EFFECT OF STABLE DENSITY STRATIFICATION ON SECONDARY FLOW IN COMPOUND CHANNEL

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Flow measurements were undertaken in a compound channel to investigate the effect of stratification on secondary flow in two-layer density-stratified flow. Secondary flow and salinity were measured using a laser induced fluorescence technique together with a laser Doppler anemometer system. Flow visualisation was also carried out using a digital video camera to demonstrate the effect of stratification on flow. The measured data shows that the size of typical twin vortices in the compound channel reduces as the degree of stratification increases. Two generation mechanisms of secondary flow were recognized on the floodplain, namely non-isotropic turbulence driven secondary flow and density driven secondary flow. The production of turbulent kinetic energy due to buoyancy was found to be not significant in most region but is significant in the water surface region.

Key Words : compound channel flow, stratification, secondary flow, Visualization, LDA

1. INTRODUCTION

Flow in a compound channel consisting of a main channel and floodplains has been extensively studied for river floods [1), 2), 3)]. As a result, complicated flow characteristics have been observed in the shear region between the main channel and the floodplain. For example there are strong secondary currents from the edge of the floodplain to the water surface due to non-isotropic turbulence in the shear layer[4)] and lateral alternative currents due to shearing between faster flow in the main channel and slower velocity[5)] in the flood plain. In estuaries, there are sand bank, wetlands, flood plains and mangrove swamps (tropical estuaries), which are considered to be compound channels. Such channels may have partially stratified flow due to salinity and suspended solids variations in cross-sections. For partially stratified flow in straight channel, Smith[6)] first postulated that, secondary flows can be induced by the effect of lateral shear in the presence of a longitudinal density gradient, thus producing a lateral density gradient. This is partially observed by Nunes & Simpson[7)] in the Conwy estuary and demonstrated by a quasi three-dimensional numerical model using the mixing length approach[8)]. In flooding rivers, density difference due to suspended solids may occur between in the main channel and in the floodplain. In a compound channel the flow structure for a stratified flow condition is not well known since the data is not available or non-existent. This paper presents measurement results of secondary flow, density distribution, turbulent kinetic energy and its production and Reynolds stress in a compound channel for a stratified flow condition in order to understand the flow structure.

2. EXPERIMENTS

The compound channel made of perspex with dimensions of 100mm top width, 50mm floodplain height, 50mm main channel width and 250mm total height was constructed within a flume 13m long, 0.3m wide and 0.3m deep (**Fig.1**). The bed slope of the channel was set to 1:2000. There were two straight ducts in the first 2.5m of the open channel separated by a thin rigid plate at 50mm height from the bottom of the channel in order to make two-layer density-stratified flow. The lower duct was used to discharge saline water and the upper duct was for fresh water. The flows discharge 20.5*l/min* in the lower duct and 31*l/min* in the upper duct in order to make the same mean velocity in both ducts. The experiments were carried out under three density differences between saline water and fresh water at the inlet, and the total discharge and the water depth kept the same while the density differences were changed to 1kg/m^3, 3kg/m^3, and 5kg/m^3. The results of the measurements presented here are only for the fresh water and 5kg/m^3 cases. Salt water mixed with fluorescent dye, Rhodamine

