An Experimental Study of Developing and Fully Developed Flows in a Wavy Channel by PIV

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An experimental study is presented for a flow field in a two dimensional wavy channels by PIV. This flow has two major applications such as a blood flow simulation and the enhancement of heat transfer in a heat exchanger. While the numerical flow visualization results have been limited to the fully developed cases, existing experimental results of this flow were simple qualitative ones by smoke or dye streak test. Therefore, the main purpose of this study is to produce quantitative flow data for fully developed and developing flow regimes by the Correlation Based Correction PIV (CBC PIV) and to conjecture the analogy between flow characteristics and heat transfer enhancement with low pumping power. Another purpose of this paper is to examine the onset position of the transition and the global mixing, which results in transfer enhancement. PIV results on the Fully developed and developing flow in a wavy channel at Re=500, 1000 and 2000 are obtained. For the case Reynolds Number equals 500, the PIV results are compared with the finite difference numerical solution.

Key Words : Wavy Channel, CBC PIV, Image Coding, Global Mixing, Heat Exchanger

1. Introduction

A channel with a periodically converging-diverging cross section is one of several devices employed for enhancing the heat and mass transfer efficiency due to turbulence promotion and unsteady vortices formation.

After the first work of flow in corrugated channels with triangular wavy cross-section by Goldstein and Sparrow (1977), many researchers, among others Nishimura and co-workers (Nishimura et al., 1986 ; 1990), Wang and Vanka (1995), have investigated this flow numerically and experimentally for sinusoidal wavy channel. Most works considered only fully developed periodic flows and Rush et al's (1999) studied developing wavy channel flow by multiple dye streak visualization and mass transfer measurement. They concluded that there was analogy between the flow instability and the heat transfer enhancement. Most experimental results on flow visualization were simple and qualitative ones by using smoke or dye streak. In this study, a flow field in a two dimensional wavy channel was investigated by PIV experiments.

The practical use of the particle image velocimetry (PIV), a whole flow field measurement technique, requires the use of fast, reliable, computer-based methods for tracking velocity vectors. The full search block matching, the most widely studied and applied technique both in the area of PIV and Image Coding & Compression is computationally costly. Many alternatives have been proposed and applied successfully in the area of image compression and coding, i. e. MPEG, H. 261 etc. Among others, the Three Step Search (TSS) (Jain, 1981), the New Three Step Search (NTSS) (Li et al., 1994), the Hierarchical Projection Method (HPM) (Sauer and Schuartz, 1996), the FFT-Direct Hybrid

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Method (HYB) and the Two Resolution Method (TRM) (Anandan, 1989) are introduced. A Correlation Based Correction technique (CBC) (Hart, 2000) is also appreciated and found to be most accurate and adequate for this flow.

For the cases Reynolds number(Re) of 500, 1000 and 2000, developing and fully developed flow data are obtained by CBC PIV with one window shifting. The global mixing phenomenon, which results in the increase in heat and mass transfer and drag, can be identified through the investigation of developing flow in beginning modules. At Re above 500, promotion to turbulence is prominent, while it happens at Re above 2300 in a straight channel.

2. PIV Algorithm

A numerical solution of a lid driven cavity flow of Reynolds number 1000 is used to produce a synthetic image with variable length scales and velocity gradients. (Kim, 1996) A Gaussian noise is superimposed on particle images. To compare the accuracy and computation time, algorithms with same validation, subpixel fit and vector smoothing schemes are applied to a synthetic image data. The three-point Gaussian fit is used for a sub pixel estimator, and the Local Median Filter (LMF) is chosen to validate a vector field. (Kim, 1999)

Vector searching algorithms compared are summarized as follows; TSS that operates in decreasing search radii, NTSS that a modification of TSS to deal with small displacement, HPM that is based on matching of integral projection image, HYB that is a hybrid method in calculation of a cross-correlation coefficient, TRM which uses Gaussian filtered image, and CBC PIV that is based on the correlation tables calculated during processing of one region is multiplied, element-by-element, by the correlation tables calculated from an adjacent region that overlaps the first region by fifty-percent.

