# Comparative study of turbulent kinetic energy and kinetic energy based on LDV measurements and average velocity computations in locally contracted channels

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This paper presents the experimental investigation by using Laser Doppler Velocimety (LDV) in locally contracted channel, sudden upstream and subsequent gradual expansion of slope of (1H:1V), (3H:1V) and (5H:1V) in a horizontal channel of constant width. For precise and accurate measurements of the mean fluctuating flow quantities such as streamwise and vertical turbulence intensity components; streamwise and vertical mean velocity components. The measurements are carried out along the depth of different cross sections upstream, within and downstream of the transition (sudden contraction subsequent gradual expansion of different slopes). The measurements are conducted at different contraction ratios of 0.3 and 0.5 in the longitudinal direction along the centerline and across the transition at different locations to assess the variation of mean and turbutent kinetic energy. The results show that, Kinetic Energy (KE) computed from LDV measurements of streamwise mean velocity component and turbulence intensity components, is slightly larger than the K.E computed from the average velocity measurement in the upstream reach. This difference is large in the downstream reach. However, within the transition KE as computed from the average velocity is greater than the KE computed from LDV. The maximum turbulence KE and mean KE do not necessary occur at the same locations. The turbulence intensities increases in the upstream region of the transition, the turbulence intensities are quite high due to the surface and oblique waves interference. Downstream of the transition, the turbulence intensities are such higher as compared to turbulence upstream or within the transition.

هذا البحث يهتم بدراسة مقارنة لطاقة حركة الاضطراب وطاقة الحركة الناتجة من القياسات باستخدام جهاز الليزر الحديث (LDV) وطاقة الحركة المتوسطة المحسوبة من السرعة المتوسطة .وتمت الدراسة على الانتقالات الأفقية المحددة الطول في القنوات الأفقية المفتوحة ذات المقطع المستطيل ثابتة العرض (مدخل الانتقال تغير مفاجئ والمخرج ذات ميول مختلفة 5:1, 3:1, 1:1). ولقد أجريت الدراسة لقياسات دقيقة لكثافات الاضطراب والسرعات للسريان المضطرب في الاتجاه الأفقي (اتجاه السريان) والاتجاه الرأسي (اتجاه عمق المياه). وتمت القياسات لنسب تقلص (Δb/b= ٠,٣ ، ٠,٥ ) لقطاعات طولية في اتجاه المحور. وقد تم اعداد منحنيات لا بعدية لطاقة حركة الاضطراب وطاقة الحركة المتوسطة وكثافات الاضطراب والسرعات في الاتجاهات المختلفة للقطاعات المختلفة أمام وداخل وخلف الانتقالات. وبتحليل ومناقشة النتائج قد تبين أن طاقة الحركة المحسوبة من القياسات بجهاز الليزر (كثافات الاضطراب في الاتجاهات المختلفة والسرعة في اتجاه السريان) أكثر قليلاً من طاقة الحركة المحسوبة من السرعة المتوسطة وذلك للقطاعات أمام الانتقالات. وقد تبين أن الفرق كبير في القطاعات خلف الانتقالات أما القطاعات داخل الانتقالات فقد وجد أن طاقة الحركة المحسوبة من السرعة المتوسطة أكبر من طاقة الحركة المحسوبة من القياسات بجهاز الليزر. وبدراسة النتائج وجد أن أقصي قيمة لطاقة حركة الاضطراب للإنتقالات المختلفة ليس من الضروري حدوثهم عند نفس القطاع. وكذلك من نتائج البحث وجد أن كثافات الاضطراب عند مدخل الانتقال تزداد بزيادة نسبة التقلص. وفي داخل وخلف الانتقال وجد أن كثافات الاضطراب تزداد زيادة كبيرة بزيادة نسبة التقلص مع التغير السريع لكثافات الاضطراب في مناطق القاع وسطح المياه. ومن النتائج لوحظ أن كثافات الاضطراب تزداد في اتجاه حركة السريان نحو الانتقال وفي داخل الانتقال تزداد كثافات الاضطراب عند سطح المياه وذلك يرجع إلى الموجات المتولدة. أما في الخلف لوحظ زيادة ملحوظة لكثافات الاضطراب مقارنة بأمام وداخل الانتقال.

**Keywords:** Kinetic energy, Contracted channels, Turbulent flow, Average velocity

## 1. Introduction

As the flow passes through a bridge, a channel transition in the form of contraction and subsequent expansion is involved. It is well known that turbulent field in open channel transition can be regarded as the superposition of many eddies with different scales, and the fundamental characteristics is the interaction among these structures. In designing a channel transition, such as

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contraction or expansion, it is always desirable to avoid excessive energy losses, to eliminate cross waves and the turbulence, to provide safely for the structure, to ensure smoothlined flow, to minimize standing waves, and to prevent the transition from acting as a choke influencing upstream flow. Free surface has a unique role in governing the turbulence in the open channel flows. The study of the problem of the open channel transitions has fundamental significance. These problems are characterized by a rapidly changing flow field which displays a high intensity of turbulence. The turbulence is highly non homogeneous and anisotropic and has very high interdependence with mean flow. One of the purposes to study the turbulence in open channel transitions is to gain insight about the role of turbulent kinetic energy, and the properties and interactions of these turbulent structures. The turbulent flow models in open channel flows are discussed by Rodi [1], Wilcox [4], and Nezu and Nakagawa [2,3]. Experimental investigation on turbulent structure of back facing step flow, have been reported by several investigators such as Nakagawa [5], Ruck [6], Armaly [7] and Kim [8].Measurement of turbulence characteristics in open channel flows using LDV have been pointed by Song [9], Papanicolaou [10, 11], Mclelland [12] and Nezu [13]. Simulation of turbulent flow at a Reynolds number, has been pointed by Atonia [14] and Bernero [15]. The present study deals with the experimental investigation by using Laser Doppler Velocimetry (LDV) in locally contracted channel, sudden upstream and subsequent gradual expansion of slope of (1H:1V), (3H:1V) and (5H:1V) in a horizontal rectangular channel of constant width. Measurements of streamwise mean velocity components $\bar{u}/U_o$ and $v/U_o$, and streamwise and vertical turbulence intensity components $u`/U_o$ and $v`/U_o$ across and along the channel length of the different cases of transition at contraction ratios $\Delta/b$ of 0.3 and 0.5 at constant flow rate of 44 l/s, were made using LDV. The main objective of the present research is, to conduct a study of turbulent kinetic energy in locally contracted channel, sudden upstream subsequent gradual expansion of slope 1:1, 3:1 and 5:1 at different cross sections upstream, within and downstream of the transitions. Another study of Kinetic Energy (KE) based on LDV measurements and average velocity computation in open channel transitions is to be conducted and compared with the study of turbulent kinetic energy.

## 2. Experimental set up and test procedure

The measurements were carried out in a horizontal rectangular open channel that is 9500 mm long, 300 mm width and 500 mm height with glass wall 6 mm thick and a steel bed. Fig. 1 shows layout of test facility. The water is supplied from a constant head overhead tank to the flume at a desired discharge that is continuously monitored with an on-line orifice meter. The flume side walls are make up of 6 mm thick glass sheets. A tail vertical gate is provided at the downstream end of the flume to maintain a required water depth of the channel flow. The water is finally collected in a sump from where it is pumped back to the overhead tank by a 15 HP pump. There different types of horizontal transitions were fabricated from transparent sheets. One type of constriction at the inlet (sudden) and expansions at the outlet were, gradual (1H: 1V), (3H: 1V) and (5H: 1V).

