Turbulence Enhancement by Ultrasonically Induced Gaseous Cavitation in the CO_2 Saturated Water

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Recent primary concern for the design of high performance heat exchanger and highly integrated electronic equipments is to develop an active and creative technologies which enhance the heat transfer without obstructing the coolant flows. In this study, we found through the LDV measurement that the gaseous cavitation induced by ultrasonic vibration applied to the CO_2 saturated water in the square cross-sectioned straight duct flow enhances the turbulence much more than the case of non-ultrasonic or normal ultrasonic conditions without gaseous cavitation does. We also found that gaseous cavitation can enhance effectively the turbulent heat transfer between the heating surfaces and coolants by destructing the viscous sublayer.

Key Words : Ultrasonic Vibration, Gaseous Cavitation, Viscous Sublayer, LDV, Square Cross-sectioned Duct

Nomenclature

c : Specific heat
D_h : Hydraulic diameter
D_{ij} : Viscous diffusion rate of Reynolds stresses
f : Ultrasonic wave frequency
k : Boltzmann constant
$\dot{m}$: Mass flow rate
P_a : Ambient pressure
P_0 : Hydraulic pressure
P_{ij} : Shear generation rate of Reynolds stress
P_v : Vapor pressure of liquid
r : Distance from bubble center
R : Bubble radius
R_0 : Critical bubble radius
Re : Reynolds number
T : Temperature
U_i : Velocity components
U_b : Streamwise bulk velocity
u : Streamwise turbulent velocity
$\sqrt{u^2}$: Streamwise RMS (root mean square) value of turbulent velocity
$\overline{u_i u_j}$: Reynolds stress components
v : Normal turbulent velocity
$\sqrt{v^2}$: Normal RMS (root mean square) value of turbulent velocity
V : Volume
V_f : Radial velocity at a distance of r
V_g : Radial velocity at a bubble surface
$\dot{W}$: Ultrasonic energy emission rate
x_i : Coordinate components

Greeks

γ : Ratio of specific heats of the gas in bubble
σ : Surface tension of liquid
ϕ_{ij} : Pressure diffusion rate of Reynolds stress
δ_0 : Local amplitude of ultrasonic vibration
ε_{ij} : Dissipation rate of Reynolds stresses
λ : Wave length
ρ : Density of liquid

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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 or rough surfaces have been used to improve 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.

Magneto-hydro-dynamic (MHD) turbulence which is the turbulence created by the body force fluctuation inflicted on the flow fields has been considered as the advanced heat transfer enhancement technique for the nuclear fusion reactors (Montagomery, 1987). By similar process, emission of ultrasonic vibration to the turbulent flow may promote the turbulence generation by applying the resonantly oscillating pressure field and thereby inducing cavitation. Bonkamp et al. (1997) reveals the effect of ultrasonic stream on boiling heat transfer. However, the enhancing effect of ultrasonic vibration on boiling heat transfer is just limited to small values because the ultrasonic vibration applied to the flowing pure fluid can not induce the gaseous cavitation. Ultrasonic vibration is well transmitted through water and not dissipated easily. The micro-bubble involved in the fluid flow induces the gaseous cavitation if the bubble is resonated by the ultrasonic vibration. In the present study, turbulence enhancement process through gaseous cavitation induced by ultrasonic vibration was investigated experimentally in the straight duct flow with square cross-section.

2. Background

2.1 Realization of violent gaseous cavitation

The meaning of cavitation concerned here is the formation of bubbles in liquids; cavities. Ultrasonic wave is a mechanical disturbance which consists of pressure oscillations above and below the pressure of the liquid. A reduction in pressure encourages a submicroscopic bubble to grow. A pressure above that of the pressure in the liquid will discourage bubble growth or cause the collapse of one that has started to grow 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 which are the sources of the cavitation bubbles remain after the bubbles collapse. They will then serve again as nuclei for new bubbles.

These bubbles may be of two types: (1) those that have been dissolved or trapped in minute bubbles in the liquid, and (2) vapors of the liquid itself. (Ensminger, 1988)

The first type of cavitation, called gaseous cavitation, may form a cavitation of relatively low intensity. Choi (1979) proved by analysing the gas bubble dynamics for the minute bubbles oscillating under ultrasonic vibration that there exists a critical resonant bubble size which generates cavitation for a given ultrasonic wave intensity and frequency. Thus, if the bubble size is deviated from the critical resonant size, the violent cavitation cannot occur.

