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Turbulence Generation by Ultrasonically Induced Gaseous Cavitation in the CO_2 Saturated Water Flow

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Emission of ultrasonic vibration to turbulent flow promotes the turbulence generation due to the resonantly oscillating pressure field and thereby induced cavitation. In addition, ultrasonic vibration is well transmitted through water and not dissipated easily so that the micro-bubbles involved in the fluid induce the gaseous cavitation if the bubbles are resonated with the ultrasonic field. In the present study, we found through LDV measurement that the gaseous cavitation induced by ultrasonic vibration to CO_2 saturated water flow in the rectangular cross-sectioned straight duct enhances turbulence much more than the case of non-ultrasonic or normal ultrasonic conditions without gaseous cavitation. We also found that the fluctuating velocity component induced by emitting the ultrasonic vibration in normal direction of a rectangular channel flow can be redistributed to stream-wise component by the agitation of gaseous cavitation.

Key Words : Ultrasonic Vibration, Gaseous Cavitation, CO_2 Saturated Water, LDV, Rectangular Cross-Sectioned Duct

Nomenclature

D_h	: Hydraulic diameter
E	: Turbulence enhancement rate
G	: Gibbs energy
ΔG	: Activation energy for bubble formation
P	: Pressure
Pa	: Atmospheric pressure
Pv	: Vapor pressure of water
P_0	: Amplitude of ultrasonically induced pressure
r	: Radius of gas bubble
r^*	: Critical radius of gas bubble
Re	: Reynolds number $\left(\equiv\frac{U_b D_h}{\nu}\right)$
U	: Stream-wise mean velocity
U_b	: Bulk mean velocity
u'	: Rms of stream-wise fluctuating velocity
v'	: Rms of normal direction fluctuating velocity
x	: Stream-wise distance from the point at which ultrasonic vibration is applied to the duct flow
ν	: Kinematic viscosity
δ_0	: Local amplitude of ultrasonic vibration
λ	: Wave length of ultrasonic vibration

1. Introduction

Enhancement of turbulent heat transfer between heat sources and coolant flows has been a primary concern for the design of high performance heat exchanger and highly integrated electronic equipments. In the past, passive techniques such as extended surfaces have been used to pro-

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mote the heat transfer and thermal mixing between coolants and heat sources. The passive techniques, however, obstruct the coolant flows to increase the pumping power. Furthermore, most of fluid flows in highly compact and integrated heat exchangers are stable laminar flows so that the heat transfer enhancements from high temperature heat sources to coolants are limited only to the short downstream region from the heating sources. Thus we need to develop new and creative technologies to enhance the heat transfer without obstructing the coolant flows.

Bonkamp et al. (1997) investigated the effect of ultrasonic stream on boiling heat transfer, but the enhancing effect was just limited to small value and short distance. Ultrasonic vibration with a frequency of tens of kHz through confined container instantaneously form standing waves so to induce cavitation bubbles, but they may disappear quickly and can not affect the energy transport even in the small inertia flow. In order to overcome this limited effects of the ultrasonic vibration on heat transfer enhancement, we proposed, a new and creative technology, the ultrasonically induced gaseous cavitation in the CO_2 saturated water flow, to enhance the heat transfer without obstructing the coolant flows (Lee and Choi, 2002).

The micro-bubbles involved in the liquid flow induce the gaseous cavitation if the bubbles are resonated by emitting the ultrasonic vibration to the flow. In addition, the ultrasonically induced gaseous cavitation makes turbulent stresses isotropic as well as enhances the normal stress that affects mostly heat transfer.

In the present study, we would like to investigate experimentally the fact that the gaseous cavitation generated by applying ultrasonic vibration to CO_2 saturated water flow in the rectangular cross-sectioned straight duct can redistribute the normal component of turbulence to the streamwise component.

