Intl. J. Engg. Sci. Adv. Research 2019 March; 5(1):12-15 ISSN NO: 2395-0730

Influence of Bed-load Transport on Turbulent Dissipation Rate

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***Abstract*— The present works aims at quantifying experimentally the turbulent kinetic energy (TKE) dissipation rate from velocity power spectra in a noncohesive bed-load transport phenomenon and comparing with those in clear-water flows. The clear water flows corroborate to an immobile-bed with no sediment transport whereas a bed-load refer to continuous sediment transport without bed-forms development. In both cases, the sediment on the fume bed remains flat and hydraulically rough. Uniform size of sediment (d50** = 2.5 mm) were used in this experiments. **A 5 cm down looking acoustic Doppler Velocimeter (ADV) probe, named Vectrino+, manufactured by Nortek (acoustic frequency of 10 MHz) was used to measure the instantaneous velocity components with a sampling rate of 100 Hz. The interference between incident and reflected pulses produced spikes in the Vectrino+ data and therefore filtering with a spike removal algorithm was performed and the velocity power spectra fitted well the Kolmogorov "–5/3 scaling-law" in the inertial subrange. The experimental results revealed a reduction in turbulent kinetic energy dissipation rate in presence of bed load and produced an excessive near-bed damping in turbulent stress distributions over the entire flow depth.**

***Keywords*— Bed-load; velocity power spectra; mobile-bed; bed-forms; energy dissipation; clear-water.**

I. INTRODUCTION

N bed load transport, a large portion of particle momentum is transferred into the bed and dissipated due to bed friction. Experimental works on energy and momentum exchanges in presence of bed load transport are very limited Advancement of flow measuring techniques and data processing puts a new impetus to explore total energy dissipation in terms of turbulent kinetic energy (TKE). In the literature, the comparison of measurements during bed-load transport conditions with respect to clear-water flows shows an reduction of the mean longitudinal velocity resulting increment of flow resistance in the near-bed flow zone (Gust and Southard, 1983; Wang and Larsen, 1994; Best et al., 1997; Song et al., 1998; Calomino et al., 2004; Dey et al., 2011, Gaudio et al., 2011, Wang and Larsen 1994; Best et al. 1997). This corroborates to the collisions of bed-particles received kinetic energy from the overlying flow, resulting in a near-bed momentum deficit and as a consequence, a prevailing reduction of the stream wise velocity (Owen, 1964; Smith and McLean, 1977; Gyr and Schmid, 1997). Bergeron and Carbonneau (1999) reported that the presence of bed-load decelerated the time-averaged velocity and an increment of roughness. Other researchers questioned the influence of sediment mobility on flow resistance. Pitlick (1992) observed that weak bed-load transport over a flat gravel-bed has a little influence on flow resistance, whereas developing bed-forms induce an increment of it. Yang and Hirano (1995) showed no influence of bed-load on flow resistance. In contrast, some investigators showed that bed-load acts by decreasing flow resistance, with an increase of streamwise velocity (Nikora and Goring, 2000). In addition, the turbulent flow structures and events, the near-wall flow was shown to be characterized by a sequence of turbulent bursting events (Kline et al., 1967; Robinson, 1991), which are the governing mechanism of TKE-production near the wall (Nezu and Nakagawa, 1993) and strongly influence sediment transport. Further. Nikora and Goring (2000) reported that the energy dissipation in streams over weakly mobile-beds differs from those over immobile-beds and beds with intense bed-load transport. Krogstad et al. (1992) and Papanicolaou et al. (2001) further evidenced that the bed packing conditions in gravel bed streams influence the turbulence level, and consequently the sediment movement. They examined the bursting events and showed that the ratio of turbulent stress to the intensity is smaller in low-densely packed beds. The effects of externally induced turbulence fields on the bed-load was studied by Sumer et al. (2003), he observed that the sediment transport rate increases greatly with the magnitude of turbulence level. Irrespective of whether the bed-load transport influences energy dissipation rate significantly from those of a clear-water flow, even if at present, our knowledge on the potential differences is still limited to narrow ranges of controlling parameters and experimental situations.

II. EXPERIMENTAL PROCEDURE

Experiments were carried out at in a rectangular open-channel glass-walled 0.91 m wide, 0.71 m deep and 12 m long flume (Fig.1). Water discharge was measured by a calibrated V-notch weir, whereas the flow depth was regulated with a tailgate and measured with point gauges. Uniform sediment of d_{50} = 2.5 mm were used in this experiments. The experimental programme consisted of two runs, the first for clear-water and the second for mobile-bed flow conditions, and both tests were run under uniform flow condition (Table 1). The rough immobile-bed was prepared by gluing sediments on the flume bottom uniformly. Longitudinal bed-slopes S = 0.3% were used for d_{50} = 2.5 mm. The shear-particle Reynolds numbers $R_*= d_{50}u_*/\upsilon$ (u_* = shear velocity) were greater than 70, indicating rough-turbulent flow conditions.

