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A comparative study of low Reynolds number $k-\epsilon$ models based on wave-current combined motion

Tohoku Univ. member ○ Ahmad SANA
Tohoku Univ. member Hitoshi TANAKA
Tohoku Univ. member Hiroto YAMAJI

1. Introduction

The popularity of low Reynolds number k-ϵ model has tempted the researchers to put forth new versions of this model by modifying various model parameters in order to achieve better performance. These modifications have been ad hoc until the concept of 'correct limiting behavior' of turbulent kinetic energy and its dissipation rate emerged a few years ago, which helped the researchers to propose modifications which are universal to some extent. Some of the older versions and most modern versions have already been studied using the data of wave boundary layer (Tanaka and Sana[1], Sana and Tanaka[2]).

In the present study a more complex phenomenon i.e. wave-current combined motion has been employed. In previous study (Sana et al.[3]), it was shown that the original model by Jones and Launder[4](JL) though predicted the velocity in an excellent manner, the turbulent fluctuation and the wall shear stress is underestimated. Therefore, two modern versions of the model namely by Myong and Kasagi[5](MK) and Nagano and Tagawa[6](NT) have been included in the present analysis. These modern models were proposed in order to depict correct near wall behavior of the flow parameters, a property which is absent in the original model of JL. The comparison is made for the velocity profile, mean turbulent intensity and the wall shear stress.

2. Approach

The governing equations comprise of the equation of motion and transport equations of turbulent kinetic energy k and its dissipation rate ϵ. These equations were non-dimensionalized by using the wave velocity amplitude $\hat{U}_w$, depth of flow z_h and angular frequency of the oscillatory motion ω ($\omega = 2\pi/T$, T =period of oscillation). These equations were then discretized employing a Crank Nicolson type implicit finite difference scheme. The solution was achieved using an iterative method. The convergence limit was set to 0.00005. Further detail of the solution procedure can be found elsewhere[1].

The experimental data of experiment B05($T = 2.84$sec, $\bar{u}_c = 8.92$cm/sec, $\hat{U}_w = 116.84$cm/sec, $z_h = 3$cm, $RE = 5.4 \times 10^5$, $R_c = 2345$) is used in the present study (see Sana et. al.[3] for further detail). This experiment was performed in a U-shaped oscillating tunnel equipped with a centrifugal pump to generate the uniform flow. The credibility of experimental data regarding wave-current combined motion, obtained from this system is much more as compared to that from an open flume. Because, in the later case, the wave amplitude can not be controlled independently. Moreover, the effect of mass transport can not be eliminated. The velocity, in the experiment B05 was measured using one component LDV. The wall shear stress was computed by assuming the logarithmic velocity profile.

3. Results

From Fig.1, it is clear that the prediction of velocity by the three models is not so different. Though, all of them underestimate the velocity gradient in the near wall region, however, the overall predictive ability is satisfactory, in this regard. Especially the velocity over-shooting is predicted very well, and the agreement far from the wall is excellent. Probably, the major discrepancy, revealed in the present study, is in the prediction of mean velocity profile as depicted by Fig.2, where, the near wall behavior could not be simulated by any of the models under consideration. It is well known that in the near wall region of a flow with wave and current combined, the current velocity profile is distorted by the action of wave boundary layer, this behavior is very well depicted by the experimental data, but this complex phenomenon could not be reproduced by any of the models.

The models provide the turbulent kinetic energy k, from which fluctuating velocity in x-direction can be approximated as $u' = 1.052k^{1/2}$, a relationship derived from the experimental data for steady flow (see Nezu et al.[7]). Figure 3 depicts that MK and NT models are superior to JL model in this case. Although the agreement far from the wall is not satisfactorily predicted by any of the three models, however, this discrepancy depends on the approximation also, which is used in the present study.

Figure 4 shows that the wall shear stress prediction by MK and NT is much more close to the experimental value in magnitude, as compared to that by JL model. The reason for the underestimation by JL model is in fact due to the underestimation of turbulence fluctuations as shown already, which in turn leads to low eddy viscosity and consequently less magnitude of wall shear stress. As can be seen from Fig.4 that although, there exists a discrepancy in predicting the phase difference, however, it may be noted that the models can show nonlinear variation over the wave cycle to some extent. The experimental data shows stepping of the wall shear within phases of about 45° and 135° and then from 270° to 310°. Three of the models show, though very mild, a similar behavior in these ranges.