2. Background

2.1 Ultrasonically induced cavitation

Ultrasonic vibration in a forced flow is a mechanical disturbance that consists of pressure oscillations above and below the pressure of liquid as shown in Fig. 1. A local reduction in the pressure field encourages a submicroscopic bubble to grow. In contrast, the local increase of pressure in the liquid will discourage bubble growth or cause the collapse of the bubble so that it produces the characteristic effects usually associated with cavitation. Growth of the bubble occurs at the interval corresponding to one-fourth of the period of the sound wave and collapse occurs in a small fraction of that time. Because of the rapidity of the collapse, large instantaneous pressures and temperatures are developed at the center of the bubble. Usually the nuclei that are the sources of cavitation bubbles remain after the bubbles collapse. They will then serve again as nuclei for new bubbles. Generally, two kinds of cavitations, vaporous and gaseous, can be generated by applying ultrasonic vibration to tap water. The vaporous cavitation is the bubble formation mechanism of vapors of liquid itself. This is the process of expansion and subsequent violent collapse, under the action of a oscillating ambient pressure. This explosive formation of transient cavities, which are largely filled with vapors, occurs when the instantaneous liquid pressure to such an extent that the nucleus bubbles cannot remain stable simply by an increase of volume to a new equilibrium value. However, in order to produce vaporous cavitation by ultrasonic vibration, the amplitude of the ultrasonic wave pressure, P_0, should be larger than $P_a - P_v$ so that liquid pressure around the bubble should fall below P_v. Therefore, vaporous cavitation can be generated only in the condition of relatively high intensity of ultrasonic vibration. The gaseous cavitation, however, is the bubble formation mechanism of dissolved or tapped nuclei, minute bubbles, in liquid and may form a cavitation of relatively low intensity. Choi (1979) proved by analyzing the gas bubble dynamics for the minute bubbles oscillating under ultrasonic field that there exists a critical resonant bubble diameter which generates cavitation for a given ultrasonic wave intensity and frequency. Generally, there are many insolvable micro-gas-bubbles in tap water.

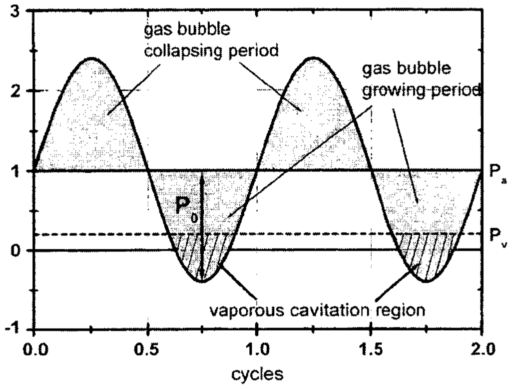


Fig. 1 The mechanisms of vaporous and gaseous cavitation

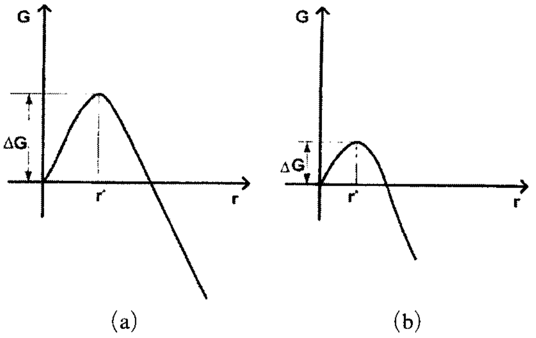


Fig. 2 Activation energy and critical radius for CO_2 evaporation bubble formation from the dissolved gas state in water for (a) normal state (b) super-saturation state

These insolvable micro-gas-bubbles in tap water may be oscillated by the ultrasonic vibration, repeatedly grow and collapse. A certain diameter of gas bubbles may highly resonate to the ultrasonic vibration and the resonance agitates the surrounding fluid, but the resonance of gas bubbles to ultrasonic field is limited by the diameter for the frequency of ultrasonic vibration. Choi (1979) revealed that only the bubble diameter smaller than 1 μm could generate gaseous cavitation under ultrasonic vibration. Therefore, we cannot expect strong fluid agitation by the gaseous cavitation of insolvable gas bubbles in tap water. CO_2 can be easily dissolved to water, and the dissolving rate increases as the liquid pressure increases. CO_2 dissolved in water can form embryos but the embryos disappear at once because the embryo sizes are too small to grow over the critical size for bubble formation and the activation energy is too high for the embryos spontaneously cross over the barrier themselves. However, if ultrasonic vibration is applied to the CO_2 saturated water flow, the water becomes super-saturated state for the CO_2 gas during the depressurizing phase of ultrasonic vibration. This super-saturation of CO_2 gas in the depressurizing phase may lower the activation energy for gas bubbles formation. The activation energy is the Gibbs energy to be overcome for the embryos to grow over the critical sizes. Thus, probability of the embryos to grow over the critical sizes for bubble formation may increase in the super-saturation state. In the present study, the generation of violent gaseous cavitation could realize even in the condition of relatively low intensity of ultrasonic vibration by applying the ultrasonic vibration normal to the stream-wise direction of CO_2 saturated water flow in the rectangular cross-sectioned straight duct.