With reference to the origin fixed at the channel bed and in the centre of the transition, transverse of measuring volume was run to obtain the profiles of both the mean velocity components and RMS of the turbulence intensities. The measuring points were closely spaced in the region of high velocity gradient. All the measurements were made for a constant free stream water depth of 330 mm irrespective of the discharge rate. This gave Reynolds number based on the free steam velocity 0.5 x $10^5$ which ensured the turbulent flow for all the test conditions. Froude number of the free stream flow $F_r$=0.248, ensured the free stream flow to be subcritical. To obtain the vertical profiles of the mean and fluctuating quantities, the measurements were conducted in the vertical plane at $z/b = 0$ and $z/b = 0.25$ at $Q = 44$ l/s. In the vertical direction, 30 measurements at 5 mm intervals up to 70 mm from the bed boundary and 15 mm for the rest were taken.

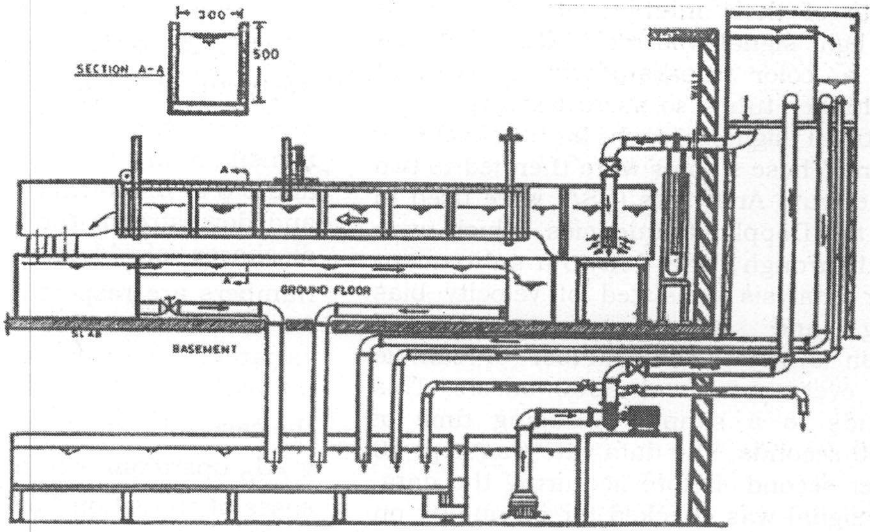

Fig. 1. Schematic layout of test facility.

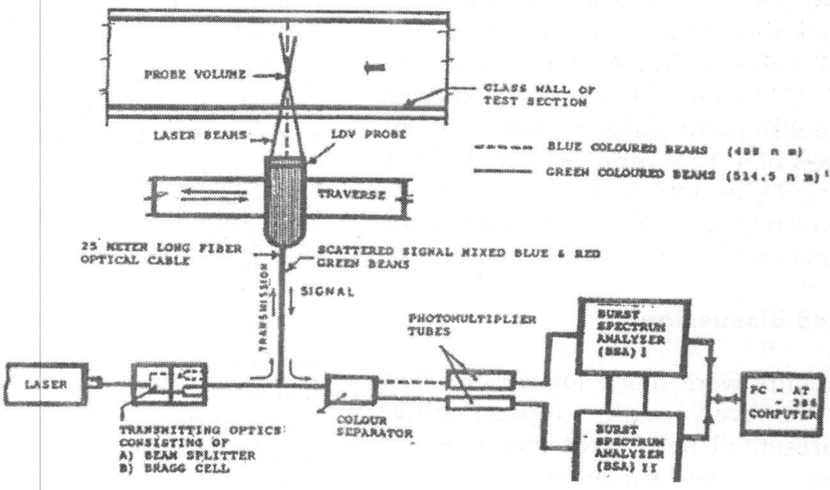

Fig. 2. Block diagram of the Laser Doppler Velocimetry (LDV).

## 3. Instrumentation

The experimental data were collected using a DANTEC two color back-scatter LDV system. Fig. 2 shows a block diagram of the component LDV set up used for the measurements. A 5 Watt Argon-ion laser with fiber optics in back scattered mode with two laser beams, one blue (488 nm) and one green (514.5 nm), were focused at a measuring point from one side of the channel through an optical lens. The LDV probe with its axis normal to the flume side wall was held in the probe holder of traverse which was mounted on a bed aligned parallel to the flume. The probe holder could be traversed in longitudinal and two cross direction along the height and along the width of the flume. Thus, it was possible to position the measuring volume (intersection point of the laser beams) at a desired point with an accuracy of 0.1 mm in any plane across the flow. Because of copious existence of natural particles in the water, no seeding arrangement was made. The LDV transmitting optical unit consisted of, color separator, beam splitter and a brag cell as a frequency shifter to detect reversal flow. Two pairs of blue and green beams in orthogonal planes were focused through a lens in the probe forming measuring volumes at the points of their intersection. The mixed reflected light signal was received and passed through a color separator to a pair of photomultiplier tubes so as to convert it into two electrical signals, each for one velocity component. These signals were then fed to two Burst Spectrum Analyzers (BSA) were used to evaluate the Doppler frequencies, which were interfaced through IEEE 488 to a subsequent computer analysis consisted of velocity bias averaging and outlier rejection based acquisition system. The number of sample taken at every point was 5000 bursts. This corresponds to a simple averaging time of about 100 seconds. The data rate was kept 50 bursts per second. Before acquiring the data, the LDV signal was checked for its quality on a 100 MHz Gold storage oscilloscope. The signals display as regular Doppler burst that correspond to particle passing through the measuring volume. The measurements were taken at ten different cross sections upstream, within and downstream of the sudden constriction subsequent gradual expansion for different slopes of 1:1, 3:1and 5:1 for the flow discharge rate, Q, of 44 l/s. Fig. 3 shows the location grid of the measuring stations for the different transitions.

## 4. Results and discussion

Measurements were made for various flow conditions. However, only representative results are presented here. Root mean square (RMS) values of the turbulence intensity components and velocity components are non-dimensionalized by the streamwise mean free steam velocity in x-direction $U_O$. The water depth is non-dimensionalized by the free stream water depth $y_O$. Turbulence at the wall is construed to be turbulence at very location from the wall of the order of 3 mm as observed in LDV experimentation and not at the wall itself purse. It may be mentioned here that the minimum distance away from the boundary at which the turbulence and velocity measurements commenced was 3 mm. At the boundary, velocity and turbulence are zero. Figs. 4-8 and 9 depict the variation of non-dimensional streamwise and vertical components of turbulence intensities $u`/U_O$ and $v`/U_O$ as function of relative channel depths $y/y_O$ in upstream sudden and downstream gradual 1:1, 3:1 and 5:1 horizontal open channel transition of contraction ratios $\Delta b/b$ of 0.3 and 0.5 at different locations upstream, within and downstream the transition for maximum discharge of 44 l/s. Reynolds and Froude numbers are respectively $0.5 \times 10^5$ and 0.248 for free steam flow. Clearly, the trend of variation of steamwise and vertical turbulence intensities $u`/U_O$ and $v`/U_O$ are similar in all the cases of transition. The trend of $u`/U_O$ and $v`/U_O$ upstream, within and downstream in all cases of transition have higher values close to the bed, following a gradual fall in the wall region (wall effect) defined by $y/y_O < 0.2$, reaching the minimum in the core region defined by $0.2 \leq y/y_O < 0.6$, where the location of the minimum values of the turbulence consistently corresponds to that of maximum streamwise mean velocity $\bar{u}/U_O$. Turbulence intensities $u`/U_O$ and $v`/U_O$ rise gradually and then rapidly in the upper region (free surface region) defined by $y/y_O > 0.6$, reaching up to the free surface. Generally, maximum turbulence intensities $u`/U_O$ and $v`/U_O$ occur at the same location of the profiles of transition, either close to the bed or at the free surface depending on the location of the profile station. Also, as a comprehensive observation, it is noted that the streamwise turbulence $u`/U_O$ is always stronger compared to the vertical turbulence $v`/U_O$.Upstream the transition, since the incoming flow is subcritical and turbulent as Froude and Reynolds are 0.248 and $0.45 \times 10^5$ on average respectively, turbulence is relatively lower upstream of the transitions. As the flow approaches the entrance, there is a gradual increase in the turbulence intensities in the core region as well as at the surface region, with a subsequent fall in water depth within the transitions.