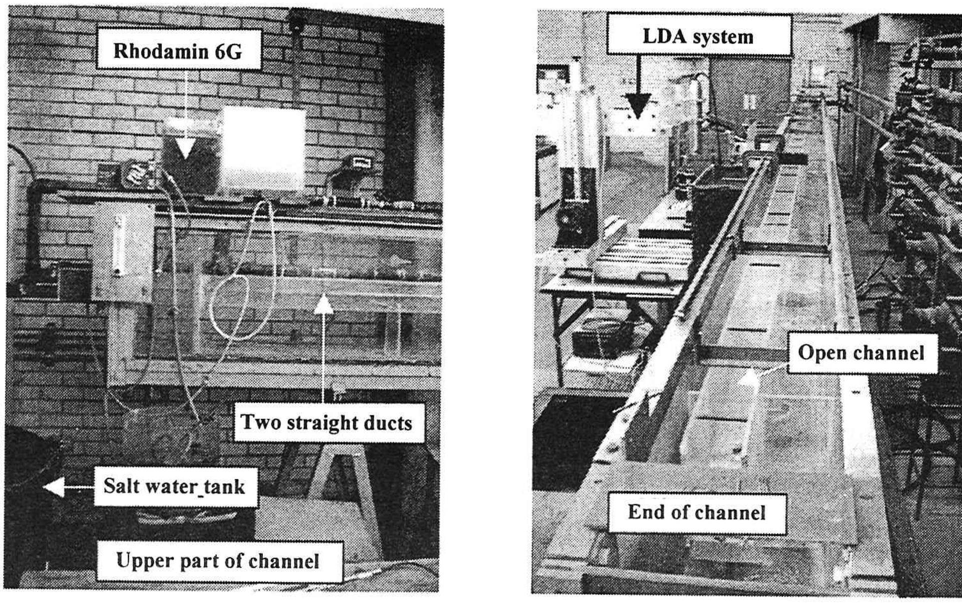

Fig. 1 Experimental set-up.

6G in the inlet lower duct (or the main channel). The measurements were undertaken at 2 sections along the compound channel (3.2m and 6.4m). A laser induced fluorescence (LIF) system was use to measure the concentration of dye, Rhodamin 6G, as a surrogate for salinity. Three components of velocity and salinity together were measured with a TSI three component fibre optic laser Doppler anemometer (LDA) together with a LIF system and a data acquisition system, which belongs to the Engineering and Physical Sciences Research Council (EPSRC) loan pool in the UK. The details of this technique can be seen in Feng and Shiono[9).

3. RESULTS

(1) Visualization

Flow visualization was first conducted using a digital video camera. Fluorescent, Rhodamine 6G was injected in the inlet lower duct and was illuminated with a laser sheet. The camera captured flow behaviour at 3 sections along the channel in the first 1m from the inlet. The 3 sections were at 27.5cm, 60cm and 100cm. A captured video source was processed by commercially available software. **Figs.2** and **3** show a few frames at 3 section along the channel with fresh water and 5kg/m^3 density difference at the inlet for shallower and deeper cases. Although the length of the test sections was short to be fully developed flow, it can be seen from the plates that the development of flow is clearly recognized.

For the deeper depth and fresh water case (**Fig.2**), at the first two sections, the dye appears to be distributing more near the left wall in the main channel, not on the flood plain wall side. At 100cm, the dye is clearly moving onto the flood plain, which is an indication of secondary currents or lateral alternative currents started developing. For the 5kg/m^3 density difference case, most dye appears to stay in the lower layer even at 100cm, which indicates that the sharp density interface reduces turbulence mixing and the magnitude of secondary flow. It is noticed at 100cm that the dye tends to move onto the floodplain from the main channel, but the height of dye is lower than that in the fresh water case, which could indicates that density induced currents occur.

For the shallower depth case, **Fig.3 (a)** shows the fresh water case, in which the behaviour of dye is noticeably different from that for the deeper depth case. The dye appears to move upwards both side of the walls in the main channel even at 27.5cm, and onto the floodplain at 60cm, and occupies most area in the main channel and diffuses on the floodplain at 100cm. From the observation of Plates, the development of secondary flow seems to be faster in the shallower depth case that for the deeper depth case. For the 5kg/m^3 density difference case, it can be seen that the action of dye in the main channel appears to be more than that for the deeper depth case. At 60cm and 100cm, a clear ejection of dye at the edge of the floodplain can be observed and the transport of dye on the floodplain is also seen.

The comparison of the flow behaviour between the deeper and shallower depth cases and the density difference cases gives a clear view of flow development in this compound channel although the flow visualization was taken near the inlet.