The mechanism of this gaseous cavitation induced by applying ultrasonic vibration to the CO_2 saturated water is the repeated evaporation of dissolved CO_2 gas in the depressurizing phase and the subsequent collapse in the pressurizing phase.

The first objective of the present study is to investigate experimentally the gaseous cavitation generated by applying ultrasonic vibration to the CO_2 saturated water. The second objective is to investigate the possibility of turbulence generation by the gaseous cavitation.

2.2 Turbulence generation by ultrasonically induced gaseous cavitation

Turbulence can be generated by ultrasonic vibration through the interaction of Reynolds stresses and mean shear gradients produced by ultrasonic vibration and thereby induced cavitations. Ultrasonic energy will be dissipated directly to heat or consumed to generate turbulence, but the theoretical study on the interaction between turbulence and ultrasonic vibration reveals that the ultrasonic stream does not contribute directly to the turbulence generation while ultrasonically induced gaseous cavitation may significantly enhance turbulence generation (Lee and Choi, 2002).

Ultrasonic vibration applying to the flowing liquid may produce turbulence through the following three mechanisms. The first is the turbulence generation through the interaction of the density fluctuations induced by ultrasonic vibration with the inherent Reynolds stresses. Rapid oscillation of fluid pressure caused by ultrasonic vibration can raise the local fluid density fluctuation. But the period and amplitude of the oscillating pressure are too small to generate turbulence. We cannot find any evidence of this kind of turbulence generation from the present experimental study. However, we can expect that the ultrasonic vibration may affect the turbulence cascade process through promoting the stretching of small eddies.

The second is the turbulence generation by the interaction of ultrasonic vibration and mean shear gradients. This kind of turbulence generation, however, cannot be expected to occur in the plane channel flow or the straight duct flow that have no acceleration or deceleration of bulk mean velocity.

The third is the turbulence generation due to the interaction of local velocity gradient generated by the cavitation and inherent Reynolds stress components surrounding the bubbles. The fluctuating velocity produced by the cavitation bubble is large enough compared with turbulent velocity scale so that the third mechanism is the most probable for turbulence enhancement through ultrasonic vibration. We could realize the violent gaseous cavitation by applying only the relatively low intensity of ultrasonic vibration to the CO_2 saturated water compared to that for vaporous cavitation. The aim of the present study is to investigate experimentally the evidence of the turbulence generation through the ultrasonically induced gaseous cavitation.

3. Experimental Apparatus and Method

The schematic diagrams of the experimental test loop and test section are presented in Fig. 3. The test loop is composed of a closed circuit for experimental measurement of turbulent characteristics using LDV system, storage tank, chemical pump, chiller, control valves, bypass valves, flowmeter, CO_2 saturator, acrylic test-section, seven ultrasonic vibrators and generator. Water of 20℃ in the storage tank is circulated by the pump through 1″ diameter PVC pipes arranged to compose a closed circuit and it flows through the test-section from the bottom toward the top. The flow rate of circulated water is controlled by a control valve and bypass valves, and measured by a LSV52A3-30 type OVAL flowmeter in the range of $0.00001 \sim 0.00083 m^3/s$ with the uncertainty of ±0.35%. The temperature of circulating water is set to 20℃ and controlled by chilling system and it involves a digital temperature controller, which can control the variation of circulating water temperature within ±0.3℃.