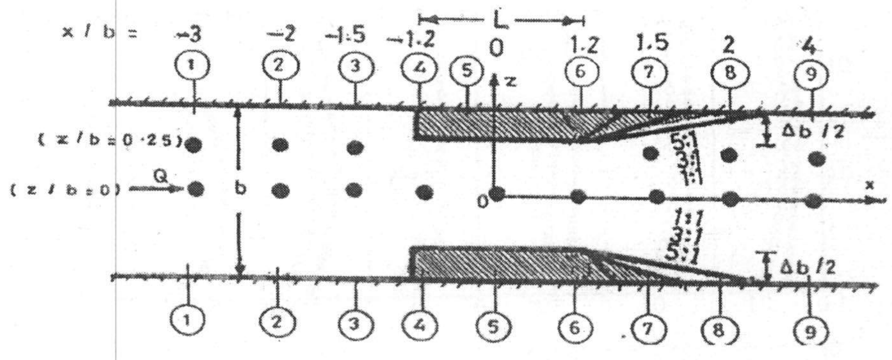

Fig. 3. Schematic plan showing the grid cross sections for the different transitions.

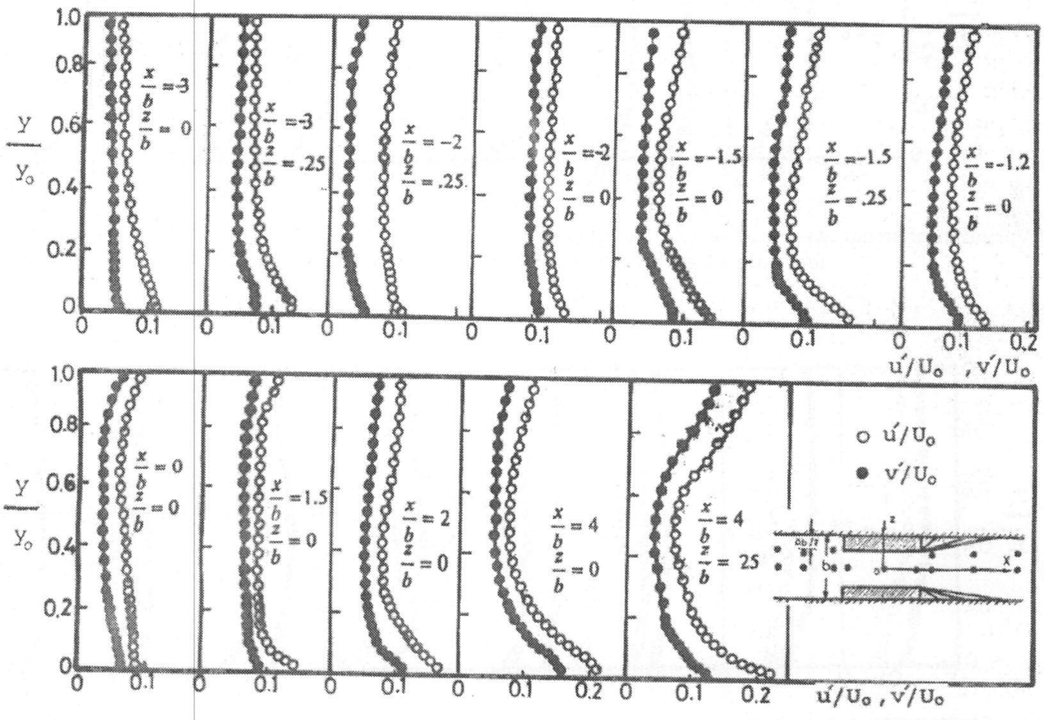

Fig. 4. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 5:1 for Q = 44 1/S at Δb/b = 0.3.

Figs. 5, 7 and 9 show the turbulence intensities u`/$U_O$ and v`/$U_O$ profiles upstream, within and downstream of transitions at Δb/b = 0.5, which depict the turbulence behavior more clearly indicate large magnitude of turbulence in wall and free surface region for gradual transition 1:1, with fairly uniform turbulence in the core region. However, for gradual transitions 3:1 and 5:1, within and downstream locations, turbulence profile is fairly uniform with comparatively less increase of the turbulence in wall and free surface region. Thus gradual transition with side slopes 3:1 and 5:1 is effective in minimizing the turbulence within and downstream location compared to the gradual transition 1:1. The minimum turbulence intensity u`/$U_O$ and v̀/$U_O$ always in core region. The maximum turbulence intensity lies close to the bed or nearer the free surface depending on the location of the profile.

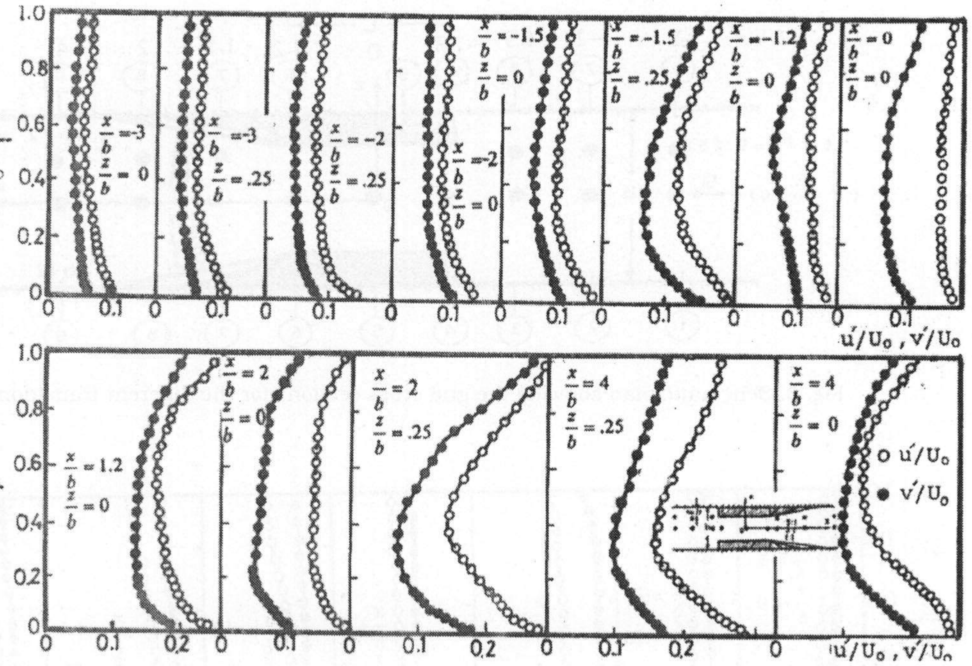

Fig. 5. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 5:1 for Q = 44 l/S at Δb/b = 0.5.