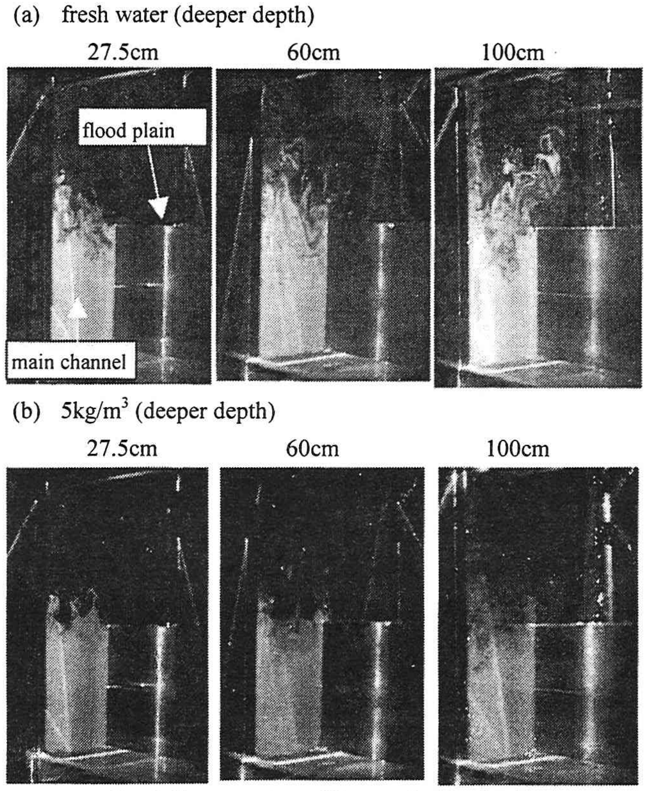

Fig. 2 Cross section of flow in deeper depth

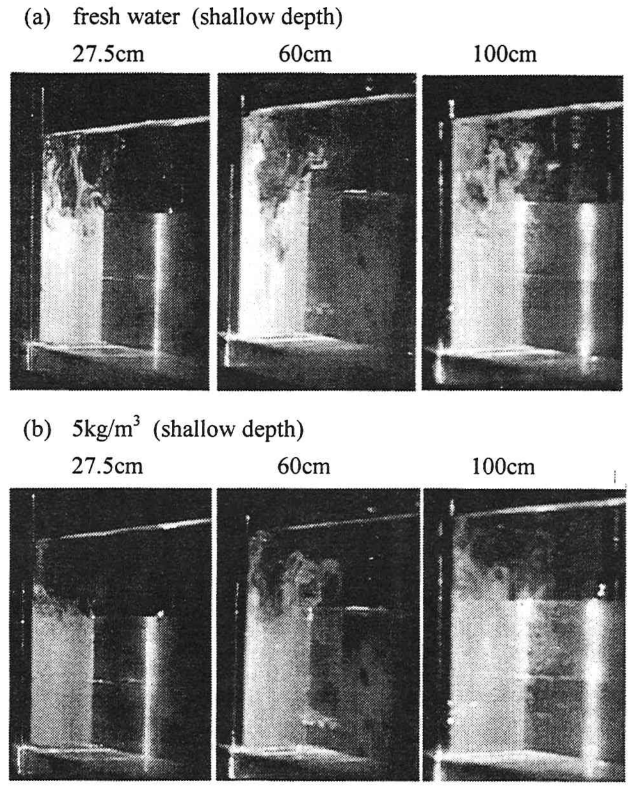

Fig. 3 Cross section of flow in shallow depth

(2) Mean flow Structure

The distributions of mean longitudinal velocity at 6.4m are plotted in **Fig. 4 (a)**. For fresh water in the lower duct at the inlet, it can be seen from **Fig. 4(a)** that there is a bulge in the flow pattern from the vicinity of the edge of the floodplain to the water surface. As density difference increases to 5kg/m^3 in the lower duct inlet this bulge appears to be less pronounced, which implies that the flow was not yet fully developed and clearly still in progress.

Secondary flow vectors are shown in **Fig. 4(b)**. For the fresh water case, at 6.4m, it can be clearly seen from the figure that there are twin vortices in the region between the main channel and the floodplain. There are three secondary flow cells on the flood plain, one in the corner of the floodplain wall, one in the area of the water surface and one near the main channel. For the 5kg/m^3 density difference case, the size of the twin vortices on the floodplain is smaller than that for the fresh water case. It is interesting to observe only two secondary flow cells on the floodplain, one of the two vortices becoming stronger and larger, in which the transverse secondary currents near the bed increased as the salinity increased. The result indicates that the secondary flow on the floodplain, in particular, is significantly affected by the transverse density variation.