Turbulent velocities in the rectangular duct flow under ultrasonic vibration can be measured by LDV. The LDV system employed by the present experiment is two-component ion laser type manufactured by Dantec. The focal length of a lens is 160 mm and the maximum output of laser beam power is 6 W. The LDV system is composed of a laser beam, fiber flow components, processor, feeding system, etc. A two dimensional traversing mechanism is used to move the measuring volume. The maximum traversing length of the measuring volume is 690 mm and increasing width is capable of minimum 0.1 mm. Generally, if tap water is used as working material, dispersion light can be obtained without any particle suspension in the fluid, but in the present experiment, we can obtain more clear data signals by suspending SiC particles (diameter : 1.5 μm, density : 3.2 g/cm^3). The number of data measured at each point is 30,000 per 30 seconds and the data are averaged to calculate mean values. Signals obtained from photo-multiplier are analyzed by correlation type processor composed of frequency filter, digital sampler, D/A converter and etc.

The test section for the LDV measurement is made out of acrylic plates of which refractive index is almost coincided with that of water. The dimension of cross-section is $0.0296 m \times 0.05 m$

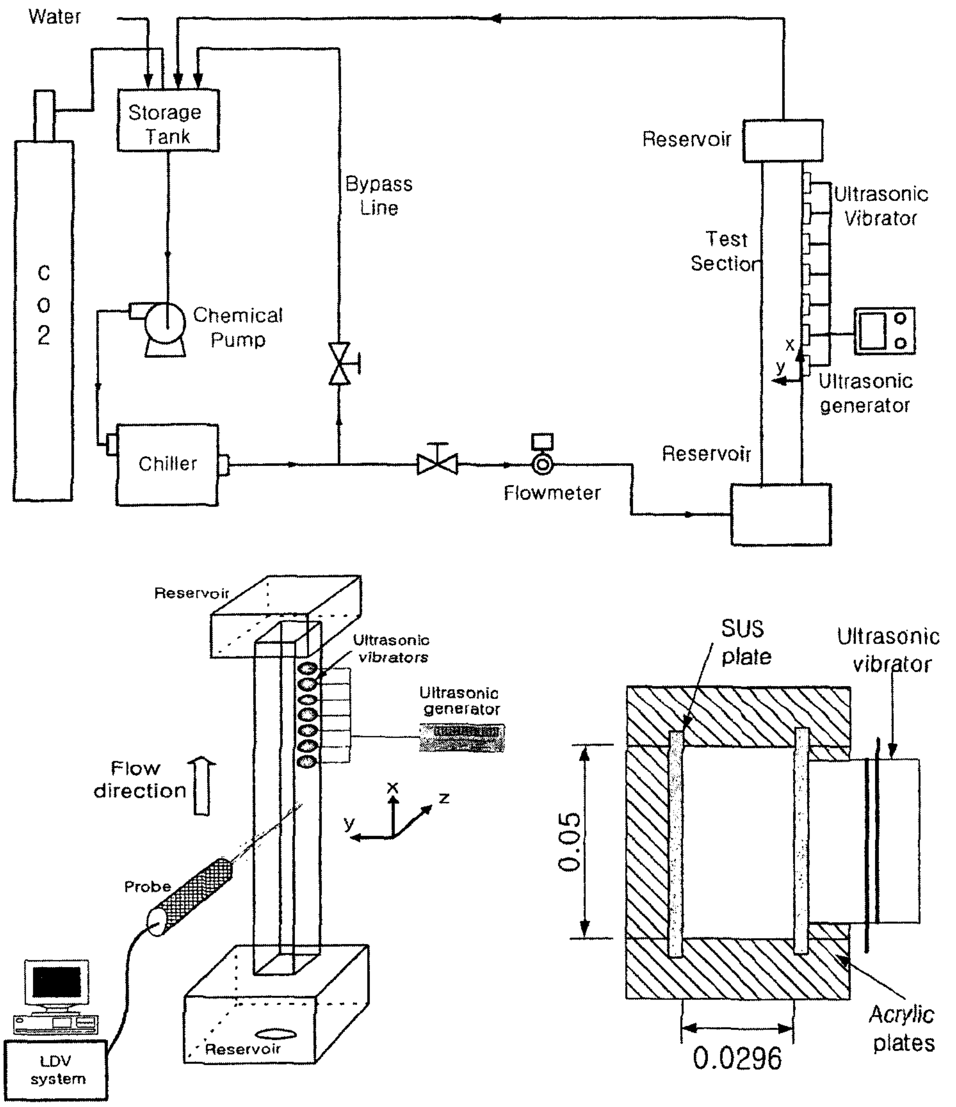


Fig. 3 Schematic diagrams of test loop and test section to investigate the turbulence enhancement by ultrasonically induced CO_2 gaseous cavitation

and its height is 1.5 m. The resonance frequency of the ultrasonic vibration is 50 ± 1.2 kHz and the driving power for each ultrasonic vibrator is 25 W. The distance between ultrasonically vibrating plate and its facing plate is set to vibration period, $\lambda=0.0296$ m.