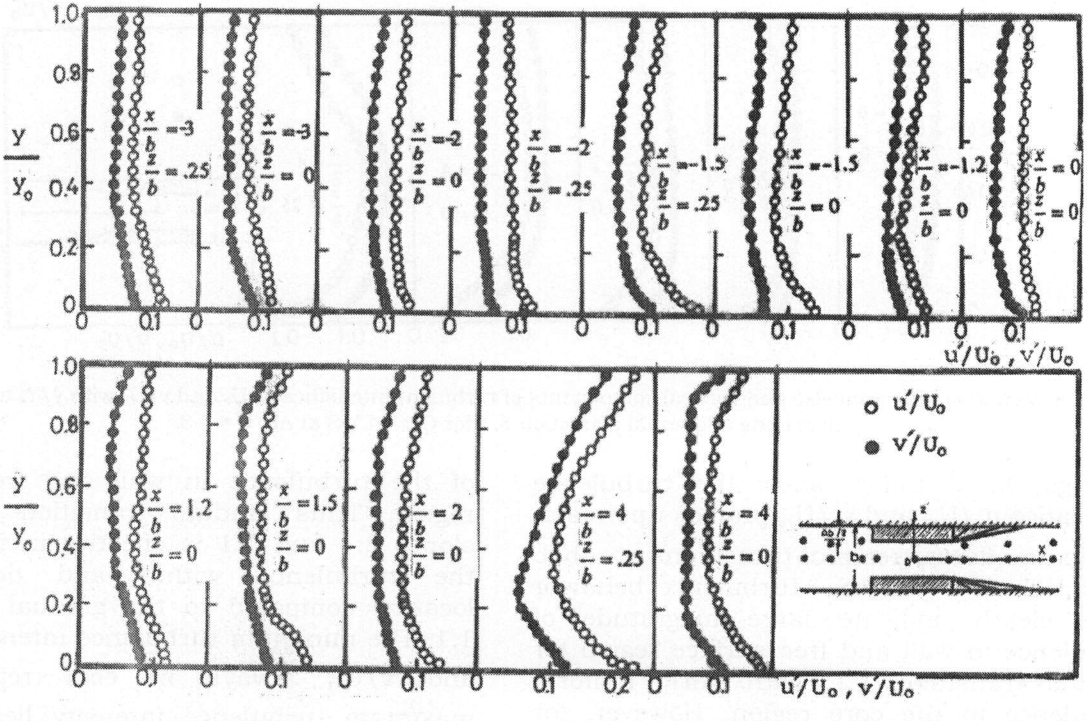

Fig. 6. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 3:1 for Q = 44 l/S at Δb/b = 0.3.

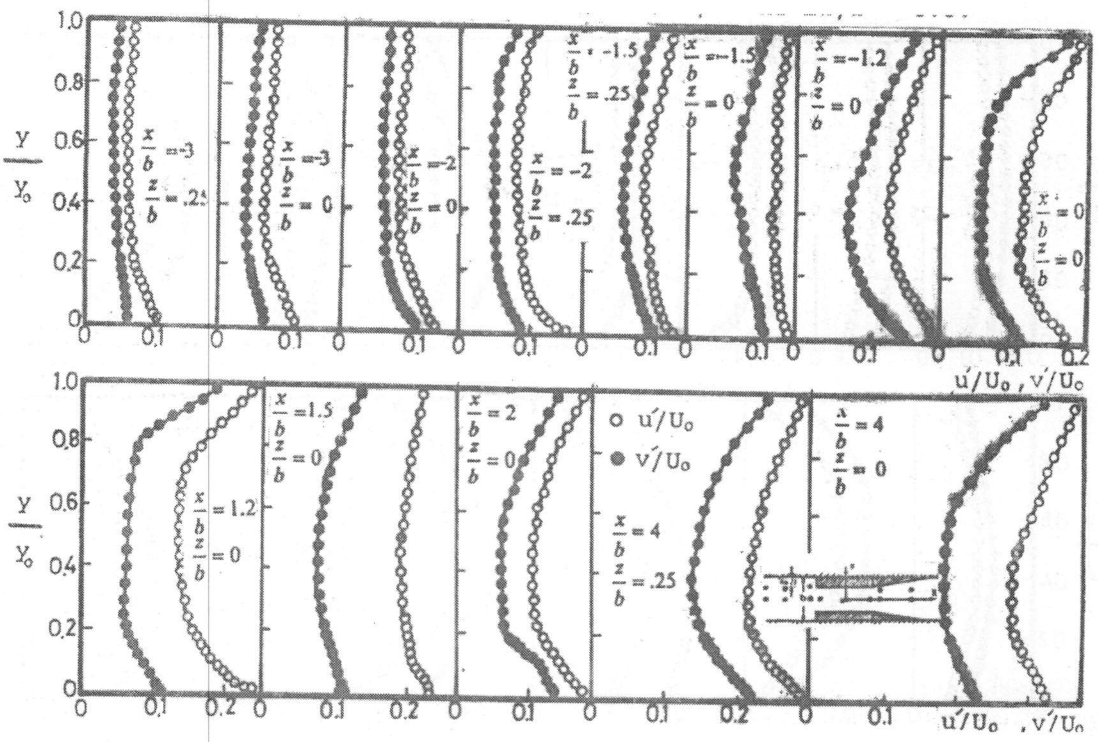

Fig. 7. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 3:1 for Q = 44 1/S at Δb/b = 0.5.

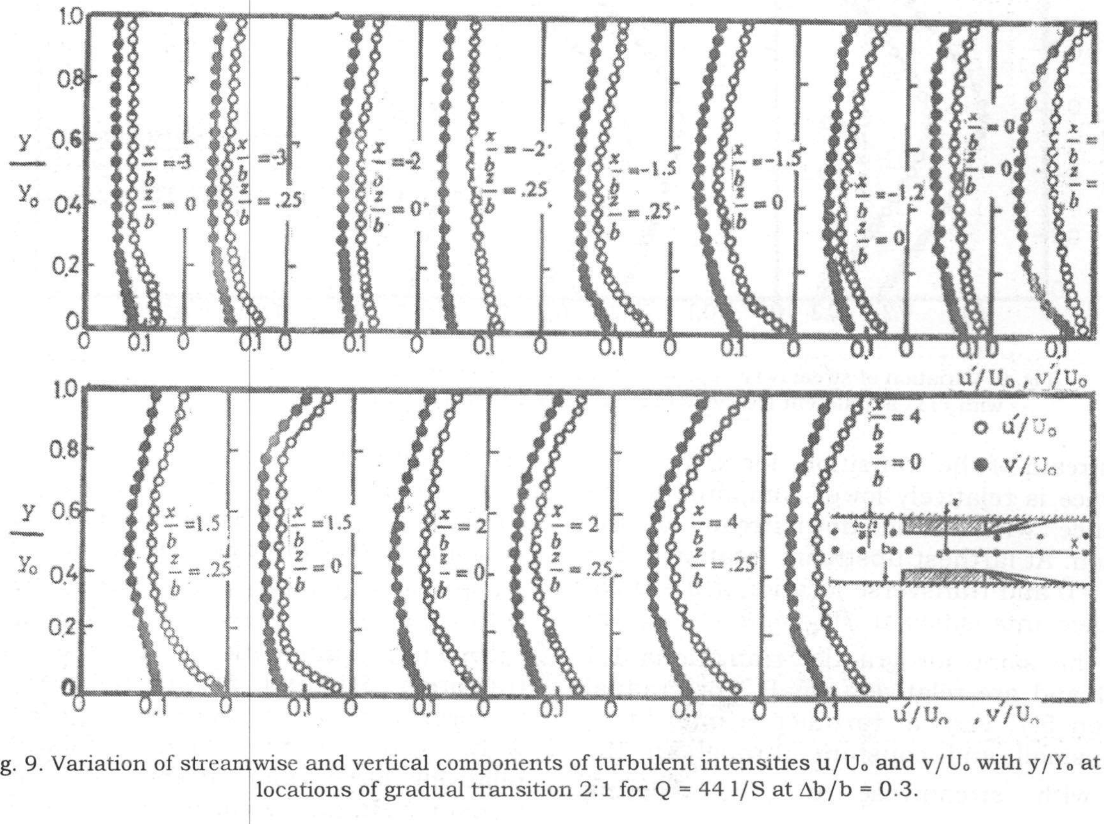

Fig. 9. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 2:1 for Q = 44 1/S at Δb/b = 0.3.

