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INVESTIGATION OF FLOW CHARACTERISTICS INDUCED BY VERTICAL HEATED ROD USING ULTRASOUND VELOCITY PROFILER

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Natural convection is a fundamental phenomenon that occurs in numerous areas of application in the industry, nuclear energy, power generation, and electronics cooling. In a nuclear reactor, natural convection is used for residual decay heat removal in case of an incident or accident after reactor shutdown. The design of fuel elements and fuel assembly could influence flow rate and therefore affect nature circulation. One of the most important parameters to understand natural convection is the spatio-temporal velocity profile. Hence, Ultrasonic Velocity Profiler (UVP) is appropriate to observe the natural convection flow behavior. The vertical heated rod with a diameter of 12 mm and length of 225 mm is immersed at the center of a vertical pipe made of acrylic with a diameter of 145.8 mm and height of 500 mm. The ultrasonic transducer is placed outside of the pipe to measure the long-term flow behavior. Using the UVP technique, the one-dimensional horizontal velocity destruction inside the pipe is observed. Accordingly, the velocity profile of UVP is confirmed with PIV method.

Keywords: Natural convection, UVP, PIV, nuclear reactor, heater rod

1. Introduction

The flow driven by natural convection is very important in geophysics, astrophysics, and nuclear engineering, such as residual decay heat removal of nuclear fuel in case of an incident or accident. The natural convection flow behavior is conventionally induced by different temperatures and driven by buoyancy force. In a nuclear reactor, the fuel element is placed sufficiently far, allowing residual heat removal. Furthermore, advanced nuclear power plant has now developed various passive cooling system types. For example, heat is removed from the steam generator by connecting it with the cooled water on the top of the reactor building. Thus, understanding the natural convection flow is significant to optimize and verifying the safety design system. In Vietnam, a new multiple purposes nuclear research reactor (MPRR) is introducing by using the hexagonal fuel element which include various layers (6-8). The distance between the layers is 2 mm, so-called narrow gap. In order to ensure the safety operation of new research reactor, the heat removal from the residual heat of narrow gap fuel need to be investigated.

Choi et al. [1] has reviewed the passive heat remove system of the advanced design of nuclear reactor and recommended that several characteristics of natural convection need to be clarified. Park et al. [2] has conducted the experiment with a single horizonal heater rod to clarified the large vortex and energy dissipation using LIF/PIV. Bazoz et al. [3] provided the simulation of natural convection with adding the temperature dependence of physical variables. However, the mentioned works have been observed the natural convection shortly and do not provide the heat transfer behavior of heated object. Therefore, for MPRR, the computational fluid Dynamic (CFD) is recommended to applied to understand the heat transfer and heat removal for each fuel element in case of normal or incident/accident scenario. However, the CFD simulation results including the turbulence model need to be validated with experimental data. Therefore, a simplified natural convection using a single heater rod is conducted. Regarding to the flow measurement, the Ultrasonic Velocity Profiler is used by giving the spatio-temporal velocity profile. Besides, the spike-excitation ultrasonic pulse has widely used in Non-destructive Testing was applied. The equipment used for the UVP measurement was 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. On the other hand, the sound speed is a function of temperature that effect on the measurement accuracy. Therefore, the flow measurement using UVP method need to be confirmed with PIV.

2. Experimental setup

2.1 Experimental apparatus of natural

The main test section is the vertical heated rod with a diameter of 12 mm and length of 22.5 mm. The heated rod was 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 was placed outside of the pipe to measure the long-term behavior of flow behavior. The working fluid is water and the initial temperature (T_{in}) was kept at room temperature (27 ºC). The power set to heater rod is 100 W corresponding to heat flux of 11864 W/m^2. The UVP measurements require the suspension of US (ultrasonic) wave-reflecting particles in the fluid. Nylon powder (d=80 μm; ρ = 1020 kg/m^3) was dispersed in working fluid as reflector particles for both UVP and PIV (Particle Image Velocimetry) measurements (Figure 1 and Figure 2). A camera with 60 fps was used to record the movement of particles illuminated by a laser sheet. This data allows one to analyze the 2-dimensional velocity distribution using the PIV method.