The comparison of CPU time, from Cross-correlation Step to Final Velocity Vector Step with PC (Pentium II 266 MHz), and the average pixel errors of algorithms are summarized in

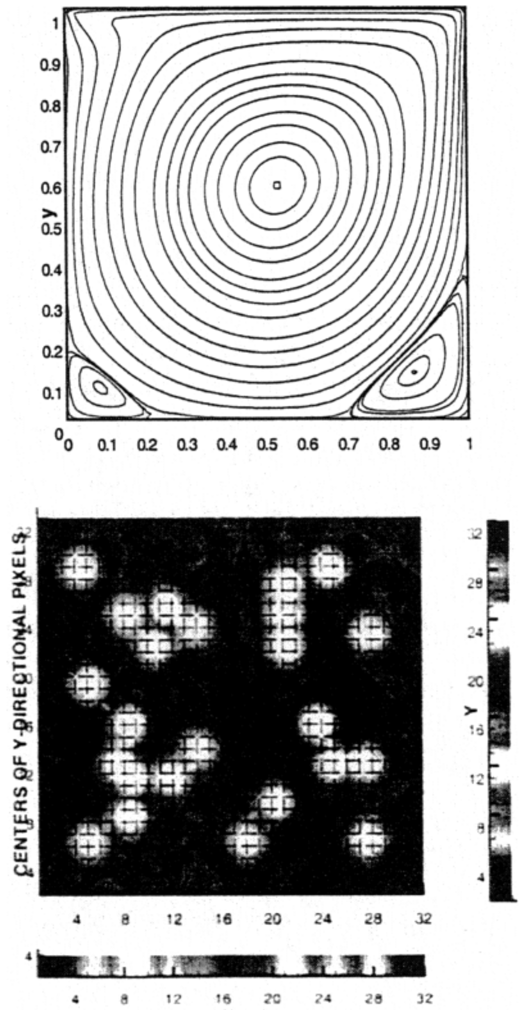


Fig. 1 Numerical solution and synthetic data

Table 1. A Correlation Based Correction PIV (CBC) is found to be most accurate with minor loss in CPU time due to having less spurious vectors. Therefore, CBC with bi-linear interpolation for recovering vectors is used for the flow analysis in this paper. (Kim, 1999)

3. Experiment

The experimental facility is shown in Fig. 2. A closed water channel of 25cm long (including 24 wavy modules), 10cm wide and 0.5cm deep (mean depth) is mounted vertically after a straight developing channel of 20cm long. A

Table 1 CPU time and mean error

	MAX MOVE=7 pixel		MAX MOVE=10 pixel		MAX MOVE=15 pixel	
	CPU (sec)	Mean Error (pixel)	CPU (sec)	Mean Error (pixel)	CPU (sec)	Mean Error (pixel)
FULL	119.84	0.181148	232.8	0.199498	965.59	0.286080
HYB	5.11	0.179420	5.99	0.2082559	20.10	0.327700
HPM	1.78	0.216993	2.42	0.322161	3.02	0.581900
NTSS	12.64	0.195907	21.09	0.218521	-	-
NTSS*	3.63	0.207645	5.98	0.267543	9.12	0.526304
CBC	4.56	0.1202406	4.61	0.1582305	4.61	0.2316873

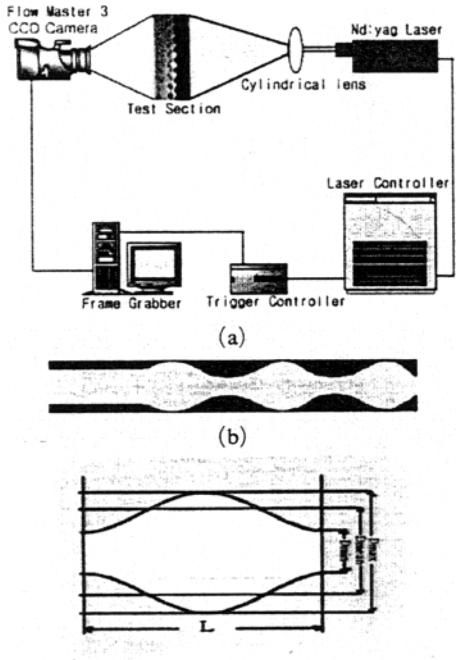


Fig. 2 (a) Experimental Set-up (b) Connection of Straight Pipe and Modules (c) Test Section : L=10mm, Dmax=7.5mm, Dmin=2.5mm

double pulse Nd:Yag Laser (SPECTRON Co., 150 mJ/pulse) is synchronized to the CCD camera (LaVision Co., 1280*1024 pixels, 8 pair frames/sec.) with a 105mm Nikkor Micro-lens by a Trigger Controller. The polyester particles (Glass Bead-Hollow's part#900890, 8-12 μm in diameter) are used as tracers.

A nineteenth wavy module (10mm*7.5mm) is chosen as a test section of fully developed flow. [Fig. 2(c)] A CBC with window shifting (64*64 to 32*32 pixels in window size) is applied to these images. Adjacent interrogation spots of a final stage were overlapped by 50%, providing a resolution of 10 μm/pixel. 1024 velocity data (80*64 vectors) are averaged to give mean velocity and RMS set.