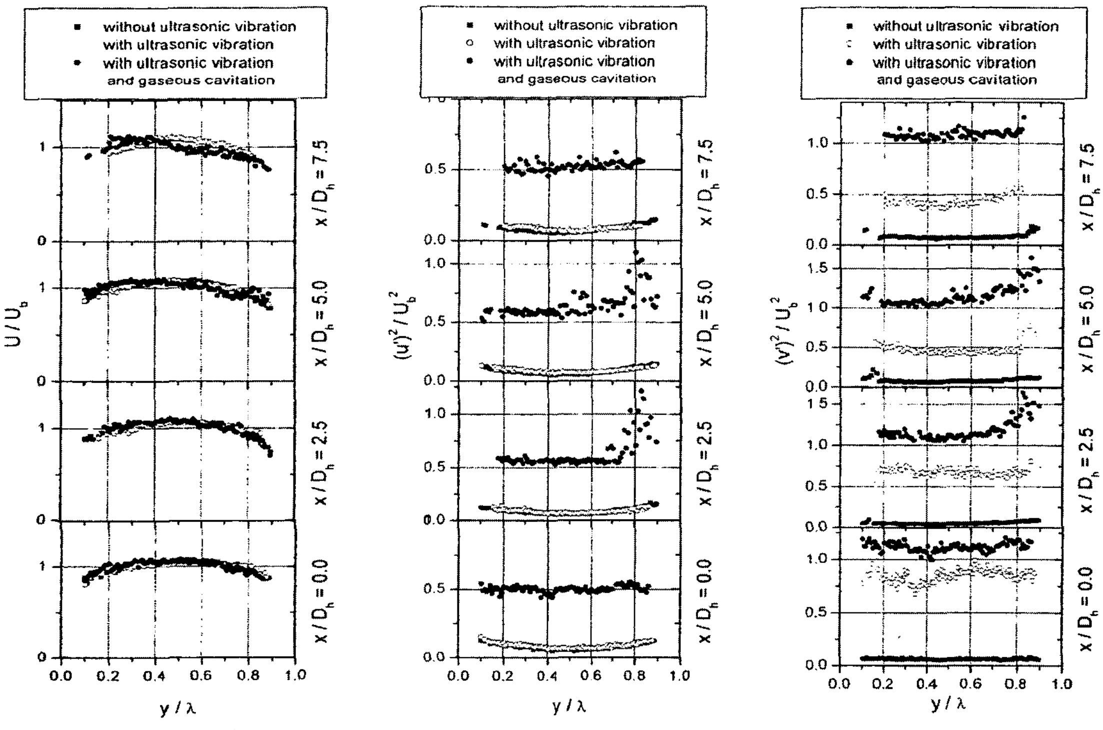
In the present study, CO_2 gas is supplied continuously to the circulating water for one hour with a constant pressure, 1.6 kgf/cm^2, to saturate the water by the dissolved CO_2 gas before the experiment.

4. Results and Discussions

In the present study, the variations of the flow characteristics due to the ultrasonic emission in the normal direction of the flow are measured by LDV system. The emission rates of ultrasonic energy per unit mass flow rate, W/m, are 1,122 J/kg and 560.9 J/kg for Re=4,000 and 8,000 respectively. Figure. 4 shows the axial variation of measured stream-wise velocity, stream-wise fluctuation intensity and normal fluctuation intensity profiles for Re=4,000 at x/D_h=0.0, 2.5, 5.0 and 7.5. Recently Lee and Choi (2002) found that the significant local acceleration of stream-wise mean velocity is induced by the ultrasonic stream at the core of the duct inlet and revealed that the stream-wise velocity is accelerated near the surface of ultrasonic vibrator by the ultrasonic wave stream. This phenomenon was also found by the experiment of Nomura et al. (1995). In the case of the emission of ultrasonic vibration in normal direction of the duct flow, however, the mean stream-wise velocity is not varied by the ultrasonic stream in any region of the test section as shown in Fig. 4(a).