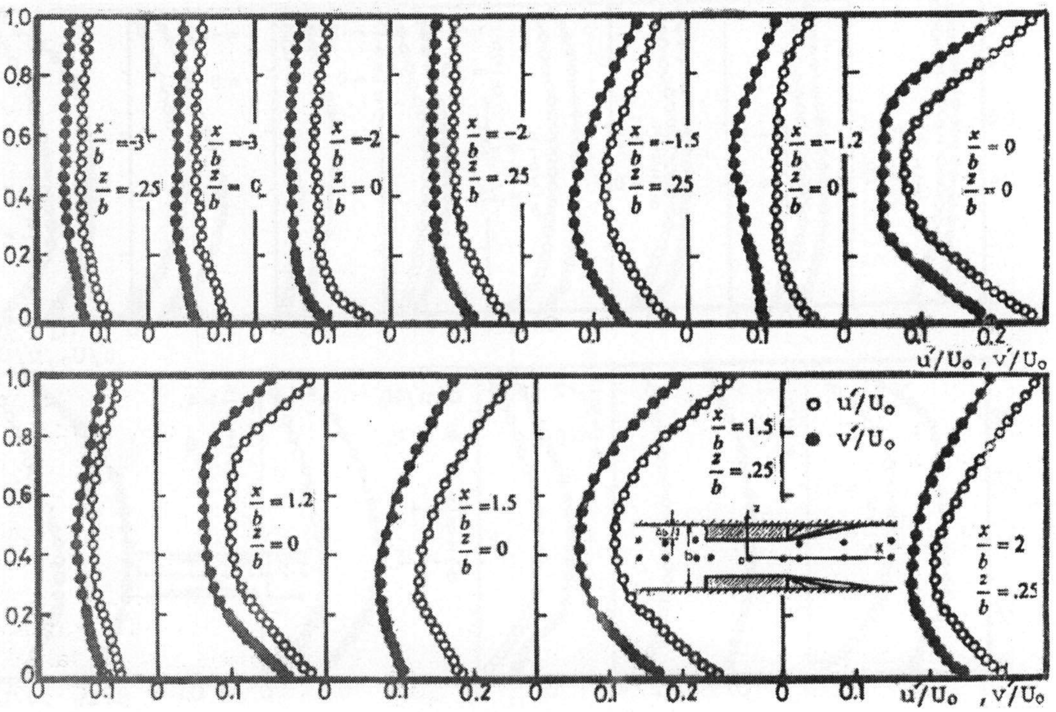

Fig. 9. Continue

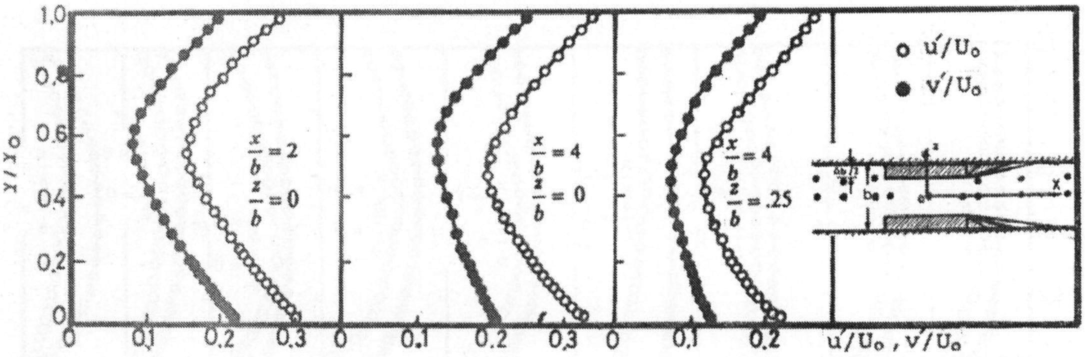

Fig. 9. Variation of streamwise and vertical components of turbulent intensities u/U₀ and v/U₀ with y/Y₀ at different locations of gradual transition 1:1 for Q = 44 l/S at Δb/b = 0.5.

Upstream of the transition, for x/b < - 1.2 turbulence is relatively lower compared to the turbulence within and downstream of the transition. At farthest upstream location x/b = -3, z/b = 0 and transverse location z/b = 0.25, turbulence intensities u`/U$_0$ and v`/U$_0$ are almost the same for gradual transitions 1:1 and 3:1 and are relatively small. For gradual transition 5:1, vertical turbulence intensity v`/U$_0$ is small and constant throughout the depth with streamwise u`/U$_0$ differing significantly. Along locations on the centerline z/b = 0 and in the upstream region of the transition, both the turbulence intensities u`/U$_0$ and v`/U$_0$ are low and almost the same except in wall regions for gradual transition 1:1. However, increase in the magnitude of turbulence intensities in the gradual transition 3:1 and 5:1 is noticeable. This uniformity of turbulence gradually breaks up within and after the transition and attains a relatively large value at the entrance of the transition. In all the cases both the turbulence intensities $u'/U_o$ and $v'/U_o$ differ significatly, $u'/U_o$ being always larger than $v'/U_o$.

Within the transition, it has been observed during this experimentation, that surface waves play an important role in the turbulence production. In the subcritical flow within the transition $F_r \approx 0.64$, the velocity of disturbance is larger. As the flow approaches critical state indicated by $F_r$ reaching close to unity, flow tends to be unstable due to higher wave disturbance. In addition, oblique surface waves are seen during experimentation within the transition and few centimeters, about (25–40) cms downstream of the exit of the transition. The combined influence of these surface waves and the oblique waves due to constriction could have enhanced, the turbulence intensities $u'/U_o$ and $v'/U_o$ in the free surface and wall region at the centre and beyond up to exit section. The turbulence intensities $u'/U_o$ and $v'/U_o$ in gradual transition 1:1 is more pronounced compared to the gradual transitions 3:1 and 5:1 as shown in figs. 5, 7 and 9. At the centre of entrance zone along the centerline at $x/b = -1.5$, both the turbulence intensities $u'/U_o$ and $v'/U_o$ are low and almost uniform over the depth. Across the transition, at $x/b = -1.2$, for all transitions, turbulence intensity differential is significant, with $u'/U_o$ relatively low of the order of 0.12 for instance. At the centre of all transitions in contrast, the sharp increase in turbulence intensities $u'/U_o$ and $v'/U_o$ at the wall and free surface regions are noticed in case of gradual transition 1:1. The nature of turbulence intensities $u'/U_o$ and $v'/U_o$ is significantly different in case of gradual transition 3:1 and 5:1.However, in the wall region $u'/U_o$ and $v'/U_o$ differ significantly and this differential being of the same order over a large segment of the depth. Somewhat higher values of turbulence at the centre of transition may be explained in light of probable role of transverse component of velocity initiated at the inlet corner and carried forward to the centre of transition. This effect is more pronounced in case of gradual transition 1:1.

Downstream of the transition in the expansion zones, the conditions of the flow at the inlet of the expansion zones cause unidirectional distortion of the fluid elements which may be expected to produce high nonhomogeneous and anisotropic turbulence downstream of the transition. Under the action of dynamic process, the turbulence is produced to some degree all over the field. The nature of variation of turbulence intensities $u'/U_o$ and $v/U_o$ at the entry of expansion zone and subsequent sections downstream is somewhat distinct compared to the turbulence profiles before and within the transition as seen in the figs. 5, 7 and 9. The profiles of turbulence $u'/U_o$ and $v'/U_o$ in the expansion zones of the transition, which depict the turbulence behavior more clearly, in gradual transition 1:1 indicate large magnitude of turbulence in the wall and free surface region, with fairly uniform turbulence in the core region. However, for gradual transitions 3:1 and 5:1, turbulence profile is fairly uniform with comparatively less increase of the turbulence in the wall and free surface region.

