NUMERICAL INVESTIGATION OF TURBULENCE SUPPRESSION IN ROTATING FLOWS

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EXECUTIVE SUMMARY

In past experiments, simulations, and theoretical analyses, rotation has been shown to dramatically affect the characteristics of turbulent flows, such as by causing the mean velocity profile to appear laminar, leading to an overall drag reduction, as well as by affecting the Reynolds stress tensor (the total stress tensor in a fluid). The axially rotating pipe is an exemplary prototypical model problem that exhibits these complex turbulent flow physics. For this flow, the rotation of the pipe causes a region of turbulence suppression that is particularly sensitive to the rotation rate and Reynolds number (the ratio of inertial forces to viscous forces within a fluid). The physical mechanisms causing turbulence suppression are currently not well understood, and a deeper understanding of these mechanisms would be of great value for many practical applications involving swirling or rotating flows, such as swirl generators, wing-tips, axial compressors, hurricanes, and the like.

The research team conducted direct numerical simulations (DNS) of rotating turbulent pipe flows at different Reynolds and rotation numbers. The main objectives of this work were to analyze the effects of rotation on turbulence considering turbulence budgets and higher-order statistics as well as to quantify turbulence suppression for rotating turbulent pipe flow.

RESEARCH CHALLENGE

Swirling flows are an important class of flows, not only because of the complex flow physics but also because of their relevance to many industrial applications such as combustion, heat exchangers, cyclone separation, mixing, etc. To design the next generation of ever-more-efficient cars, aircraft, or energy systems, it is important to understand turbulent swirling and rotating flows in order to predict and manipulate them. Thus, enhanced understanding of the physical mechanisms for swirling and rotating flows and improved prediction capabilities for these types of flows are highly beneficial for key U.S. industries where swirling and rotating flows appear, such as in the oil and gas, biomedical, energy harvesting, and aerospace sectors. When rotating a turbulent flow, a phenomenon known as turbulence suppression has been observed (see flow visualization in Fig. 1), which can cause a reduction in wall-shear stress or skin friction [1–5], making the understanding of turbulence suppression highly valuable for engineering applications. A key objective of this research is to obtain high-quality simulation data (in conjunction with ongoing experiments) that can be used to study the nature of the highly complicated flow physics of turbulent rotating flows.

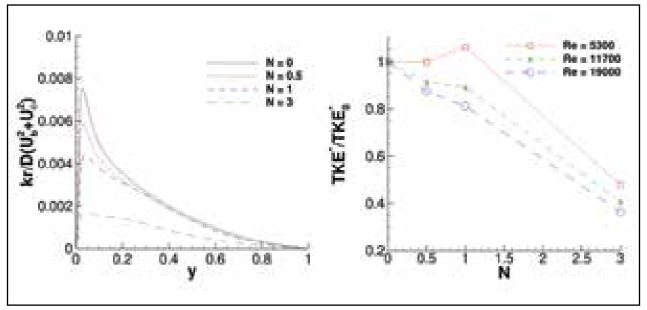

Figure 1: (a) Turbulent kinetic energy multiplied by radial position and normalized by total mean kinetic energy for Re = 19,000 and (b) ratio of total turbulent kinetic energy for rotating and stationary turbulent pipe flow.

METHODS & CODES

The research team solved the incompressible Navier–Stokes equations in a reference frame rotating with the pipe walls where the centrifugal and Coriolis forces (inertial forces that act on objects that are in motion within a frame of reference that rotates with respect to an inertial frame) were added as source terms. For these simulations, the researchers assumed fully developed turbulent flow and periodic boundaries in the streamwise direction. Sufficient temporal and spatial resolution is required to thoroughly study the intricate nature of turbulence and the relevant temporal and spatial scales. The computational meshes ensure that the wide range of turbulent scales are well resolved with grid spacing close to $\Delta y+ = 1$. Simulations were conducted using the spectral-element solver Nek5000, developed by Fischer *et al.* [6]. Nek5000 is a higher-order accurate, open source, spectral-element solver used to solve the incompressible Navier–Stokes equations and is well known for its (spectral) accuracy, favorable dispersion properties, and efficient parallelization [7]. The spectral-element method is based on a weighted-residual approach for spatial discretization. For parallel computations, Nek5000 utilizes the MPI protocol and has shown excellent scaling characteristics on high-performance computing systems—making it well-suited for large-scale turbulence flow computations.