The distributions of density for 5kg/m^{3}density difference at the inlet condition are also shown in **Fig. 4(c)**. The saline water intrudes onto the floodplain as the flow travels downstream. In the main channel, it can be observed that the stratification is more or less stable. It is noticeable that the denser water creeps upwards along the main channel wall on the side of the floodplain at the 3.2m downstream section. On the floodplain, salinity is vertically mixed in the region of one of the twin vortices. From the secondary flow structure in the vicinity of the floodplain edge, as indicated before, it appears that the twin vortices transport denser saline water upwards from the main channel into fresh water in the upper layer to induce a transverse density gradient. As a result a difference of the hydrostatic pressure in the lateral direction over the water depth occurs which generates secondary currents flowing towards the floodplain wall as a density driven circulation. This circulation appears to supersede the secondary flow circulation in the corner region of the floodplain wall generated by non-isotropic turbulence. There therefore exist two types of secondary flow circulation mechanisms on the floodplain, namely the non-isotropic turbulence driven circulation and density driven circulation.

(3) Turbulent parameters in the shear layer

Turbulent kinetic energy (TKE) is shown in **Fig. 5(a)**. TKE is defined as:

$$\mathrm{TKE}=\frac{1}{2}\left(\overline{u^2}+\overline{v^2}+\overline{w^2}\right).$$