Fig. 1. Photograph of experimental set up

Table 1. Experimental data: U = mean velocity, h = flow depth, F = flow Froude number, u_{*s} = shear velocity obtained from slope, $u_{*\tau}$= shear velocity obtained from RSS, κ = von Kármán coefficient

d_{50} = 2.5 mm; S = 0.3 %	Clear Water	Bed load
h(m)	0.12	0.12
U (m/s)	0.80	0.75
F	0.75	0.70
u_{*s}(m/s)	0.059	0.059
$u_{*\tau}$(m/s)	0.058	0.052
κ	0.40	0.38

Nortek's *Vectrino*$^+$ four-receiver Acoustic Doppler Velocimeter (ADV) probe, working at an acoustic frequency of 10 MHz, was used to measure the instantaneous velocity components with a sampling rate of 100 Hz. The sampling duration of 300 s was considered to obtain time-independent averaged velocity and turbulence characteristics. Velocities were measured along the vertical at a distance of 6 m from the flume inlet. The x-axis is aligned with the bed surface (along the centerline of the flume), being $x = 0$ at the measuring location and positive in the streamwise direction; the transverse axis is y, being positive in the right (right-hand rule).

III. Results and Discussion

Fig. 2(a) shows the velocity fluctuation recorded by *Vectrino*$^+$ in presence of bed load. The data captured in the near-bed flow zone contained spikes resulting from the interference between incident and reflected pulses. Fig. 2(b) shows the velocity power spectra $F_{ii}(f)$ for all the three velocity components (u',v' and w') before spike removal. The velocity power spectra $F_{ii}(f)$ were calculated, with the discrete fast Fourier transforms. Fig. 2(b) shows that the velocity power spectra computed do not conform the Kolmogorov "–5/3 scaling-law". So, the data were processed through a high pass filter in association with a spike removal algorithm based on the *acceleration thresholding method* (Goring and Nikora, 2002) with threshold values (= 1 to 1.5) for despiking. Fig. 3(a) shows the despiked velocity power spectra for streamwise velocity component only. Now, the velocity power spectra are well fitted with the Kolmogorov "–5/3 scaling-law" in the inertial subrange (Lacey and Roy, 2008). The power spectra of despiked signals are in a good agreement with the Kolmogorov law for $f > 1$ Hz, corroborating the adequacy of the ADV measurements in both clear water flows and bed-load conditions. The power spectra for all the three velocity components (u',v',w') revealed no discrete spectral peak for $f > 0.5$ Hz, implying that the signals for $f \le 0.5$ Hz and $f > 0.5$ Hz contained large-scale motions and pure turbulence, respectively

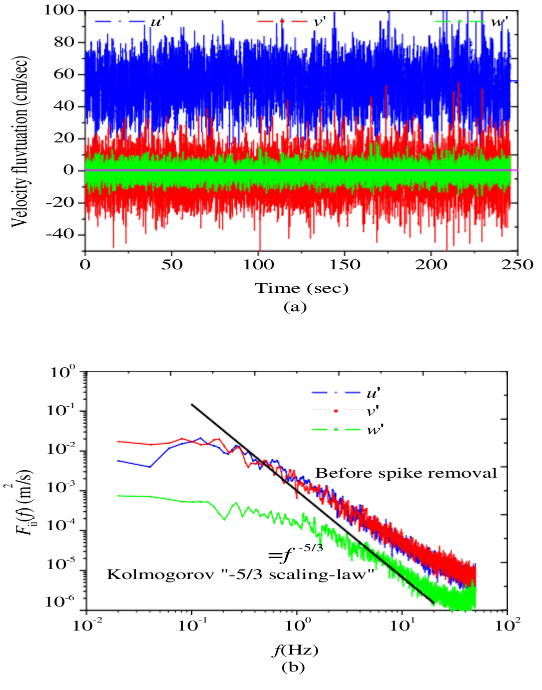

Fig. 2. (a) Velocity fluctuation recorded by *Vectrino*$^+$ in near-bed flow zone, (b) Velocity power spectra $F_{ii}(f)$ before spike removal

The TKE-dissipation rate obtained from the relevant length scale of turbulence (Taylor microscale λ_T), given by:

$$\varepsilon = \frac{\lambda_T^2}{15\upsilon\sigma_u^2} \quad (1)$$

where $\sigma_u = (\overline{u'u'})^{0.5}$ = streamwise turbulence intensity. The assessment of ε is performed by using Kolmogorov's second hypothesis and the following equation describing the true inertial subrange (Pope, 2001):

$$k_w^{5/3} S_{uu} = C\varepsilon^{2/3} \quad (2)$$

where k_w = wave number, $S_{uu}(k_w)$ = spectral density function for u', and C = constant approximately equal to (Monin and Yaglom, 2007). Despiked instantaneous velocity data were used to develop spectra $S_{uu}(k_w) = (0.5\,\bar{u}/\pi)F_{uu}(f)$ as a function of $k_w = (2\pi/\bar{u})f$ to obtain the average value of $k^{5/3}S_{uu}$. Fig 3(b) shows the average value of TKE dissipation rate in the near-bed flow region (5mm above the bed surface level) for both clear water and in presence of bed load. The experimental results revealed a reduction in TKE dissipation rate in presence of bed load.