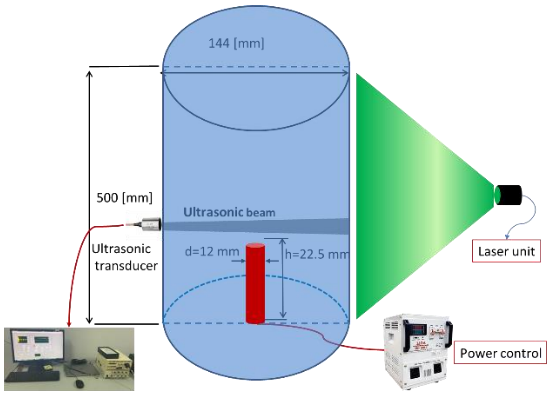


Figure 1: Sketch of vertical heated rod natural convection and test section for measurement. Number shows the length in mm.

The Rayleigh number (Ra) is defined as follows:

$$Ra = \frac{g\beta\Delta TL^3}{\alpha\nu} \quad (1)$$

Where L is characteristic length, $\Delta T = (T_{bulk} - T_{in})$, g is the coefficient of acceleration, β is the thermal expansion coefficient, α is the thermal diffusivity, and ν is the kinematic viscosity of the fluid. The Ra $=2.3 \times 10^{10}$ and is supposed to be convective natural turbulent flow.

2.2 Principle of UVP technique

The flow behavior in the test was observed using the ultrasound technique. The principle of the UVP method is based on the echography of ultrasound [5].

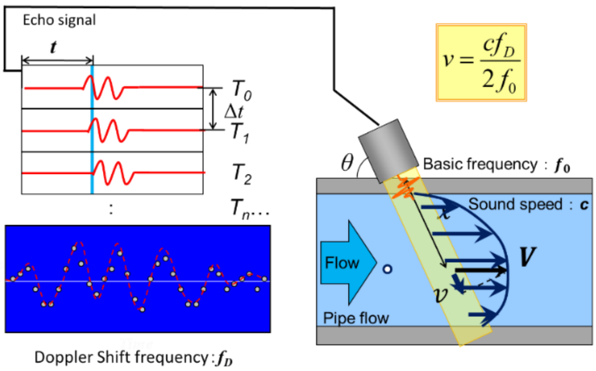


Figure 2: Principle of UVP technique

Table 1: Condition for UVP measurement

Basic frequency	4 MHz
Effective diameter	4 mm
Sound velocity	c = 1480 (m/s) at 26 ºC
Pulse repetition frequency	4 kHz
Temporal resolution	51 ms
Velocity resolution	0.21 (mm/s)
Chanel distance	0.74 mm
Pulse type	Spike-excitation pulse

The transducer emitted a pulse and receives the echo signal reflected from the particle suspended in the liquid. The information of position in each channel was extracted from the time delay τ_{prf} or pulse repetition frequency $f_{prf} = 1/\tau_{prf}$ as follows:

$$x = \frac{c \times \tau_{prf}}{2} \quad (2)$$

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, $V_{UVP}(x)$ was derived from Doppler shift frequency(f_D)at the time and position as:

$$V_{UVP}(x) = \frac{c \times f_D}{2f_0} \quad (3)$$

where f_0 is the basic ultrasonic frequency.

The basic frequency of ultrasound was 4 MHz using a transducer of 4 mm in effective diameter. The spatial, temporal and velocity resolution of UVP measurement were 0.74 mm, 51 ms, and 0.21 mm/s, respectively. In this measurement, the transducer is put outside the pipe and make an angle of 45 ºC with the pipe and located 5 cm away from the top of heater rod.

3. Results

3.1 Experimental data

The horizontal component of velocity in the direction of the ultrasonic beam was measured. The figure 3 show the average horizontal velocity profile. Figure 4 shows the vertical velocity component by the UVP for the natural convection induced by a single heated rod. The vertical axis means the distance from the transducer, and the horizontal axis is the time elapsed from starting measurement (500 s in this case). The most advantage for using the UVP is that we can get the spatiotemporal velocity profile. The magnitude of the vertical velocity along the measurement line is displayed in color scale: yellow to red (0<velocity<-0.025) indicates the velocity moving toward from the transducer (upward in the figure), and green to blue (0.025<velocity<0) is the velocity moving away the transducer (downward in the figure) and black color indicates velocity is zeros. The spatio-temporal velocity profile using UVP technique shows clearly that the upward flow is occurred at the center of pipe where the heater rod is located. Flow near the pipe wall is very low. This result is confirmed by 2-dimensional velocity distribution using PIV method in figure 5.