The second type, called vaporous cavitation, is of fairly high intensity. This is the process of expansion and subsequent violent collapse, under the action of a varying ambient pressure. This explosive formation of transient cavities, which are largely filled with vapour, occurs when the instantaneous pressure decreases to such an extent that the nucleus bubbles cannot remain stable simply by an increase of volume to a new equi-

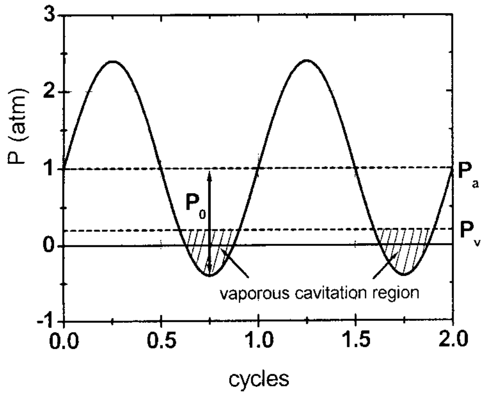

Fig. 1 Generation of vaporous cavitation for the normal ultrasonic vibration condition

librium value. In order to produce vaporous cavitation by ultrasonic vibration, the amplitude of ultrasonic wave, P_0 should be larger than $P_a - P_v$ so that liquid pressure around the bubble should fall below P_v as shown in Fig. 1. Therefore, vaporous cavitation can be generated only in the condition of requires high intensity ultrasonic vibration.

In the present study, we are trying to realize the generation of violent cavitation even in the condition of relatively low intensity ultrasonic vibration by applying it to the CO_2 saturated water flowing in the straight duct. If ultrasonic vibration is applied to the CO_2 saturated water, numerous CO_2 gas bubble nuclei may appear and disappear and some of them may grow in the depressurizing phase, in which the water pressure falls below P_a, due to the supersaturation of CO_2 gas bubble in the water. Then the growing bubbles are collapsed and produce violent cavitation in the subsequent pressurizing phase in which the water pressure rises above P_a.

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

2.2 Turbulence generation by ultrasonic vibration and thereby induced cavitation

Generally, the heat transfer coefficient is proportional to the square of turbulence intensity, so if the turbulence intensity of the fluid decreases, the heat transfer coefficient will decrease accordingly. Therefore, turbulence enhancement techniques have been the most important factor for the design of high performance heat exchanger which requires high heat transfer coefficient between coolants and heat sources. Ultrasonic vibration has relatively high frequency, small amplitude and short length scale compared to normal turbulence. By the way, turbulence can be generated by the ultrasonic vibration through the interaction of Reynolds stresses and mean shear gradients produced by the ultrasonic vibration and thereby induced cavitations. Reynolds stress equations which involve the turbulence generation rate term by ultrasonic vibration are expressed as the following relation (Lounder, 1975 ; 1989).

$$\frac{D\overline{u_i u_j}}{Dt} = P_{ij} + D_{ij} + \phi_{ij} - \varepsilon_{ij} + P_{ij}^{ultra} \quad (1)$$

where P_{ij}^{ultra} is the turbulence generation rate by ultrasonic vibration and thereby induced cavitation.

Ultrasonic energy will be dissipated to directly 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 cavitation may significantly enhance turbulence generation.

Ultrasonic vibration applying to the flowing liquid may produce turbulence through the following three mechanisms. The first is the turbulence generation through the interaction between the density fluctuation induced by ultrasonic vibration and the inherent Reynolds stresses. Ultrasonic vibration generates the rapid oscillation of fluid pressure so as to raise the local fluid density fluctuation. But the period and amplitude of ultrasonic vibration 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, for example, the turbulence generation by $-\overline{u_i^2}\frac{\partial U_i}{\partial x_i}$ in the Cartesian coordinate. This kind of turbulence generation can not be expected to occur in the plane channel flow or the straight duct flow which has no acceleration or deceleration of flow.

The third is the turbulence generation due to the interaction of mean velocity gradient induced by the cavitation and inherent Reynolds stress components surrounding the bubbles. The fluctuating velocity induced by the cavitation bubble is so large enough to be compared with turbulent velocity scale, so that the third mechanism is the most promising mechanism for turbulence enhancement by ultrasonic vibration. We could realize the violent gaseous cavitation by applying relatively lower intensity 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 that ultrasonically induced gaseous cavitation may be the most efficient turbulence enhancement technique.

