Experimental Thermal and Fluid Science 98 (2018) 594–603

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental and numerical analysis of grid generated turbulence with and without mean strain

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A R T I C L E I N F O

Keywords:
Grid generated turbulence
Turbulence decay
Reynolds stress modeling
Turbulence modeling

A B S T R A C T

This paper presents experimental and numerical analysis of grid generated turbulence with and without the effects of applied mean strain. We conduct a series of experiments on decaying grid generated turbulence and grid turbulence with mean strain. Experimental data of turbulence statistics including Reynolds stress anisotropies is collected, analyzed and then compared to the predictions of Reynolds Stress Models to assess their accuracy. The experimental data is used to evaluate the variability in the coefficients of the rate of dissipation model and the pressure strain correlation models used in Reynolds Stress Modeling. For both models we recommend optimal values of coefficients that should be used for experimental studies of grid generated turbulence.

1. Introduction

Turbulent flows appear in problems of interest to many fields of engineering sciences such as aeronautics, mechanical, chemical engineering and in oceanographic, meteorological and astrophysical sciences, besides others. Improved understanding of turbulence evolution would lead to important advances in these fields.

At present there are no analytical solutions to predict the evolution of complex engineering turbulent flows. Studies of turbulence have to use turbulence models that characterize the statistical evolution of turbulence. Industrial studies use simple eddy viscosity based turbulence models like the $k-\epsilon$ and $k-\omega$ models. Recent emphasis in the scientific research community has shifted to Reynolds stress models [1–9]. Reynolds stress models have the potential to give better predictions than turbulent viscosity based models at a reasonable computational expense. They may be able to model the directional effects of Reynolds stresses and complex interactions in turbulent flows [10,11]. They have the potential to accurately model the return to isotropy of decaying turbulence and evolution in the rapid distortion limit [12–14]. Reynolds stress models are used to develop improved simplified eddy viscosity based $k-\epsilon-a$ models for variable density flows [15], better algebraic closures and more accurate sub-grid scale models.

The fruition of this potential of Reynolds stress models depends on the quality of the closures for the individual turbulence processes in the Reynolds Stress Modeling approach. Along with progress in modeling, this requires accurate, varied and detailed data from experimental investigations. Experimental studies have a symbiotic relationship with turbulence modeling. Data from such experiments can guide the development and testing of models. For example the experiments of [16] pointed to a non-linear return to isotropy phenomenon in decaying turbulence. This led to the formulation of advanced slow pressure strain correlation models like [17]. The shortcomings in models also guide the organization of new experiments. For example the drawbacks of turbulence models in rotation dominated mean flows led to the investigations of [18,19]. While established models are available for the evolution of turbulence processes there remain many questions about the model expressions and the closure coefficients. For example the closure coefficient values used in the rate of dissipation evolution model are varied between different studies in literature. Most of these studies use closure coefficient values that are well outside the range established by theoretical guidelines and experimental investigations. Similarly the form of the model expression used in pressure strain correlation models is also not universally accepted. The model of [20] is linear in the Reynolds stress anisotropies, but the model of [17] is non-linear with coefficients that are functions of the Reynolds stress invariants. While the models of [20,17] use a modeling basis consisting of the Reynolds stress anisotropies, the model of [21] uses additional tensors in the modeling expression. Using the experimental data from this study we evaluate these variabilities and make recommendations for improvement.

In this investigation we study the canonical cases of Homogeneous Isotropic Turbulence (HIT) and Homogeneous Anisotropic Turbulence

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https://doi.org/10.1016/j.expthermflusci.2018.07.001
Received 7 February 2018; Received in revised form 24 May 2018; Accepted 2 July 2018
Available online 06 July 2018

(HAT). HIT conditions are well replicated in experimental grid generated turbulence. Such tests are conducted in wind tunnels or water tanks where the grid is placed at the beginning of the test section. The rods in the grid interact with the flow through them leading to wakes. Just downstream of the grid, the wakes from individual rods interact with each other producing turbulence. If there is no externally imposed forcing downstream of the grid this turbulent kinetic energy is viscously dissipated at small scales leading to a decay in the velocity fluctuations. This turbulent velocity field becomes statistically isotropic at a distance of the order of 10–20 mesh lengths from the grid [16]. Beyond this length this turbulent flow is statistically stationary with variation along the stream wise direction as the turbulence decays. The rate of energy decay is approximately equal to the viscous dissipation rate. Many authors have explored grid generated turbulence [22–25]. In addition to the insight into the decay of turbulence such studies provide data for benchmarking and calibrating turbulence models.

HAT conditions are imposed by using passage of the turbulent flow through an area change in the flow duct. Axisymmetric contraction increases the turbulent velocity fluctuations along the transverse directions. Ref. [25] have studied wind-tunnel turbulence experimentally and explored plane distortion, axisymmetric expansion and contraction to introduce anisotropy in grid turbulence. Ref. [26] investigated the grid generated turbulence experimentally using a water tank and have studied the evolution of turbulence kinetic energy, dissipation rate and other flow parameters. Ref. [27] experimentally investigated grid-generated turbulence subjected to axisymmetric strain and indicated that single-point turbulence models may not be adequate to describe the relaxation of the turbulence towards an isotropic state. In a very important investigation [28] studied the properties of turbulence downstream of a passive grid. This experimental data was used to evaluate the accuracy of eddy viscosity models and suggest optimal values of model coefficients. Such studies provide essential guidance for the limitations and development of improved turbulence models. In spite of these investigations few researchers have investigated the detailed evolution of Reynolds stress anisotropies near the grid at a large range of grid Reynolds numbers.