Figure 4(b) and Figure 5 show that the stream-wise turbulence intensity, in the case of the ultrasonic vibration without gaseous cavitation, is not enhanced along with the flow progress while normal turbulence intensity is significantly enhanced as shown in Fig. 4(c). The enhancement of normal turbulent intensity occurs due to the continuous transformation and accumulation of the fluctuating velocity. In this case, we cannot find any evidence of the redistribution of Reynolds stresses by pressure strain that is the characteristics of turbulence. Therefore, we conclude that the enhancement of normal direction fluctuating velocity is not pure turbulence fluctuation, but simple agitation of fluid by ultrasonic vibration.

However, in the case of ultrasonic vibration to the CO_2 saturated water flow, the gaseous cavitation agitates effectively the stream-wise turbulence intensity by the accumulation and redistribution of the fluctuating energy of bubbles in all directions as shown in Table 1. The normal turbulence intensity is one of the most important parameters for the enhancement of wall heat transfer. Figure 4(c) shows that the ultrasonic condition reinforces the normal turbulence



(a) (b) (c)

Fig. 4 Axial variations of the stream-wise velocity and fluctuation intensities due to the ultrasonic vibration and there by induced gaseous cavitation for Re=4,000; (a) stream-wise velocity (b) stream-wise fluctuation intensity (c) normal fluctuation intensity

intensity about 13 times as much as that of non-ultrasonic condition. The duct width is designed as the maximum ultrasonic vibration occurs at the center face and two facing walls, $y=0$ and $y=\lambda$.

Figure 4(c) and Table 1 show that CO_2 gaseous cavitation enhances the normal turbulence intensity twice as much as that of the condition of ultrasonic vibration without gaseous cavitation. In addition, it reveals that the artificially generated gaseous cavitation with the saturation of CO_2 in water flow promotes fluid fluctuation more and the fluctuation is redistributed to stream-wise direction.

Table 1 Comparison of fluctuation enhancements by the ultrasonic vibration with CO_2 gaseous cavitation and without gaseous cavitation

x/D_h	Stream-wise turbulence intensity enhancement		Normal turbulence intensity enhancement	
	Re=4,000	Re=8,000	Re=4,000	Re=8,000
0.0	6.15	1.75	1.33	1.26
2.5	7.02	3.44	1.74	1.59
5.0	7.65	3.35	2.42	1.66
7.5	6.26	2.94	2.49	1.75