4. Results

First, fully developed Flow data of Re 500, 1000, 2000 are obtained through the CBC PIV measurements of flow in the 19th wavy module. 1024 instantaneous velocity data are post-processed to produce mean and RMS quantities.

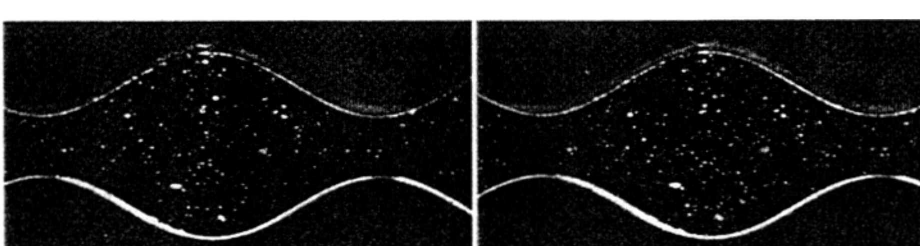


Fig. 3 A pair of images: 1280x1024 pixels

Figure 4 show the numerical and PIV streamlines on Reynolds number 500, which agrees well with (Rush et al., 1999). The instantaneous and mean velocity of Re 500 and 2000, depict in Figs. 5 and 6. While there is difference in the amount of turbulence and instability varying Reynolds numbers, there exist the turbulence and instability in both cases, which become prominent at higher Re. Urms and Vrms reaches 25% of average velocity in a section for Re=500, and 40% for Re=2000, while flows in a straight channel is laminar at those Reynolds numbers. In the transition problem, the upstream flow condition is important. The average velocity data of Re 1000 at a inlet portion of the first wavy module are given in Fig. 7. It shows a typical parabolic velocity profiles with maximum Urms and Vrms of 2~3% of average velocity, which is within accuracy limit of algorithm and image resolution, 0.2 pixel movement error. Therefore, the increase in turbulence

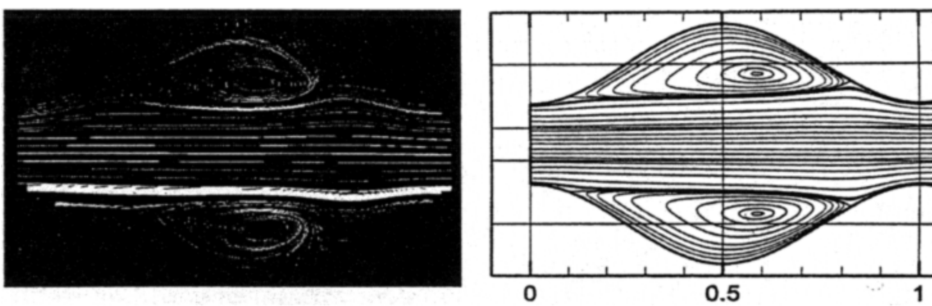


Fig. 4 Mean Streamlines of Numerical Solution (Right) and PIV Result (Left) : Re=500