In case of gradual transition 1:1 fig. 9, the nature of variation in turbulent intensities $u'/U_o$ and $v'/U_o$ at the downstream in the expansion zones is somewhat distinct compared to the turbulence profiles in the case of gradual transitions 3:1 and 5:1.Herein, in the core region of gradual transitions 1:1, turbulent intensity profiles $u'/U_o$ and $v'/U_o$ do not exhibit the tendency towards constancy unlike in the gradual transition 5:1. Generally, in gradual transition 1:1 after reaching the minimum turbulence intensities $u'/U_o$ and $v'/U_o$ as the distance increase from the wall, the turbulence tends to increase consistently till the free surface is reached. Turbulent intensities are particularly largest $u'/U_o = 30\%$, $v'/U_o = 22\%$ and $u'/U_o = 36\%$, $v'/U_o = 28\%$ at $x/b = 2$, $z/b = 0$ and $x/b = 2$, $z/b = 0.25$ closer to the wall region and free surface region respectively. Similarly, both the turbulence intensities $u'/U_o$ and $v'/U_o$ are large at all the sections investigated downstream of the inlet of the expansion zone in gradual transition 1:1 in the wall region and free surface region. The general trend in variation of depthwise turbulence is similar in the expansion zone up to $x/b = 4.0$ observed in this work. Also, it can be seen that gradual transition 5:1 decrease the turbulence intensities $u`/U_o$ and $v`/U_o$ in wall and free surface regions compared to gradual transition 3:1. This dampening effect could be attributed to the reduced magnitude of surface waves observed in the gradual transition 5:1 compared to relatively larger surface waves in the gradual transition 3:1.. Downstream, the turbulence differential between $u`/U_o$ and $v`/U_o$ is larger in gradual expansion 3:1 throughout compared to the 5:1 expansion. Farthest downstream at $x/b \geq 4$, the turbulence intensities $u`/U_o$ and $v`/U_o$ along the axis and $z/b = 0.25$ are lowest for 5:1 expansion.

Generally, the turbulence intensities $\grave{u}/U_o$ and $\grave{v}/U_o$ grows rapidly after the flow separation and spreads in vertical direction in all the transitions. Also, it can be seen that gradual transition 5:1 is more effective in minimizing the turbulence intensity in the expansion zones compared to the gradual transition 1:1 and 3:1.

Further, the results show the influence of the transition angle (diversion angle) on the turbulence intensities $u`/U_o$ and $v`/U_o$, which decrease with reduced transition diversion angle. Morever, with the increasing transition angle and the contraction ratio $\Delta b/b$, the vertical variation in turbulence intensities $u`/U_o$ and $v`/U_o$ become more pronounced. Changing rapidly in the wall, core and the free surface regions. This observation is consistent with observation reported by Nezu and Nakagawa [2].

Figs. 10, 11 and 12 depict the profiles of streamwise mean velocity distribution $\bar{u}/U_o$ of gradual 1:1 and 5:1 transitions along the depth for discharge 44 l/s at different locations upstream, within and downstream of the transitions at free stream Reynolds and Froude numbers of $0.5 \times 10^5$ and 0.248 respectively at contraction ratio $\Delta b/b$ of 0.3 and 0.5. The streamwise mean velocity profile $u`/U_o$ along the longitudinal direction at the centerline of the transitions are increased from upstream to the entrance zone of the transitions. Also, $\bar{u}/U_o$ varies considerably according to the transitions. This variation becomes significant within the transition for the increase in the angle of divergence at the exit of the transition. Interesting, the gradual transition 5:1 not only reduces the velocity acceleration, but also influences the viscous effects close to the channel bed since wall shear stress is reduced from the velocity at the closest point to the bed. This indicates gradual transition 5:1 has reduced velocity profiles compared to gradual transition 1:1 indicating better efficacy of smoother transition in energy reduction, within the same length. Downstream in expansion zone of the transition, however, the gradual transition 1:1 drastically changes the profiles shape. Velocity profiles in gradual transition 5:1 show greater uniformity of streamwise mean velocity distribution along the channel depth, except in the boundary layer close to the wall region. In gradual transition 1:1, the velocity distribution along the depth shows a curvilinear nature, with greater magnitude carried over larger distance downstream in the expansion zones.

To assess the difference in KE, if any, as computed on basis of average velocity based on the discharge and depth ($Q^2/2gA^2$), and computed from the measured streamwise component of mean velocity $\bar{u}$ (mean kinetic energy) and turbulence intensities u`, v` and w`(turbulent kinetic energy) across these vertical in the cross sections using Laser Doppler Velocimetry LDV, as shown in following terms:

Turbulent kinetic energy (turbulence energy)

$$= \frac{1}{2gy}\int_0^y (u'^2 + v'^2 + w'^2)dy, (v' \approx w'). \tag{1}$$

Turbulent kinetic energy =

$$\frac{1}{2gy}\int_0^y (u'^2 + 2v'^2)dy. \tag{2}$$

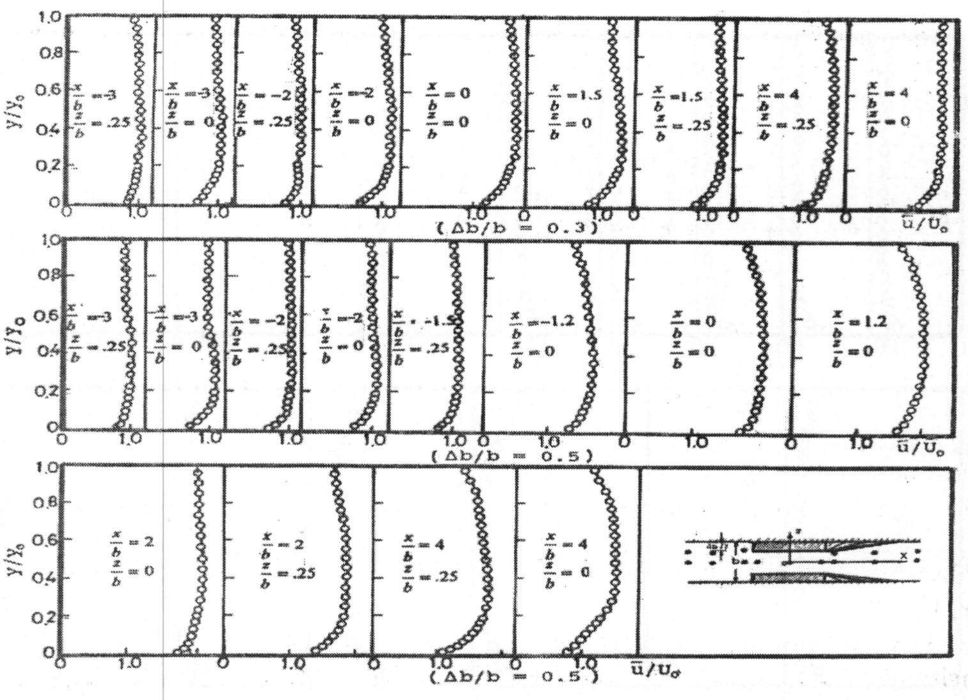

Fig. 10. Variation of streamwise and vertical components of turbulent intensities $\overline{u}$ /U₀ over the depth at different locations of gradual transition 5:1.