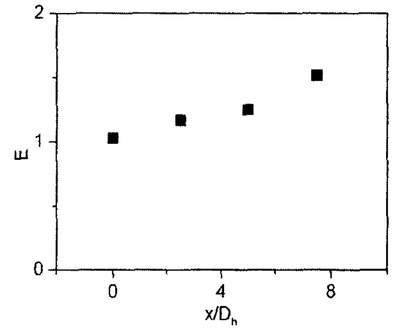
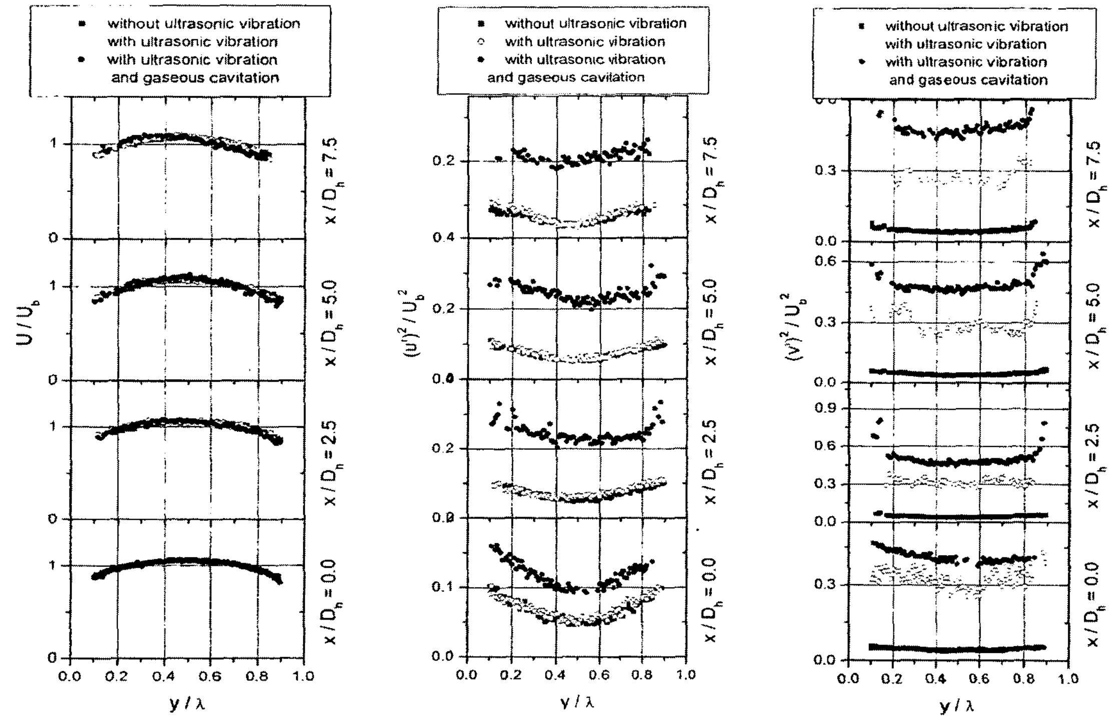


Fig. 5 The stream-wise fluctuation intensity enhancement due to the ultrasonic vibration without gaseous cavitation for Re=4000



(a) (b) (c)

Fig. 6 Axial variations of the stream-wise velocity and the fluctuation intencities due to the ultrasonic vibration and there by induced gaseous cavitation for Re=8,000 ; (a) stream-wise velocity (b) stream-wise turbulence intensity (c) normal fluctuation intensity

Figure 6 shows the axial variation of measured stream-wise velocity, stream-wise fluctuation intensity and normal fluctuation intensity profiles at x/D_h=0.0, 2. 5,5. 0, and 7.5 for Re=8,000. The mean stream-wise velocity is not varied by the ultrasonic stream in any region of the test section as shown in Fig. 6(a). As shown in Fig. 6(b) the stream-wise fluctuation intensity in the case of ultrasonic vibration without gaseous cavitation for Re=8,000 is not enhanced with the flow progress as for of Re=4,000, while the gaseous cavitation enhances the stream-wise fluctuation intensity 2.7 times as compared with the case of non-ultrasonic vibration. It is caused by the redistribution of turbulence energy from the agitation of gaseous cavitation. Figure 6(c) shows that the normal fluctuation intensity in for the ultrasonic vibration without gaseous cavitation is enhanced 5.5 to 7.0 times as much as the case of non-ultrasonic condition for Re=8,000. Comparing with to the case for Re=4,000, the enhancement rate decreases to the halves because the emission rate of ultrasonic energy per unit mass flow rate is cut by half. In the case of ultrasonic vibration to tap water, fluctuating velocity is enhanced mostly in the direction of ultrasonic vibration so that it is difficult to regard the enhancement of fluctuating velocity in normal direction as the turbulence production. On the other hand, in the case of ultrasonic vibration to the CO_2 saturated water flow, the normal component of fluctuating velocity is redistributed to stream-wise component so that it shows some characteristics of turbulence generation.

5. Conclusions

In the present study, we found through the LDV measurement that the gaseous cavitation induced by the ultrasonic vibration to the CO_2 saturated water flow enhances the turbulence much more than the case of non-ultrasonic or general ultrasonic vibration in tap water flow does. We also found that the gaseous cavitation can reinforce the stream-wise turbulence intensity as well as the normal turbulence. The repeated growth and collapse of gas bubbles disperse the fluctuating energy in all direction.

Increasing Reynolds number of duct flow for the same emission rate of ultrasonic energy leads to the decrease in the emission rate of ultrasonic energy per unit mass flow rate of water. Decrease in turbulent intensity as with the increase in Reynolds number reveals the evidence of the fact.

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