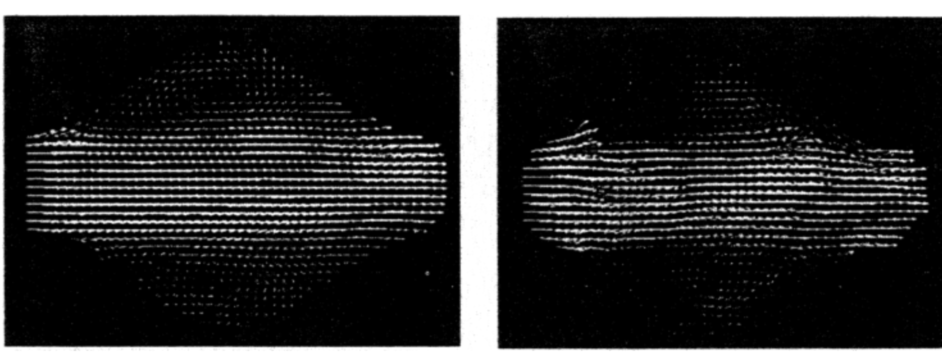


Fig. 5 Mean (Left) and instantaneous velocity: Re=500

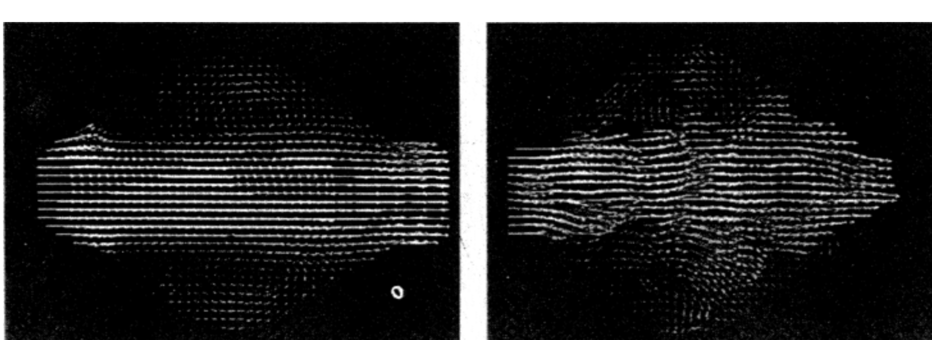


Fig. 6 Mean (Left) and instantaneous velocity: Re=2000

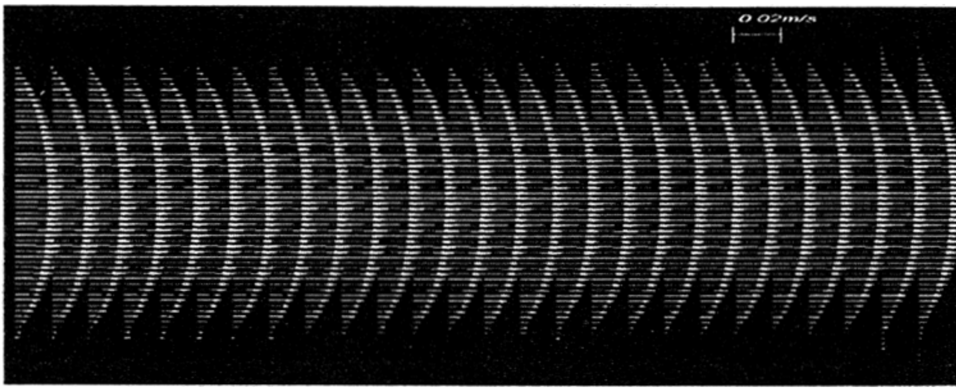
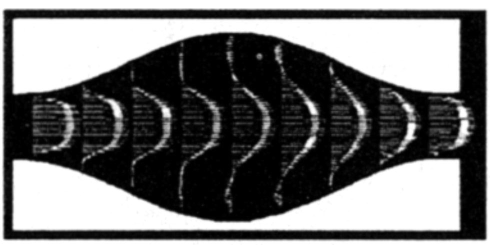
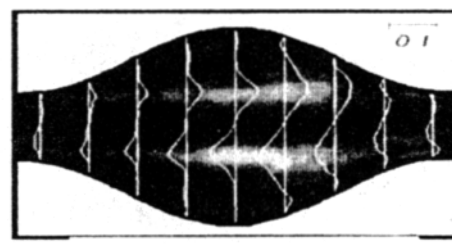


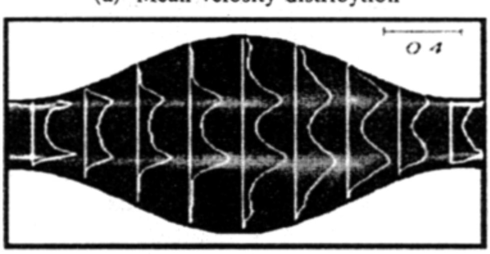
Fig. 7 Mean Velocity Data in a inlet of wavy module for Re=500



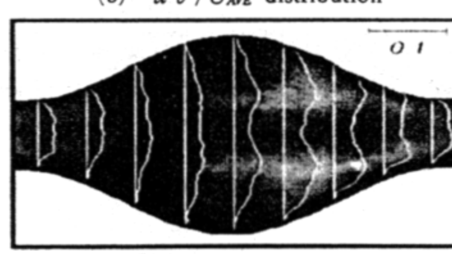
(a) Mean velosity distribytion



(b) $-\overline{u'v'}/U^2_{AVE}$ distribution



(c) $\overline{u'^2}/U^2_{AVE}$ distribution



(d) $\overline{v'^2}/U^2_{AVE}$ distribution

Fig. 8 Mean and Turbulent Intensities for Re = 1000

and instability is due to the geometry of this flow.