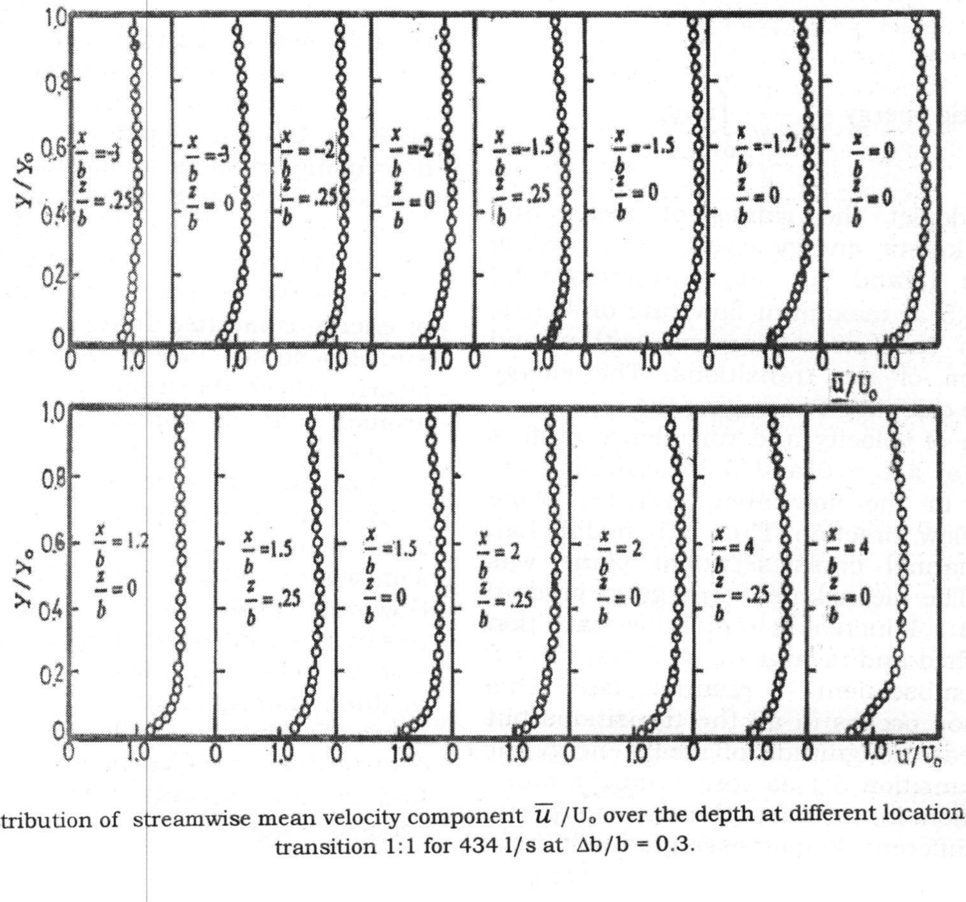

Fig. 11. Distribution of streamwise mean velocity component $\overline{u}$ /U₀ over the depth at different locations of gradual transition 1:1 for 434 l/s at Δb/b = 0.3.

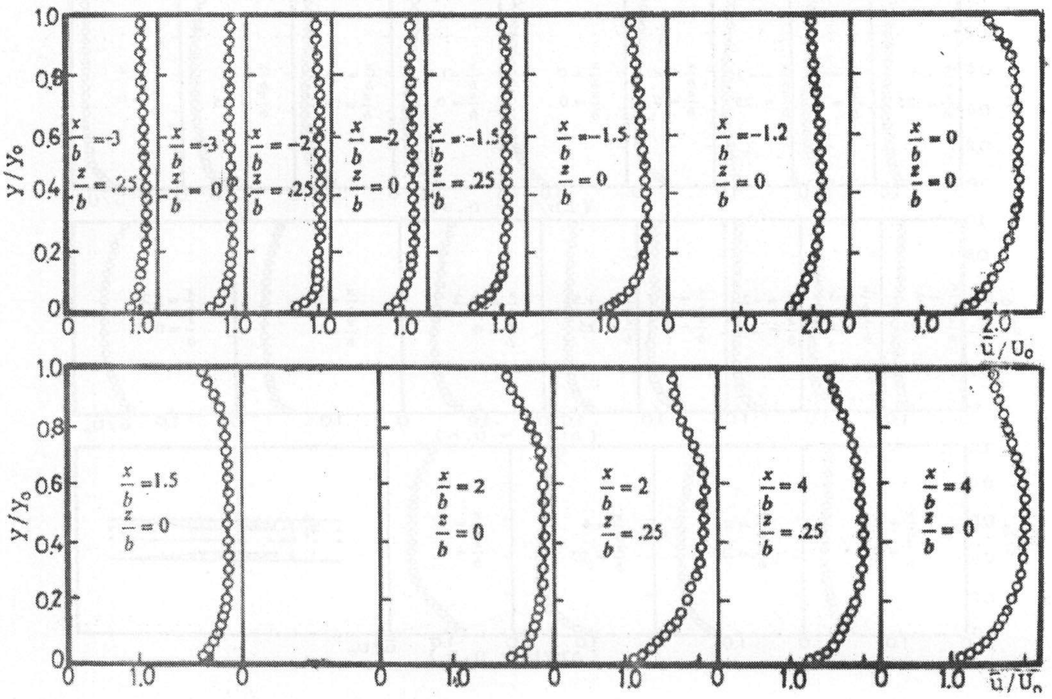

Fig. 12. Distribution of streamwise mean velocity component $\overline{u}$ /U₀ over the depth at different locations of gradual transition 1:1 for Q = 44 l/s at Δb/b = 0.5.

And

$$\text{Mean kinetic energy} = \frac{1}{2gy}\int_0^y \overline{u}dy.$$

Table 1 depict the values of mean and turbulent kinetic energy levels for gradual transitions 1:1and 5:1, at contraction ratio Δb/b, of 0.5 at maximum flow rate of 44 l/s, at various sections, upstream, within and downstream of the transitions. The energy levels were calculated averaging the integration of velocity and turbulence profiles measured at z/b = 0 and 0.25 assuming the symmetry in the flow about vertical plane along the flow direction. Thus only middle half of the channel cross sectional plane was explored. The mean kinetic energy in gradual transitions 1:1 increases rapidly as transition is approached and is large in – 1.2 < x/b < 1.5 with a subsequent gradual fall. This phenomenon occurs in all the transitions but with decrease magnitude of mean energy for gradual transition 5:1 as seen from the table. The variation in turbulent kinetic energy is, however, different. It increases gradually from the inlet side of the transition with a relatively rapid increase in the magnitude downstream of the transition reaching a maximum at x/b of 4 for gradual transition 1:1, after which decreasing trend is analogous to decrease in turbulence intensity. The same trend occurs in all the transitions. The turbulence kinetic energy is observed to be a small fraction of the mean kinetic energy. For comparison, values of energy computed from the average velocity are also shown in the table. The differences clearly reflect the influence of the transition geometry. It may noticed that for gradual transition 1:1 the maximum turbulent K.E. in the downstream zone occurs at x/b = 4 just away from the exit section, but the maximum mean K.E occurs at x/b = 1.5, that is somewhat away from the exit section. However, in the case of gradual transition 5:1, position of the occurance of maximum K.E. and turbulent K.E. always conside. This could be due to flaring of the exit wall reducing wake effect. Further, regardless of its magnitude, contribution of the turbulence energy is a new finding and that has been made possible by the use of LDV.

Table 1
Values of mean and turbulent kinetic energy of different transitions at different location for $\Delta b/b = 0.5$.

| Transition | | K.E. Based on LDV measurements | | KE Based on discharge |
|---|---|---|---|---|
| | | Mean KE $\frac{1}{2gy}\int \bar{u}dy$ mm | Turbulence energy $\frac{1}{2gy}\int(u^2+2v''^2)dy$ mm | $(Q^2/2gA^2)$ mm |
| Gradual 1:1 | -3 | 10. 78 | 0. 12 | 9. 1 |
| | -2 | 11. 53 | 0. 27 | 9. 8 |
| | -1.5 | 12. 20 | 0. 30 | 10. 5 |
| | -1.2 | 36. 47 | 0. 23 | 41. 5 |
| | 0 | 37. 50 | 0. 30 | 44. 8 |
| | 1.2 | 39. 75 | 0. 35 | 44. s1 |
| | 1.5 | 33. 30 | 0. 40 | 15. 2 |
| | 2 | 29. 60 | 0. 90 | 13. 9 |
| | 4 | 20. 95 | 1. 15 | 12. 8 |
| Gradual 3:1 | -3 | 11.35 | 0.13 | 10.6 |
| | -2 | 12.42 | 0.17 | 11.5 |
| | -1.5 | 13.65 | 0.19 | 12.5 |
| | -1.2 | 34.97 | 0.26 | 40.6 |
| | 0 | 35.30 | 0.31 | 43.5 |
| | 1.2 | 36.88 | 0.45 | 43.4 |
| | 1.5 | 30.76 | 0.46 | 17.0 |
| | 2 | 25.15 | 0.84 | 15.1 |
| | 4 | 16.42 | 0.80 | 14.2 |
| Gradual 5:1 | -3 | 12. 47 | 0. 13 | 11. 9 |
| | -2 | 14. 36 | 0. 14 | 13. 1 |
| | -1.5 | 16. 64 | 0. 16 | 14. 5 |
| | -1.2 | 33. 21 | 0. 29 | 39. 5 |
| | 0 | 34. 48 | 0. 32 | 42. 2 |
| | 1.2 | 34. 60 | 0. 60 | 42. 1 |
| | 1.5 | 28. 30 | 0. 50 | 19. 2 |
| | 2 | 23. 40 | 0. 80 | 16. 8 |
| | 4 | 13. 96 | 0. 73 | 14. 9 |