2.3 Cavitation dynamics in the ultrasonic vibration field

On the assumption that the gas nuclei giving rise to cavitation are merely very small free bubbles, simple relations have been derived for the pressure and other conditions of cavitation dynamics in the ultrasonic vibration field. The equation of motion for bubble dynamics in ultrasonic vibration field of $\sin \omega t$ is as follows.

$$-R\frac{\partial V_g(r)}{\partial t}-\frac{3}{2}V_g(r)^2=\frac{1}{\rho}\Big\{P_v-P_a+P_0\sin\omega t-\frac{2\sigma}{R}+\Big(P_a-P_v+\frac{2\sigma}{R_0}\Big)\Big(\frac{R_0}{R}\Big)^3\Big\} \quad (2)$$

If the radial fluid velocity of the bubble surface is denoted to V_g, then the fluid velocity at the arbitrary position of distance r from the center of the bubble may be given by (4).

$$V_g=\frac{\partial R(t)}{\partial t} \quad (3)$$

$$V_f(r)\approx V_g\frac{R^2}{r^2} \quad (4)$$

Then the local mean velocity gradient can be written as following equation.

$$\frac{\partial V_f}{\partial r}=-\frac{2R^2V_g}{r^3} \quad (5)$$

If the cavitation occurs, the local mean velocity gradient of fluid is so large enough to generate turbulence by the relation (6) which represents the turbulence generation through the interaction of mean velocity gradient, $\partial V_f/\partial r$, and the Reynolds stress component in radial direction, $\overline{v_r^2}$ in the spherical coordinate.

$$P^{ultra}=-\overline{v_r^2}\frac{\partial V_f}{\partial r} \quad (6)$$

2.4 Gaseous cavitation in the CO_2 saturated water

Generally, there are many micro-gas bubbles in tap water. However, there is a critical bubble size which produces gaseous cavitation for a given frequency and amplitude of ultrasonic vibration. Choi(1979) revealed that only the bubbles diameter smaller than $1\mu m$ could generate gaseous cavitation under ultrasonic vibration. Therefore, there is little possibility to produce gaseous cavitation by applying the ultrasonic vibration to the 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 gas pressures in embryos are too large for the CO_2 gas existing as micro-bubbles. However, if ultrasonic vibration is applied to the CO_2 saturated water, the water becomes supersaturated with CO_2 gas during the depressurizing phase of ultrasonic vibration. This supersaturation of CO_2 gas may lower the activation

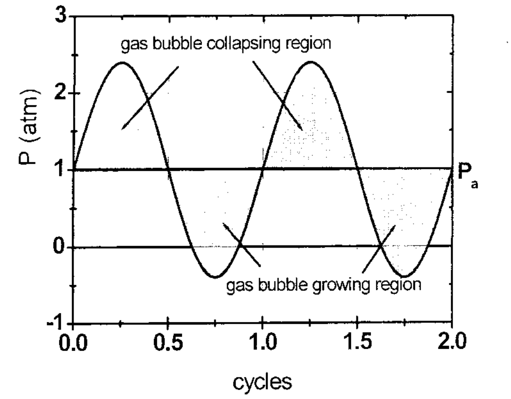

Fig. 2 Generation of gaseous cavitation by applying the ultrasonic vibration to the CO_2 saturated water

energy for the formation of the gas bubbles. Thus, probability of the embryos to grow over the critical sizes for bubble formation may increase.

3. Experimental Method

Figure 3 shows the test loop which is composed of a closed circuit for experimental measurement of turbulent characteristics using LDV system, a storage tank, chemical pump, chiller, control valve, bypass valve, OVAL flowmeter, 0.04×0.04 m^2 acrylic test-section, ultrasonic vibrator and generator. Water in the storage tank is circulated by the chemical pump. 1″ PVC pipes are arranged to compose a closed circuit. The temperature of circulating water is set to 10℃ and controlled by chiller. THIS-1000NAF-typed chiller involves a digital temperature controller, which can control the variation of circulating water temperature within ±0.5℃.