The contribution of this article are twofold: firstly concerning the experimental investigation carried out and secondly regarding the utilization of this experimental data to aid numerical investigations of grid generated turbulence.

In the experimental facet of this investigation we study the evolution of the anisotropy in the Reynolds stress tensor near the grid at multiple Reynolds numbers. This study is carried out both for cases with and without mean strain to provide a comprehensive overview of the anisotropy behavior. This represents one of the novel contributions of this paper. While grid generated turbulence is one of the simplest and best approximations of isotropic turbulence, it is accepted that grid generated turbulence is not exactly isotropic. For example it is known that longitudinal velocity fluctuations are more energetic than the lateral in such cases. This leads to many important hurdles in our understanding of turbulence and specifically the return to isotropy phenomenon. For example the existence of anisotropic structures in the flow may slow down the return to isotropy at different scales of flow. Numerous investigations (for example [29,30]) have stated that to develop a detailed understanding of the differences between grid generated turbulence experimental realizations and the ideal case of perfectly isotropic turbulence, we need to study the anisotropy in the Reynolds stresses specifically in the region near the grid under different conditions. This necessity is addressed by the experimental work conducted in this investigation. In addition to the anisotropy, the evolution of the turbulent kinetic energy and the Reynolds stress components are plotted downstream of the grid for giving a comprehensive picture of turbulence structure near the grid.

In the numerical analysis, we use this experimental data to analyze the closure coefficients of the rate of dissipation model and the pressure strain correlation models used in Reynolds Stress Modeling simulations. This addresses important doubts in the turbulence community regarding the validity of the use of RANS models to simulate grid generated turbulence. Grid generated turbulence experiments represent a cornerstone for fundamental investigations into turbulence. Study of the decay of turbulent fluctuation in such cases represents a classical methodology to develop concepts and theories on the kinematics and dynamics of turbulent flows. Till very recent developments wherein turbulence could be generated in a periodic cube via direct numerical simulations (for instance in [31,32]), such experimental studies represented the only recourse for studying isotropic turbulence.

However experimental studies have many limitations with respect to the possible information that can be gathered and the fidelity of such measurements. Due to experimental limitations, the entire three-dimensional structure cannot be studied using experiments. Similarly higher order spectral quantities cannot be reliably recreated using experimental methods. These limitations have lead to the rise of numerical studies of grid generated turbulence. The recourse offer the highest fidelity is Direct Numerical Simulations. For example [33,34] have conducted detailed dns studies of turbulent flows generated by different grids. However because of the high computational cost such numerical investigations are limited to small Reynolds numbers and for very short times. This limits such investigations from providing a complete picture of the time evolution of such turbulent flows. Due to this recent investigators have started to use Reynolds Averaged Navier Stokes models to simulate the decay of grid generated turbulence. These RANS models can handle varying initial conditions, complex geometries, different types of grid and arrangements and simulations for long time periods. However owing to limitations in the accuracy of RANS models there are questions in the scientific community about the validity of such simulations to account for fundamental turbulence features in such simulations. Most RANS models are calibrated for simple homogeneous flows and can lead to significant discrepancies for grid generated flows.

Thus a significant hurdle in gaining confidence in studies using RANS models for grid generated turbulence is calibration of the closure model coefficients with relevant datasets. A major objective of this study is to use the data set generated by our experiments to tune to closure coefficients and find the optimal values of these parameters, specifically for different cases of grid generated turbulence. The closure coefficients of the rate of dissipation model and the pressure strain correlation models used in Reynolds Stress Modeling simulations are analyzed. Based on this analysis we make recommendations for optimal values of the coefficients for studies of grid-generated turbulence.

2. Experimental and numerical modeling details

The experiments for this paper were conducted in the recirculating water tank at the department of Ocean Engineering and Naval Architecture, IIT Kharagpur. Side walls of the water tank are made up of glass. The schematic of the experimental apparatus is shown in Fig. 1. The water is recirculated by a pump, the rpm of the pump is controlled by an electrical control unit. x, y and z are the main flow(streamwise), transverse and vertical directions respectively. U, V and W are the corresponding mean velocities and respective small letters indicate fluctuating velocities. A mean flow velocity of 1 m/s is achievable for a water depth of 0.8 meter in the main flow direction. The water tank has width 2 meters and depth 1.5 meter. The grids were placed immediately preceding the test section through a grid holder (at the grid position, x = 0). The depth of water was 0.8 meter for all the cases of the experiments. Turbulence was generated by using a grid made up of cylindrical pipes. The diameter (d_b) of the pipes used was 0.025 meter. The mesh length of the grids (M) was 10 cm. The rigidity of the grid was calculated as 0.43 by using Eq. (1) as described in [24]

$$\sigma = d_b/M\,(2-d_b/M) \tag{1}$$

Reynolds number based on the grid mesh size [34] is calculated as: