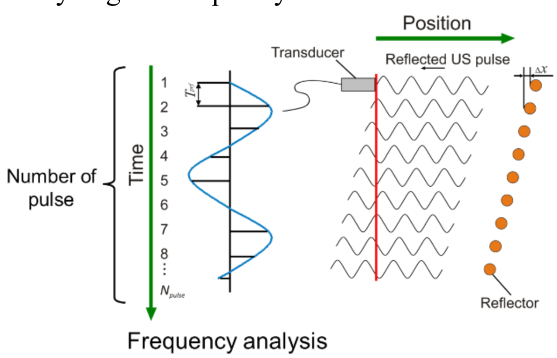

Fig. 3. Principle of detection of Doppler shift frequency using UVP method [5]

The signal processing for Doppler frequency is basically based on the FFT (Fast Fourrier Transform). It is well known that the frequency resolution depends on the sampling frequency and the data length. In this case, sampling frequency is ultrasonic repetition frequency, and the data length depends on the number of pulses. The lesser number of pulses is, the higher time resolution is. Therefore, fewer number of pulses is suitable for higher time resolution. However, it is difficult to reduce the number of pulses because of the frequency resolution. The Auto-correlation approach is the method to calculate the Doppler frequency with the auto-correlation function. In case of the auto-correlation, the frequency can be theoretically obtained by only two pulses. In the Fig. 3, a pulser and receiver is used to emit and receive the ultrasonic waves through same sensor. The received echo signals contains both carrier and shifted signals. The quadrature detection where echo signals are multiplied by sine and cosine components is applied to separate signals. Then low pass filter is used to eliminate the carrier waves. The complex envelope signal z (t) after the low pass filter is explained [5, 6] as following:

$$z(t) = I(t) + jQ(t) \tag{4}$$

where, I (t) and Q (t) are the in-phase signal and the quadrature phase signal with the received signal, respectively. The autocorrelation function Rf is expressed as following:

$$Rf = (T_{PRF}, t) = \int z(t) \times z^*(t - T_{PRF})dt = R_x(T_{PRF}, t) + jR_y(T_{PRF}, t) \tag{5}$$

where, T_{PRF} is the time interval of the pulse emission, z* is the conjugate complex signal of z (t), R_x and R_y are the real and imaginary part of Rf, respectively. The phase shift between consecutive echo signals is expressed as following:

$$\varphi(T_{PRF}, t) = \tan^{-1}\frac{R_x(T_{PRF}, t)}{R_y(T_{PRF}, t)} \tag{6}$$

Doppler shift frequency is estimated as follows:

$$f_D = \frac{1}{2\pi T_{PRF}} \tan^{-1}\frac{R_x(T_{PRF}, t)}{R_y(T_{PRF}, t)} \tag{7}$$

The equipment used for the UVP measurement is in-house development including hardware and software. The UVP system comprises an Ultrasonic transducer (emitting the ultrasound pulse) and the pulser/receiver which has highspeed digitizer and a signal processing algorithm developed by Labview and C++. The signal processing is developed based on the pulse repetition Doppler Shift Frequency. Ultrasonic spike-excitation wave is used for measurement and the basic frequency of ultrasound was 4 MHz using a transducer of 4 mm of effective diameter. The spatial, temporal and velocity resolution of UVP measurement are 0.75 mm, 51 ms, and 0.21 mm/s, respectively. The conditions of UVP measurement are summarized in Table I.

The Particle Image Velocimetry (PIV) method is employed to visualize the two-dimensional velocity distribution, serving to validate the measurements obtained through the UVP technique. A laser sheet, 2 mm thick, is projected from the side wall. This laser sheet passes through an acrylic resin before reaching the fluid. Particles dispersed within the fluid acted as reflectors for both the ultrasound in the UVP method and the laser in the PIV method. Particle images are captured using a camera with a frame rate of 60 frames per second (fps), allowing for the visualization and calculation of the two-dimensional velocity profile using the PIV technique.

Table I. Condition of UVP measurement

Basic frequency	4 MHz
Effective diameter	5 mm
Sound velocity	c = 1500 (m/s) at 27 ºC
Pulse repetition frequency (f_{prf})	800 Hz
Temporal resolution	51 ms
Velocity resolution	0.21 (mm/s)
Chanel distance	0.75 mm
Pulse type	Spike-excitation pulse

III. RESULTS

1. Effect of temperature on the UVP measurement

The natural flow is induced by buoyancy force in which the thermal flume is produced in accordance with difference temperature between heated rod and water. Thus, the different temperature along the US measurement line needs to be estimated. The author [9] used the ANSYS/FLUENT to simulate the flow and temperature distribution of this experimental apparatus. Hence, the difference temperature in US measurement line was ΔT=7 ºC that corresponded the difference of the sound speed [10] in the medium is Δc = 26 m/s. Among the experimental conditions, the error is within the range of 2 % shown in Fig. 4.

$$\frac{\Delta c}{c1}=\frac{c1-c2}{c1}=\frac{26}{1500}\times\%\leq 2\% \qquad (8)$$

On the other hand, in order to confirm the accuracy of velocity profile measurement by using UVP technique, the 2-dimensional velocity distribution by using PIV method is applied. After the 5 minutes (300 s) the velocity profile is measured and synchronized with PIV method. The averaged velocity distribution by using PIV method is showed in Fig. 5. The vertical component of velocity in the direction of the ultrasonic beam that set 5 mm from the top of heater rod is measured. In this setup, the transducer is positioned outside the pipe at a 65 ºC relative to the pipe's axis. The Fig. 6. shows the averaged vertical velocity profile by using UVP. Due to the complicated flow behavior changing in time, the 20 s of averaged velocity is selected for comparison. The comparison showed good agreement between UPV and PIV and the error is estimated around 5 % (Fig. 7.).

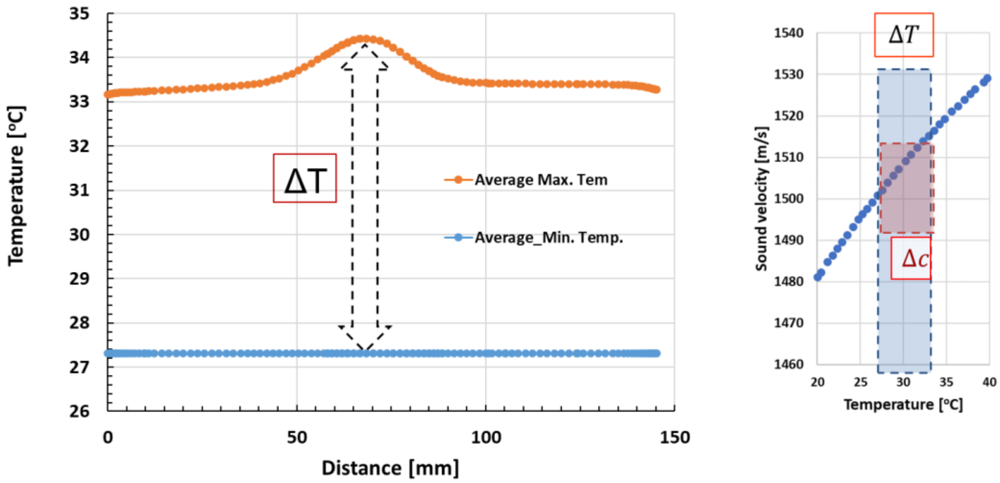

Fig. 4.: The error estimation of sound speed in medium for natural convection flow measurement

2. The spatio-temporal velocity profile by using UVP

The primary advantage of employing UVP is its capability to measure spatiotemporal velocity profiles, enabling the observation of long-term flow behavior. The magnitude of the vertical velocity along the measurement line is represented using a color scale: yellow to red (0 < velocity < 0.025 m/s) denoted velocity directed towards the transducer (dowward in the figure), while green to blue (-0.025 < velocity < 0) indicated velocity moving away from the transducer (upward in the figure), with black representing zero velocity.

The spatiotemporal velocity profile obtained using UVP for natural convection induced by a single heated rod is illustrated in Fig. 8. The vertical axis denotes the distance from the transducer, while the horizontal axis represents the elapsed time from the start of the measurement (1000 s in this instance). The UVP technique clearly revealed that upward flow occurred at the center of the pipe where the heater rod was located, while flow near the pipe wall remained low. This information proved valuable for estimating the efficiency of natural convection phenomena in specific scenarios, such as those encountered in nuclear fuel applications.

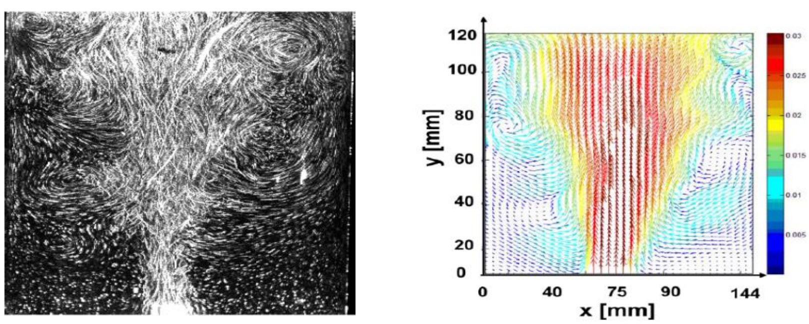

Fig. 5. Flow visualization (a) and mean flow field by using PIV method

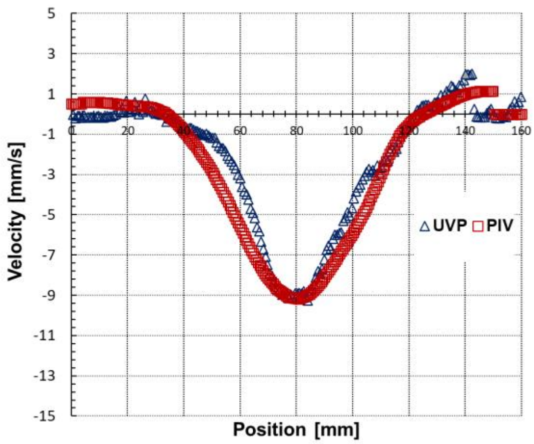

Fig. 6. The comparison of the averaged velocity profile (20 s) between UVP and PIV

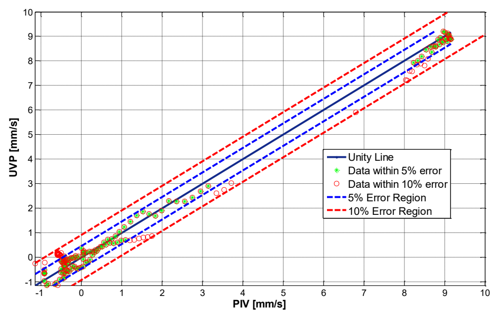

Fig. 7. Error estimation of measured velocity profile between UVP and PIV

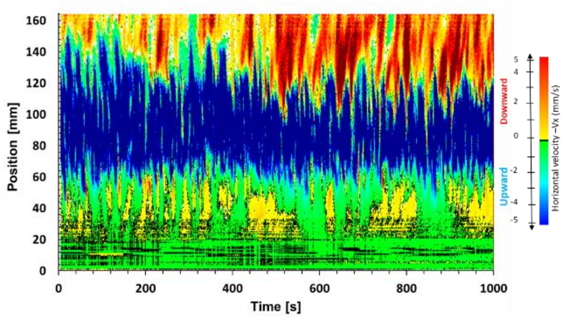

Fig. 8. The spatio-temporal of vertical velocity profile using UVP for 1000 s

III. CONCLUSIONS AND REMARKS

The experiment on natural convection flow around a single heater rod connecting to an alternating current power source is investigated. The in-house developed Ultrasound Velocity Profiling (UVP) technique is employed for measuring the natural convection flow. The influence of temperature on the velocity profile measurement using UVP is examined and deemed negligible under the experimental conditions. Additionally, Particle Image Velocimetry (PIV), which provides a two-dimensional velocity distribution, is utilized to validate the accuracy of the UVP technique for measuring natural convection flow. The comparison between the two methods demonstrates a good agreement.

Consequently, both techniques were utilized to observe the fundamental characteristics of natural convection flow induced by a single heated rod. It is observed that the primary flow ascended in the vicinity of the heater rod. The middle-upper portion of the vertical container served as the mixing zone between the upward buoyancy-driven flow and the downward flow originating from the upper portion of the container.

Ultrasound techniques proved valuable for instantaneously observing natural convection flow by providing spatiotemporal velocity profiles, which could be easily configured along the pipe. Hence, this technique is highly beneficial for comprehending flow characteristics in regions where the effects of buoyancy or large/small-scale circulation are significant.

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