The flowrate of circulated water in the closed circuit is controlled by a control valve and a bypass valve, and measured by a OVAL flowmeter. The LSV52A3-30 type OVAL flowmeter has the flowrate range of 0.4~3 m^3/h and uncertainty of ±0. 35%. Water flows through the test-section from the bottom toward the top.

When ultrasonic vibration is exerted on the natural water, the cavitation occurs by the gaseous bubble naturally dissolved in the water. However, the turbulence enhancement by the

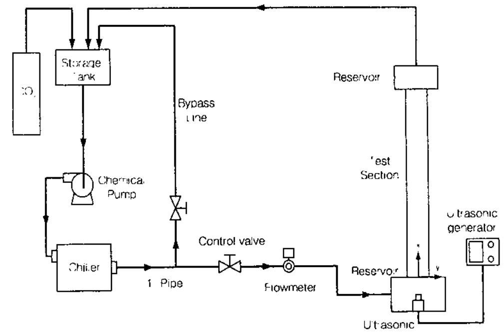

Fig. 3 Test Loop

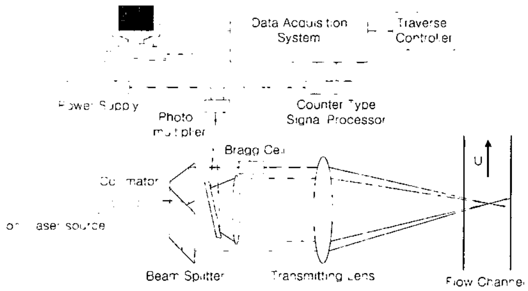

Fig. 4 Schematic of LDV system

cavitation is restricted by the number of trapped gas bubbles that resonate to the ultrasonic vibration. CO_2 can be easily dissolved to water, but it can also be easily formed to gaseous bubble by external disturbances. In the present study, CO_2 is supplied to the circulating water for one hour with constant pressure, 1.6kg/cm^2, to saturate the water by the dissolved CO_2 gas before the experiment.

Turbulence enhancement by ultrasonic vibration is measured by LDV. The LDV system used in the present study is two-components ion laser type manufactured by Dantec. Lens focus length is 160mm and the maximum output of laser beam power is 6kW. The LDV system is composed of a laser beam, fiber flow components, processor, feeding system, etc. as shown in Fig. 4.

A two-dimensional traversing mechanism is used to move the measuring volume. The maximum traversing length of the measuring volume is 690mm and increasing width is capable of minimum 0.1mm.

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 part icl es (di amet er : 1.5μm, density : 3.2g/cm^3). The number of data measured in the present experiment are 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 which is composed of frequency filter, digital sampler, D/A converter, etc.

4. Results and Discussions

In the present study, we measured the emission rate of ultrasonic energy by temperature gradient of water in an adiabatically closed volume using following formula.

$$\dot{W}=\rho c V\frac{dT}{dt} \qquad (7)$$

The emission rate of ultrasonic energy to water is 0.138kW and the efficiency of amplifier and vibrator is about 78%. The emission rates of ultrasonic energy per unit mass flowrate, $\dot{W}/\dot{m}$, for Re=1,000 and Re=4,000 are 3,440J/kg and 860J/kg respectively in the present experimental conditions.

Figure 5 shows the axial variation of measured streamwise velocity and turbulence intensity profiles for the Re=1,000 at $x/D_h=2.5$, 5 and 7. 5. Significant local acceleration of streamwise mean velocity is induced by ultrasonic stream at the core region of the duct as shown in Fig. 5 at $x/D_h=2.5$. The streamwise 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 ultrasonic vibration with gaseous cavitation, however, mean streamwise velocity is not so greatly accelerated by ultrasonic stream near the surface of ultrasonic vibrating cone because the CO_2 gas cavitation may strongly transfer the streamwise ultrasonic stream energy to all the directions.