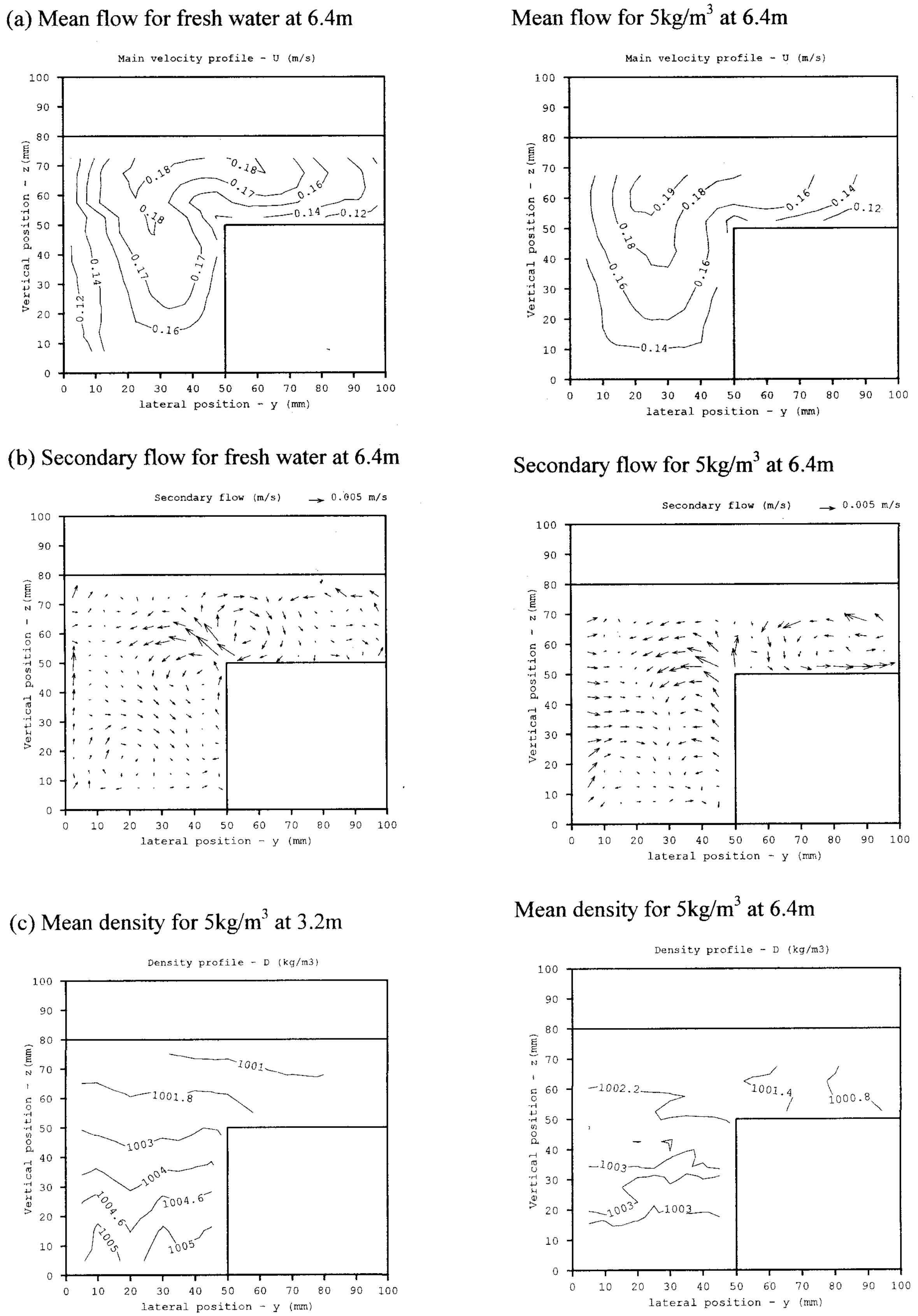

Fig. 4 Flow and density structures

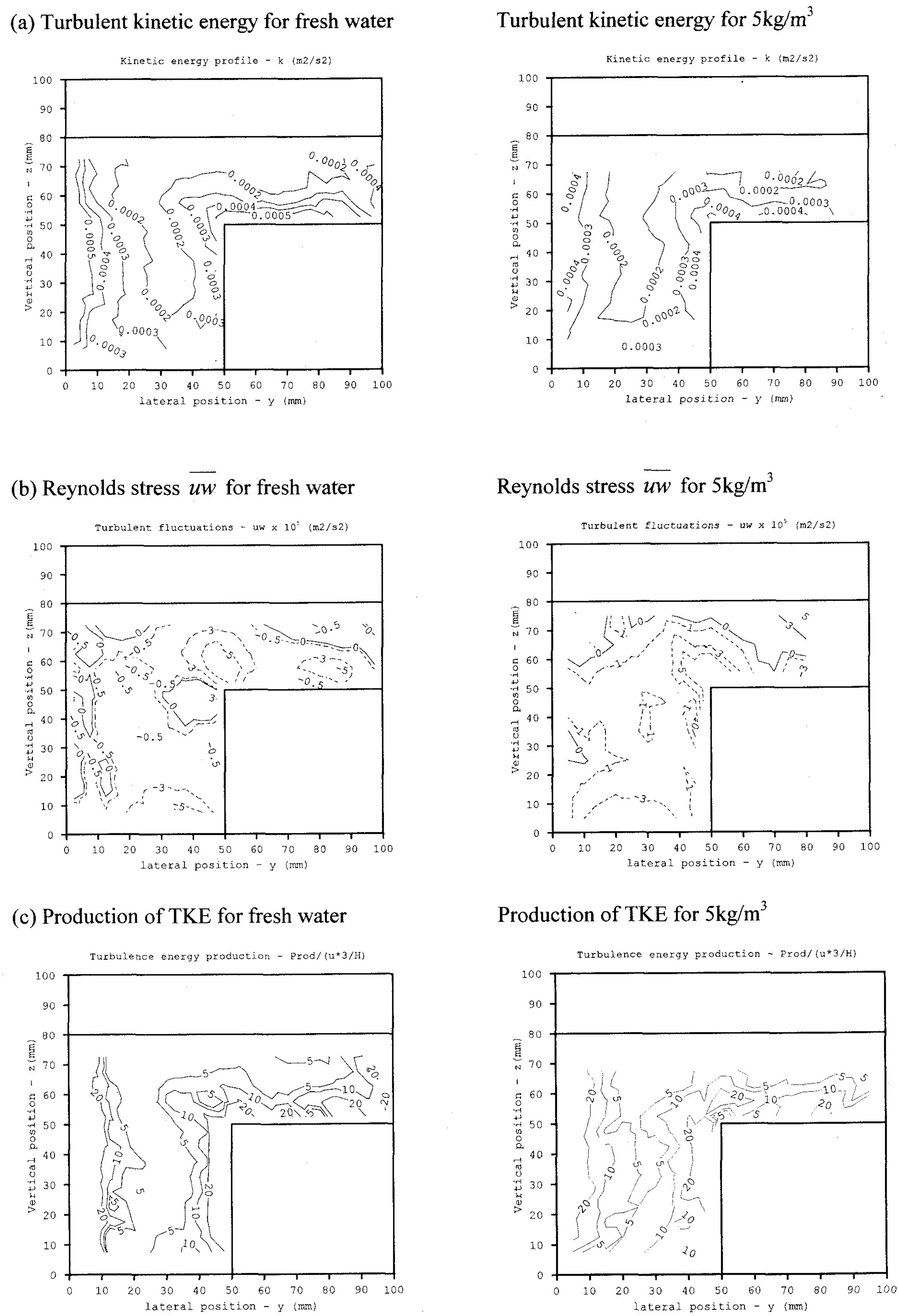

Fig. 5 Turbulent parameters

The u, v and w are turbulent perturbations in the longitudinal, lateral and vertical directions. The bar is time average.

For fresh water, a bugle in the TKE distribution is more pronounced and skewed in the main channel than that for 5kg/m^{3}density difference. The magnitude of TKE on the floodplain appears to be less for the 5kg/m^3 difference case than for the fresh water case. The Reynolds stress due to the horizontal plane shear shown in **Fig. 5(b)** indicates that there is a negative region in the vicinity of the edge of the floodplain for the fresh water case, but it disappears for the 5kg/m^3 density difference case. This shows a clear effect of stratification on the momentum transfer. The production of TKE due to all Reynolds stresses was calculated using the measured data and is shown in **Fig.5(c)**. The production of TKE is defined as:

Production=

$$-\overline{v^2}\left(\frac{\partial \overline{V}}{\partial y}\right)-\overline{w^2}\left(\frac{\partial \overline{W}}{\partial z}\right)$$

$$-\overline{uv}\left(\frac{\partial \overline{U}}{\partial y}\right)-\overline{uw}\left(\frac{\partial \overline{U}}{\partial z}\right)-\overline{vw}\left(\frac{\partial \overline{V}}{\partial z}+\frac{\partial \overline{W}}{\partial y}\right)$$

The component of the longitudinal direction is ignored in the equation because of small.

It is clearly noticed that the production is larger on the floodplain for the fresh water case than for the 5kg/m^{3}density difference case. There is a more distinct bulge in the distribution in the shear layer region for the fresh water case. For the 5kg/m^3 density difference case, it is interesting to notice a large value (20) of the production