A mean velocity and turbulent intensities of Re 1000 are shown in Fig. 8 , where U_{RMS} dominates V_{RMS} and $\overline{u'v'}$ (look at scale). As Re increases above a critical value, from beginning modules, there exists the global mixing between core and near wall re-circulating flows through the flow instability, which results in the increase in heat and mass transfer and drag. This phenomenon can be seen through instantaneous velocity and RMS distributions in beginning modules. It occurs at 4th wavy module in case Re equals 500, and 2nd module in case Re equals 1000, that shows a good agreement with Rush et al's predictions (Rush et al., 1999). URMS dominates VRMS and $\overline{u'v'}$ in fully developed flow (Re=1000). For the case Reynolds Number equals 500, a streamline plot of PIV result shows a good agreement with the finite difference numerical solution. At Re above 500, promotion to turbulence is prominent, while it happens at Re above 2300 in a straight channel.

Figure 9 is presented to conjecture the analogy between the flow instability and the heat transfer enhancement. Distributions of RMS quantities are parallel to those of local Nusselt No. in 3 dim. wavy pipe (Russ and Beer, 1997) and local Sherwood No. in 2 dim. Wavy channel. (Rush et

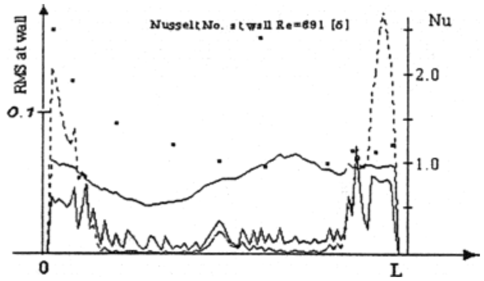
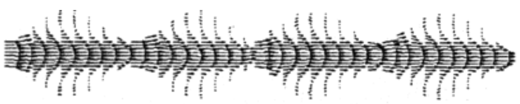
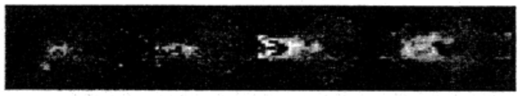


Fig. 9 Fig. 9 RMS Intensities near wall for Re = 1000. : URMS (Long dashed line), V_{RMS}* 10 (Solid line), Mean RMS in section (Short dashed line)



(a) Average velocity

(b) Instantaneous velocity

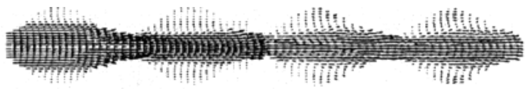


(c) RMS($U^2_{RMS}+V^2_{RMS}$) distribution

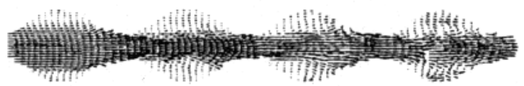
Fig. 10 Developing flow results(2-5 Modules) ; Re=500

al., 1999)

To obtain the position of the unsteady stall, a global mixing between the core and near-wall fluid which gives the increase in heat transfer and drag, a developing flow in the beginning wavy modules are investigated by PIV measurements. Figure 10 shows an instantaneous velocity field in 2-5 wave modules for Re 500 case. From 4th wavy module, instantaneous velocity deviates severely from mean velocity and RMS increases abruptly. Onset of macroscopic mixing can be seen at the 4 to 5 wavy modules, excluding a beginning half module, which agrees well with Rush et al. 's observation. (Rush et al., 1999) As same analogy, onset happens at 2nd module in case Re equals 1000, as shown in Fig. 11. In engineering applications with a finite number of wavy



(a) Average velocity



(b) Instantaneous velocity

(c) RMS distribution

Fig. 11 Developing flow results(1-4 Modules) ; Re=1000

modules, developing flow analysis is inevitable due to variance of the onset position of the global mixing. PIV can be a good tool for this problem.

5. Summary

Unlike a simple dye or smoke streak visualization, the PIV analysis can resolve the exact flow structure, even in turbulent flow situation. It can also deal with the unsteady behavior of global mixing. In this paper, fully developed and developing flow data in a wavy channel of Re 500, 1000, 2000 are obtained through the CBC PIV measurements. The analogy between flow characteristics and the enhancement of heat and mess transfer in a wavy channel can be visible through the RMS distribution near wall. The onset point of the global mixing is clearly identified through instantaneous velocity and RMS intensity distributions of a couple of beginning modules. It happens at 4th wavy module for Re=500, and 2nd module in case Re equals 1000, which are in a good agreement of Rush et al.'s prediction from dye streak visualization.

The phase averaging of PIV results will give a more precise insight of flow structure, like instability and shedding vortices etc. , will be a future work.

Acknowledgement

This work was supported by Grant No. 2000-1-30400-002-3 from the Basic Research Program of the Korea Science and Engineering Foundation, Republic of Korea.

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