Turbulence intensity is largely enhanced at $x/D_h=2.5$, but the enhanced turbulence decreases sharply with the flow progress in the case without

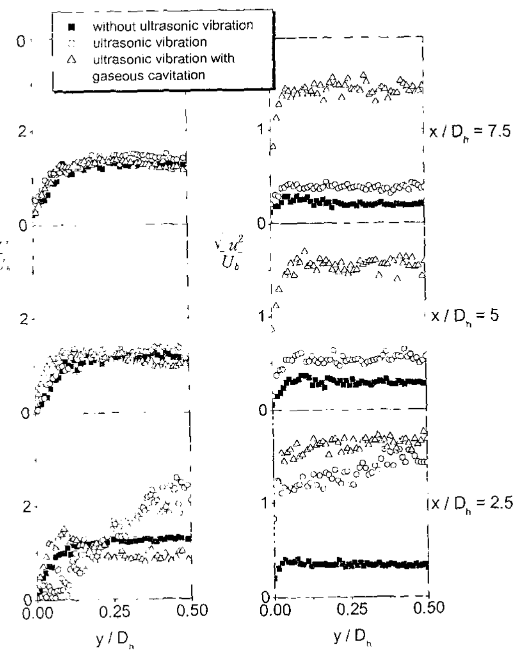

Fig. 5 Axial variations of streamwise velocity and turbulence intensity for Re=1,000

gaseous cavitation. This phenomenon may be occurred due to the vaporous cavitation generated just above the vibrator cone face in which ultrasonic vibration intensity is very high, but they disappear soon as the ultrasonic energy intensity decreases with the flow progress. However, in the case of applying the ultrasonic vibration to the CO_2 saturated water, the enhanced turbulence intensity is almost maintained up to $x/D_h=7.5$ because the gaseous cavitation under the CO_2 saturated water can be maintained under the low ultrasonic vibration intensity.

Figure 6 shows the axial variation of streamwise velocity and turbulence intensity at $x/D_h=2.5$, 5, 7.5 for Re=4,000. In this case, streamwise velocity profiles are affected just slightly by the ultrasonic vibration and gaseous cavitation in comparison with the cases for Re=1,000. The effect of ultrasonic vibration and gaseous cavitation on the turbulent enhancement decreases with the increase of Reynolds number. With the increase of Reynolds number, the emission rate of ultrasonic energy per unit mass flowrate of water, $\dot{W}/\dot{m}$, may decrease so that

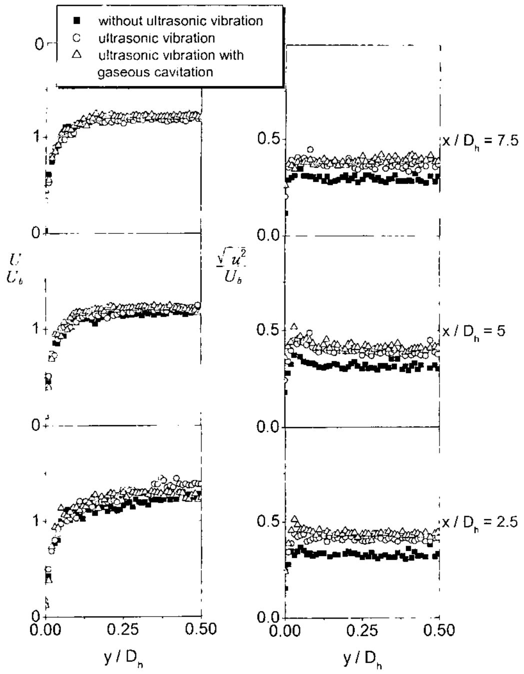

Fig. 6 Axial variations of streamwise velocity and turbulence intensity for Re=4,000

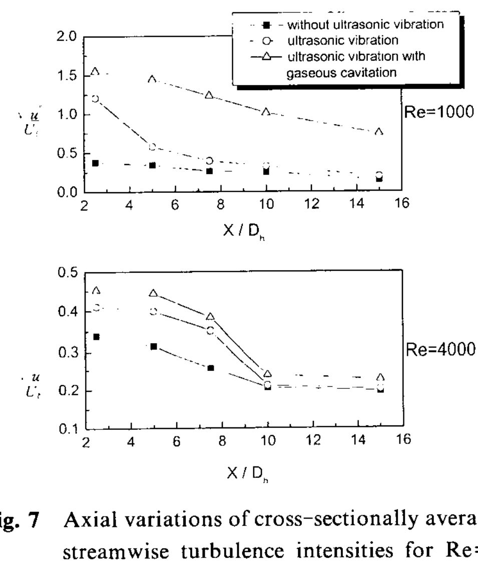

Fig. 7 Axial variations of cross-sectionally averaged streamwise turbulence intensities for Re=1, 000 and Re=4,000

ultrasonic intensity becomes insufficient to arouse the gaseous cavitation. Choi (1979) performed the simulation of gas bubble dynamics under ultrasonic field and verified that there is threshold pressure which gives rise to cavitation for a given gas bubble diameter and ultrasonic frequency.