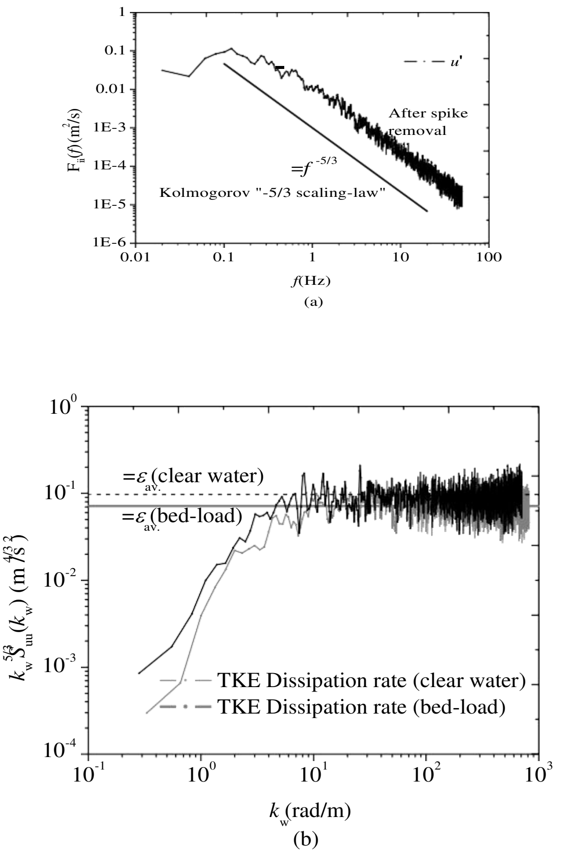

Fig. 3 (a) Velocity power spectra $S_{uu}(k_w)$ after spike removal and (b) assessment of turbulent dissipation rate ε

The vertical distributions of TKE dissipation rate for both the cases are plotted in Fig. 4 and from the data plot, it is noted that the TKE-dissipation rate near the bed in case of bed-load transport is decreased in comparison to the clear water condition and gradually reduces towards the water surface.

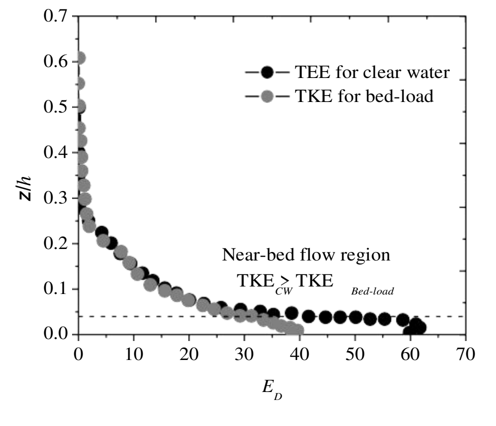

Fig. 4 TKE-dissipation rate, ε as a function of flow depth for under clear water and mobile bed case

In addition, a near-bed damping in total turbulent stress distributions over the entire flow depth is noticed and the vertical distributions of dimensionless turbulent stress are shown in Fig. 5. The turbulent stress, $\tau_{uw} = -\rho \overline{u'w'}$ and the vertical distance z were scaled by the bed shear stress, u_*^2 and the flow depth h, respectively. In the flow-layer > 0.1, the data plots for both the cases collapse on the so-called gravity line, for the free surface flows with a zero-pressure gradient. The stress distributions present a near-bed damping with respect to the gravity line (Fig. 5). This near-bed damping can be attributed to the fact that the particles on motion result in a reduction in flow velocity relative the particle velocity to drag them.

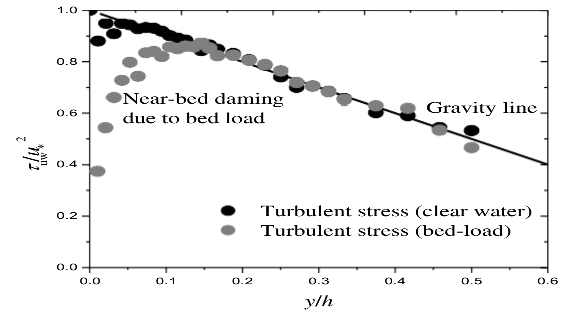

Fig. 5 Vertical distributions of dimensionless turbulent stress for clear-water and bed-load cases

IV. Conclusions

The present experimental work illustrated the measurement of turbulent kinetic energy in presence of bed-load and under clear-water flow conditions by ADV. The results revealed drastic changes in the turbulence parameters due to the different bed conditions. Some interesting conclusions were drawn about the influence of bed-load on the turbulence characteristics.

The influence of bed-load on the turbulent energy is noticeable, reducing the TKE-dissipation rate strongly in the near-bed flow zone. A reduction in RSS distributions over the whole flow depth in presence of bed-load is associated with the provided momentum from the main flow to maintain grain motion overcoming the bed resistance and the near-bed RSS distributions experience an excessive damping due to a decreasing level of turbulence fluctuations.

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