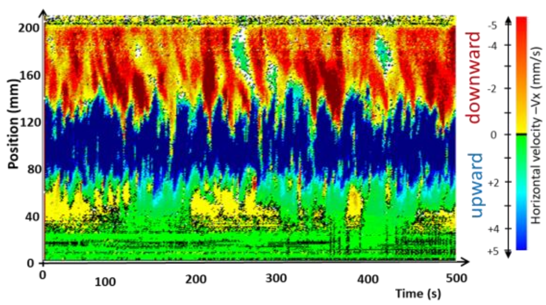
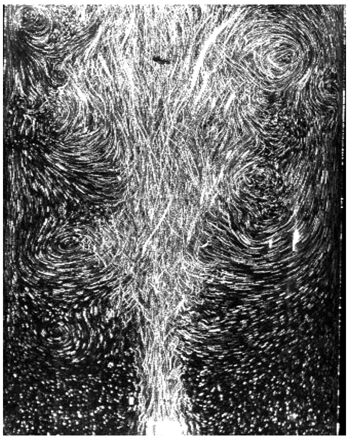
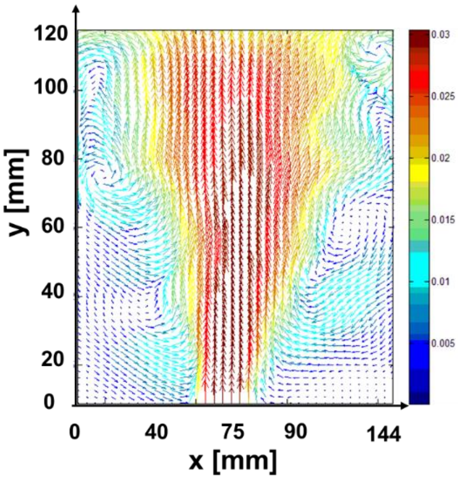


Figure 3: The spatio-temporal of horizontal velocity

profile using UVP method



(a)



(b)

Figure 4: Flow visualization (a) and mean flow field using PIV method

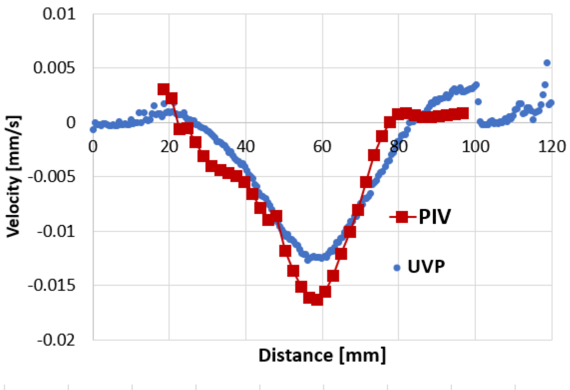


Figure 5: The comparison of UVP and PIV method.

The Figure 5 shows the confirmation of UVP and PIV method. This result shows very good agreement between 02 methods and the error is less than 5%.

The figure 4 shows the typical natural flow induced by heater rod. The upward flow along the heater rod is very clearly observed. The density of water close to the heater rod is decreased and went to the colder region due to the bouyancy force. The water descends when reaching the upper wall. Therefore, in the upper region of heater rod and the upper part of the container, the upward and downward flow induce a very complicate flow behavior in which the energy dissipation and transfer is need to be investigated. The results show clearly that the plume is mainly concentrated on the region close to the heater rod.

3.2 Simulation results

The Ansys/Fluent was applied to simulate the natural convection induced by single heater rod. Since the flow was turbulence, the realizable k-ε was chosen and coupled algorithm was applied for solution. And the four physical properties blow were modeled as a function of temperature as follows [4]:

- Dynamic viscosity (Pa.s)

$$\mu = [-0.00018567 \times T^3 + 0.19712 \times T^3 - 70.15 \times T + 1801.04]/100000$$

- Specific heat (J/kg.K)

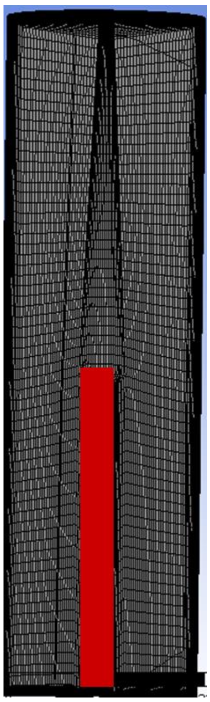
$$c_p = 0.0092 \times T^2 - 5.6859 \times T + 5058.24$$

- Thermal conductivity (W/m.K)