4. Conclusion

The three models under consideration, perform well in predicting the velocity profile. However, MK and

NT models are superior by virtue of their better performance regarding the fluctuating velocity and the wall shear stress. More experimental data is needed to further inspect the performance of contemporary turbulence models. A number of other modern models may also be tested for the performance in predicting wave-current combined motion, which may be regarded as an excellent test case for the testing of turbulence models.

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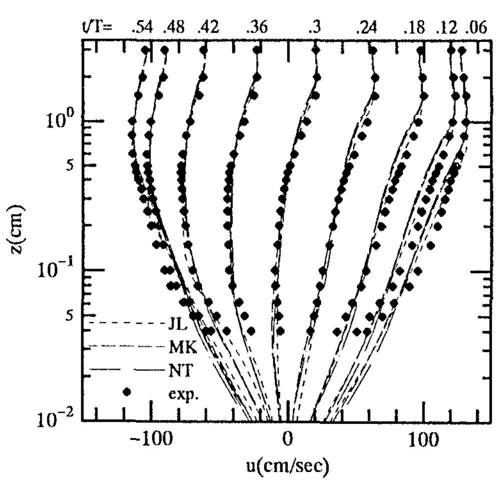

Fig.1 Velocity profile for case B05.

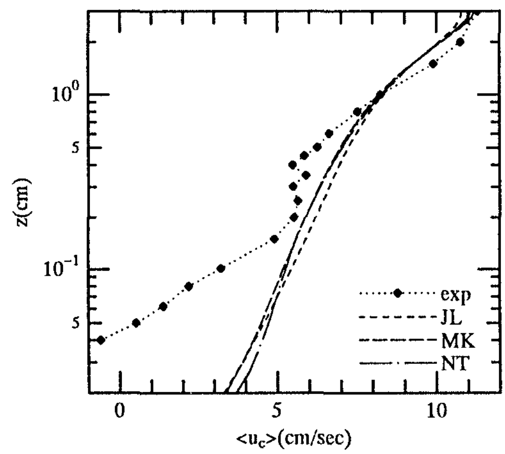

Fig.2 Period average velocity for case B05.

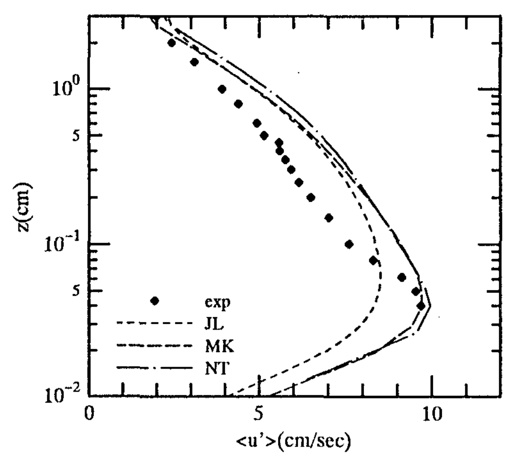

Fig.3 Period average fluctuating velocity.

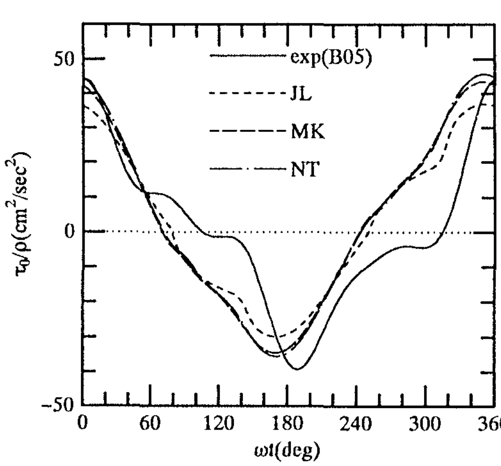

Fig.4 Wall shear stress for case B05.