Figure 7 shows the variation of cross-sectionally averaged streamwise turbulence intensity for Re=1,000 and Re=4,000. In the normal ultrasonic vibration conditions without gaseous cavitation, enhanced turbulence intensity decreases more sharply with the increase of x/D_h while the decrease of turbulence enhanced by the ultrasonic vibration to the CO_2 saturated water slows down for Re=1,000. For Re=4,000, however, the turbulence enhancement effects by the gaseous cavitation decrease. It is due to the decrease of the emission rate of ultrasonic energy to the unit mass of fluid flow with the increase of Reynolds number. It suggests that there is a critical emission rate of ultrasonic energy to activate gaseous cavitation and thereby to enhance turbulence. From Fig. 7, we can expect that the critical emission rate of ultrasonic energy which arouses the significant gaseous cavitation may exist between $\dot{W}/\dot{m}=860$ and $\dot{W}/\dot{m}=3{,}440$. As shown at $x/D_h=15$ in Fig. 7, gaseous cavitation for Re=4,000 holds relatively higher turbulence intensity and it reveals also that the primary factor for the turbulence enhancement is not the ultrasonic stream but the ultrasonically induced gaseous cavitation.

Table 1 shows the enhancement of turbulence intensity for the various ultrasonic vibration conditions. In the case of ultrasonic vibration without gaseous cavitation, the enhancement of turbulence in the near wall region shows lower value than the cross-sectionally averaged value for all the Reynolds numbers. In the cases of ultrasonic vibration with CO_2 gaseous cavitation, however, the turbulence enhancements by ultrasonic vibration in the near wall region are larger than the cross-sectionally mean values.

Figure 8 shows the axial variation of cross-sectionally averaged streamwise turbulence intensity for the stations of $x/D_h=5$, 10, 15 with respect to Reynolds number at the local position of $y/D_h=0.1$. Turbulence intensity decreases sharply with the increase of Reynolds number for all the streamwise stations, but at the position of $x/D_h=5$, the decreasing rate of enhanced turbulence for the normal ultrasonic condition becomes

Table 1 Turbulence enhancement for the various ultrasonic vibration and cavitation conditions

Re	$\dot{W}/\dot{m}$ [J/kg]	y/Dh	Turbulence intensity enhancement (%)			
			ultrasonic vibration without gaseous cavitation		ultrasonic vibration with gaseous cavitation	
			$x/D_h=2.5$	$x/D_h=10$	$x/D_h=2.5$	$x/D_h=10$
1,000	3,440	averaged	289.0	11.0	369.5	58.1
		0.1	220.9	7.5	312.9	64.9
4,000	860	averaged	23.6	31.7	32.6	38.8
		0.1	21.2	11.5	33.5	42.1

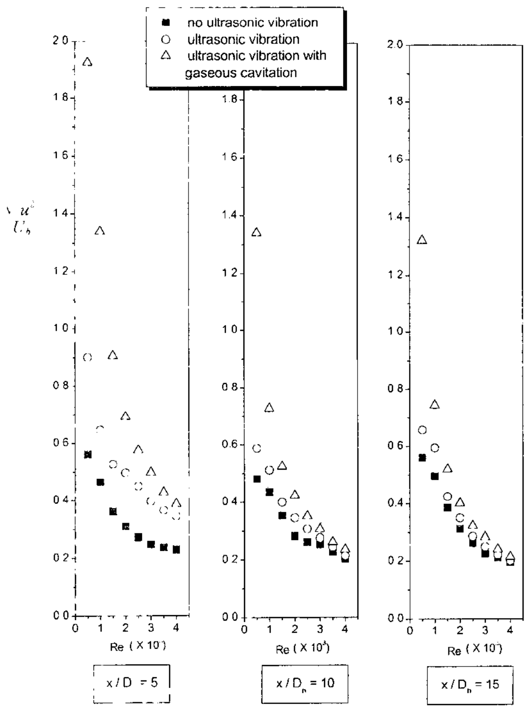

Fig. 8 Axial variations of streamwise turbulence intensities with respect to Reynolds number at $y/D_h=0.1$