in the region just above the floodplain edge at which one of twin vortices appears. This value seems to be larger than that for the fresh water case, for which, in the previous flow visualization section, the denser fluid moves onto the floodplain from the main channel and make unstable stratification, as a result, an extra turbulence may be possibly generated by this unstable stratification. To compare the magnitude of each term in the equation, the fourth term is dominated on the floodplain, but the third term is the main contribution to the production in the main channel.

4. CONCLUSIONS

Flow visualization was first undertaken using a digital video camera in order to observe flow behaviour in a compound channel for stratified flow. Fluorescent, Rhodamine 6G illuminated by a laser sheet clearly shows the difference of mixing processes in stratified flow although the locations of the pictures taken were near the inlet.

Velocity contour lines show that a bulge in the flow pattern is clearly less pronounced as the density difference at the inlet increases. The size of the twin vortices on the flood plain was also reduced as the density difference increased. It was observed that, on the floodplain, density is well mixed vertically in the region of one of the twin vortices and the transverse variation of salinity in the rest of the floodplain. This transverse salinity gradient induces the density driven secondary circulation on the floodplain by which the secondary flow due to non-isotropic turbulence driven circulation in the corner region of the floodplain wall is superseded. The distributions of turbulent kinetic energy, the Reynolds stress and the production of TKE in the shear layer show the effect of density stratification on the turbulence in the shear layer region.

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