Fig. 13 shows the profiles of mean and turbulent kinetic energy computed from the measured streamwise component of mean and turbulence intensity by the using LDV technique, and kinetic energy as computed on the basis of average velocity based on the discharge. The results are plotted at selected locations along the channel for gradual transitions 1:1 and 5:1 at $\Delta b/b$ of 0.5. The difference in both the computed magnitudes upstream, within and the downstream of the transition are noteworthy. Let us take a case of gradual transitions 1:1; as the transition is approached from upstream, KE from LDV measurements becomes larger than the K.E. computed from average velocity. This difference is largest just outside the entrance of the transition. Some observation is true for gradual transition 5:1. This is measured by LDV which gives higher KE computed to KE as K.E. as computed on the basis of average velocity which should give a lower value on account of whole cross section area being taken into consideration. KE increases steeply within the transition associated with corresponding fall in the water depth. Within the transitions, K.E. computed from the average flow measurement is much higher than the KE computed from LDV, even more than the largest difference between these two values in the upstream reach. This trend is reverse in relation to the trend observed upstream. This is an important distinction observed. The probable explanation for this phenomenon can be identified in the velocity distribution across the central location. Since only one vertical profile of streamwise velocity at the centre was obtained by measurement. It reduced the kinetic energy compared to the one computed from the average velocity. Obviously, more LDV measurements of velocity profile across the section would have reduced the difference between these two computed K.E. with improved accuracy. Again in the downstream expansion zone, the KE from LDV measurements is much larger than the K.E. from average velocity computation. Just upstream the exit, K.E. from average velocity consideration is slightly larger than the KE from LDV. Just downstream of the transition this difference is the largest, with a steep fall in the KE computed from the average velocity. Surprisingly, the K.E. from LDV measurement increases slightly just outside the gradual transition 1:1 in both the sets of measurements as shown in fig. 13. The difference in the two kinetic energies is the largest for gradual transition 1:1 in the downstream reach at all the sections, and minimum for gradual transition 5:1.

Fig. 14 depict the water surface profiles in gradual transitions 1:1, 3:1 and 5:1 at $\Delta b/b$ of 0.5 for Q = 44 l/s along the longitudinal central axis. For clarity the vertical scale is somewhat enlarged. In the upstream zone water level for the gradual transition 1:1 is highest and that for gradual transition 5:1 it is the lowest, being intermediate for gradual transition 3:1. In the intermediate zone, water level is lowest for gradual 1:1 transition in the beginning rises and assume again the lowest values subsequently downstream, whereas, the water level which was lowest in the upstream reach for gradual transition 5:1 rises to the highest value in the transition zone and continues to be highest throughout the downstream reach, except a very small portion in the transition. These behavioural changes occur due to the velocity variation along the channel axes, as observed in the fig. 14, the velocity being largest upstream for gradual transition 5:1 and the minimum for gradual 1:1, contributing to the largest and smallest velocity head respectively. Similar reasons can be attributed to the changes in velocity in the transition and downstream zones.

## 5. Conclusions

The conclusions arising out of this study can be summarized as follows:

The turbulent kinetic energy is observed to be small fraction of the mean kinetic energy, regardless of its magnitude, contribution of the turbulence energy is a new finding in open channel transitions and that has been possible by the use of LDV technique. Kinetic energy KE computed from LDV measurements of streamwise mean velocity component ($\bar{u}$) and turbulence intensity components, ($u'$, $v'$ and $w'$) is slightly larger than the KE computed from the average velocity measurement in the upstream reach, this difference is large in the downstream reach. However, within the transition kinetic energy as computed from the average velocity is greater than the KE computed from LDV. It is also concluded that, the maximum turbulence K.E. and mean KE do not necessary occur at the same locations. Kinetic energy rises rapidly in gradual transition 5:1 upstream of the transition, as the transition entrance is approached compared to the gradual transition 1:1. The turbulence intensities $u'/U_0$ and $v'/U_0$ along the depth increase in the upstream region of the transition, as the flow approaches the transition. Upstream of the transition, turbulence intensities $u'/U_0$

and $v`/U_o$ are of the same order for contraction ratio of 0.3 and 0.5, but just before the entrance of transition, the turbulence intensities are higher for greater contraction. In the upstream region, the turbulence intensities $u`/U_o$ and $v`/U_o$ and their differential are the highest for gradual transition 5:1 and the lowest for gradual transition 1:1 and an intermediate level for gradual transition 3:1. The turbulence intensities $u`/U_o$ and $v`/U_o$ along the depth are higher nearer the bed in the wall region due to wall effect and the free surface region due to the free surface effect, the maximum values of $u`/U_o$ and $v`/U_o$ occur at the same location of the profiles, either close to the bed or at the free surface. Also, the minimum values of $u`/U_o$ and $v`/U_o$ occur at the same location of the profiles of transitions within the core region, and consistently corresponds to the maximum streamwise mean velocity $\bar{u}/U_o$. Within the transition, in gradual transition 1:1, the turbulence intensities $\grave{u}/U_o$ and $v`/U_o$ increase due to the surface waves, oblique waves and chocking state, compared to gradual transition 3:1 and 5:1. Within and downstream of the transition, gradual transition 3:1 and 5:1 decrease the values of $\grave{u}/U_o$ and $v`/U_o$ in the wall and free surface regions compared to gradual transition 1:1. Farthest downstream, $u`/U_o$ and $v`/U_o$ along the depth at the axis $z/b = 0$ and $z/b = 0.25$ are lowest for gradual transition 5:1 and largest in the gradual transition 1:1 due to the interference of the oblique waves generated within and downstream the transition.

## Nomenclature

| | |
|---|---|
| $A$ | Cross sectional area, ($L^2$) |
| $B$ | Channel width, (L) |
| $\Delta b$ | Channel contraction, (L) |
| $F_r$ | Froude number, |
| $Re$ | Reynolds number, |
| $U_o$ | Streamwise mean free stream velocity (averaged over the cross section) (L/T), |
| $\grave{u}$ | Streamwise turbulence intensity component in x-direction, (RMS) |
| $\bar{u}$ | Streamwise mean velocity, component in x-direction, (L/T) |
| *RMS* | Root Mean Square, |
| *KE* | Kinetic energy, |
| $\grave{V}$ | Vertical turbulence intensity, component in y-direction, (RMS), |
| $\bar{v}$ | Vertical mean velocity component in y-direction, (L/T) |
| $X$ | Longitudinal axis along channel length, (L) |
| $Y$ | Transverse axis along channel height |
| $y_o$ | Free stream water depth (L), |
| $z$ | Lateral axis along channel width, (L), |
| $G$ | Gravitation accelerational, ($L/T^2$) |
| $Q$ | Flow discharge, ($L^3/T$), and |
| $w`$ | Lateral turbulence intensity component in z - direction (RMS). |

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