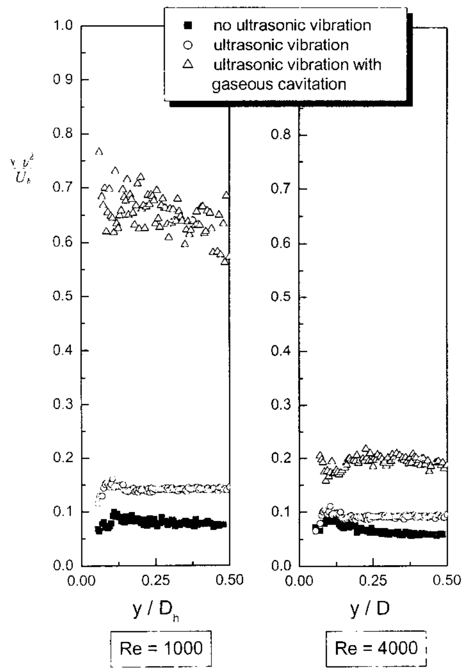

Fig. 9 Distributions of normal turbulence intensities at $x/D_h=10$ for Re=1,000 and Re=4,000

smaller than the downstream conditions.

The turbulence intensities normal to wall at the station of $x/D_h=10$ for Re=1,000 and 4,000 are compared in Fig. 9. The turbulence intensity normal to the wall may influence the heat transfer coefficient of the wall most significantly. DNS data and measurement of the Reynolds stresses for the plane channel flows show that Reynolds stress in normal direction to the wall is highly damped as approaching to the wall. However, Fig. 8 shows that the gaseous cavitation intensifies the near wall turbulence much more significantly than the turbulence in the core region. Generally, the turbulence generated by the shear of mean velocity is damped as approaching to the wall. But the turbulence generated by gaseous cavitations appears not to be damped by the existence of the wall. Therefore, gaseous cavitation acting in the near wall region may break down the viscous sublayer to arouse the significant turbulent heat transfer enhancement in the near wall region.

In the flows without ultrasonic vibration or CO_2 gaseous cavitation, $\sqrt{v^2}/U_b$ decreases sharply as approaching to the wall. For the ultrasonic vibration with gaseous cavitation, however, $\sqrt{v^2}/U_b$ does not show any wall damping effects for Re=1,000 in the LDV measurement range of normal direction because radially fluctuating bubbles make Reynolds stress field more isotropic. But, for Re=4,000, it shows some wall damping effect in the region of $0.125 < y/D_h < 0.2$. The scattered data for $\sqrt{v^2}/U_b$ for Re =1,000 may be caused by the LDV measurement uncertainty due to the violent cavitation. For Re=4,000, scattering of $\sqrt{v^2}/U_b$ data by the gaseous cavitation decreases with the decrease of cavitation. Near wall enhancement of $\sqrt{v^2}/U_b$ by gaseous cavitation may induce the significant heat transfer enhancement.

5. Conclusions

In the present study, a new turbulent heat transfer enhancement technique by ultrasonically induced gaseous cavitation in the CO_2 gas saturated water is proposed to be used for the design of next generation high performance heat exchangers. The gaseous cavitation induced by ultrasonic vibration, the repeated growth and subsequent collapse of small gaseous bubbles may enhance turbulence significantly in the near wall region so that it may increase the heat transfer coefficient much more than the conditions of ultrasonic vibration without gaseous cavitations by breaking down the viscous sublayer. The turbulence generated by the ultrasonically induced gaseous cavitation is maintained far downstream in the straight duct flow. In the present study, we found that there exists a threshold emission rate of ultrasonic vibration energy which generates intense gaseous cavitation for a given ultrasonic frequency. The turbulence enhancement by ultrasonic vibration and thereby induced gaseous cavitation decreases with the increase of Reynolds number due to the decrease of emission rate of ultrasonic energy per unit mass flow rate of water. Measurement of the turbulence intensity in the direction of normal to the wall also reveals that the non-diminishing characteristics of gaseous cavitation in the near-wall region may break down the viscous sublayer so as to increase the turbulence in the near-wall sublayer to yield the significant heat transfer enhancement.

Post Script

We gratefully acknowledge the support provided for this research by Ministry of Science and Technology as part of the nuclear RND program in 1999.

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