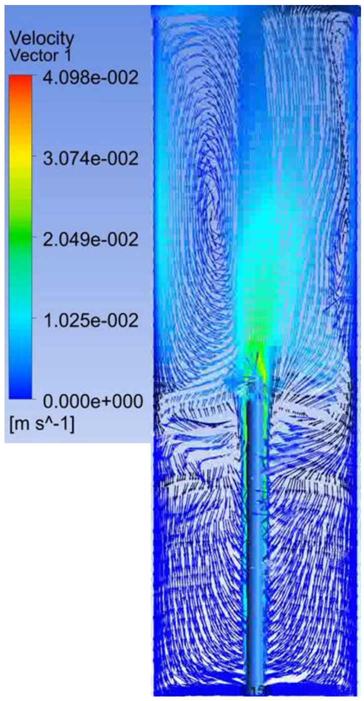
$$\kappa = -0.00000905 \times T^2 + 0.007048 \times T - 0.6893$$

- Thermal expansion coefficient (1/K)

$$\beta = -0.000000029783 \times (T - 273.15)^2 + 0.0000103247 \times (T - 273.15) + 0.00000755683$$



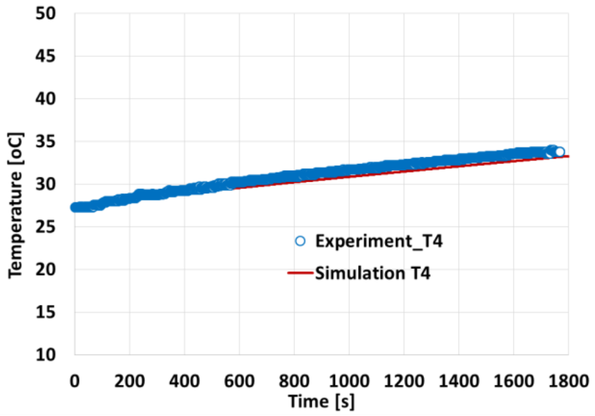
(a)



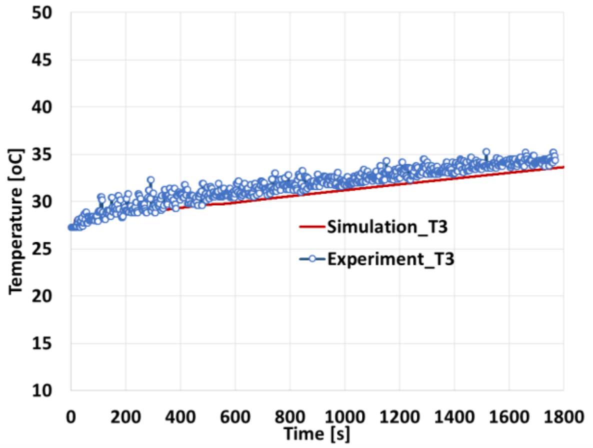
(b)

Figure 6: The mesh used for simulation (a) and the simulation result at 600 s using ANSYS/Fluent (b)

In order to compare the simulation results as well as the turbulence model, the flow behavior and temperature history were selected. The pointwise temperature at (x*=-72, y*=7.5, z*=0) (T4) and (x*=-72, y*=7.5, z*=0) (T3) were measured using k-type couple.



(a)



(b)

Figure 7: The comparison of temperature history between simulation and experimental data (a) at x*=-72, y*=7.5, z*=0) and (b) at (x*=-72, y*=7.5, z*=0)

The figure 7 show very good agreement between the experimental data and simulation result. That could conclude that the realizable k-ε is suitable for natural convection simulation.

4. Summary

The experiment of natural convection flow for a single rod is built up. The experimental data show that the flow behavior is significant for understanding heat transfer in natural convection. The advanced UVP technique is applied to measure the spatial-temporal velocity profile, supplemented with PIV and Image processing techniques for flow characteristics.

The thermal plumes are observed by 2-D visualization in which the middle-upper part of the vertical pipe is the competitiveness of small and large-scale circulation induced by upward flow (buoyancy flow) and downward flow from the upper container part.

Ultrasound technique is useful to observe instantaneously natural convection flow by giving a spatiotemporal velocity profile which is easy set up along the pipe. Therefore, this technique is very helpful to understand the flow characteristic in the given region where the effect of buoyancy or large/small scale circulation is determined. For simulation of natural convection induced by vertical heated rod, the realizable k-ε was suitable for simulation.

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