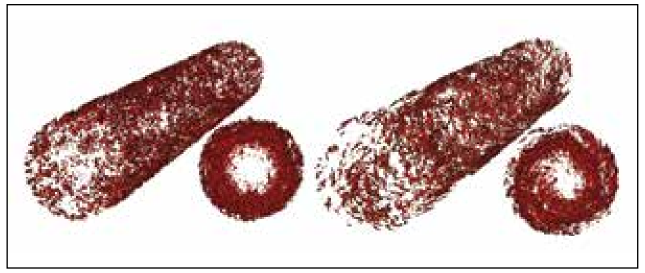

Figure 2: Iso-contour surface of Q-criterion with Q = 65 for stationary and rotating turbulent pipe flow at N = 1 and Re = 19,000.

RESULTS & IMPACT

The current research is concerned with axially rotating pipe flow. In this flow, the axis of rotation is parallel to the mean flow direction and, therefore, for the laminar case the axial mean flow is not directly affected by the rotation. Hence, the parabolic mean flow profile observed in laminar nonrotating pipes also describes the axial (laminar) velocity profile for the rotating case. The axially rotating pipe can be described by two nondimensional parameters: the Reynolds number $Re = UD/\nu$ based on the mean bulk flow velocity U, the pipe diameter D, and the kinematic viscosity ν as well as the rotation number $N = V_w/U$ of the pipe, which is sometimes also referred to as swirl rate. The rotation number characterizes the angular velocity through the azimuthal velocity of the pipe inner wall, V_θ $(r = R) = \Omega D/2$ (in nonrotating reference frame).

While models such as Reynolds-averaged Navier–Stokes (RANS) and wall-resolved large-eddy simulation fail to accurately reproduce the flow physics involved in turbulence suppression, DNS can be used to effectively study rotation effects on turbulent structures. Ashton *et al.* [8] demonstrate some of the severe limitations of several advanced RANS models when compared to the DNS data presented here. Existing DNS studies of rotating pipe flows have been restricted to relatively low Reynolds numbers [9–11], and a strong dependence on rotation number has been observed. Thus, one of the goals of the current work is to provide detailed DNS data at large Reynolds numbers.

The streamwise velocity profiles (not shown here) illustrate how the turbulent flow is affected by rotation in the mean. The velocity profiles are plotted versus the distance from the wall $y = 1\text{-}r/R$, where r is the local radius and R is the total radius of the pipe. It can be seen that the streamwise velocity profile tends toward the laminar profile as the rotation number N is increased. Near the wall, the wall-normal velocity gradient is reduced, which leads to a reduction in skin friction and a speed-up of the flow toward the center of the pipe.

Fig. 1a displays the turbulent kinetic energy versus wall distance compensated by the local radius (accounting for the area contribution in the integrand) and normalized with the total mean kinetic energy ($MKE = 1/2(\langle V_z\rangle^2+\langle V_\theta\rangle^2)A$). A clear reduction in turbulent kinetic energy can be observed throughout the cross-section for Re = 19,000. The total turbulent kinetic energy for all three Reynolds numbers versus rotation number is illustrated in Fig. 1b, and a reduction in turbulent kinetic energy was obtained for all rotation numbers at Reynolds numbers of Re = 11,700 and 19,000. Interestingly, an initial increase in turbulent kinetic energy can still be observed until N = 1 for Re = 5,300 and, thus, considering turbulence as being suppressed may not appropriately describe the characteristics of this flow at these conditions.

In summary, turbulence suppression is occurring (for large enough rotation numbers) for all three Reynolds numbers used in this study. The results for the turbulent kinetic energy also seemingly display a change in trends at N = 1 for all three Reynolds numbers, which is discussed in more detail in [12,13].

WHY BLUE WATERS

As described in the research results discussion above, sufficient temporal and spatial resolution is required for these DNS to thoroughly study the intricate nature of turbulence, turbulence suppression, and relaminarization. In particular, to obtain data that are suitable for the description of the entire statistical distribution of the dissipative scales of turbulence, the DNS require sub-Kolmogorov scale grid resolution. Access to Blue Waters' resources was essential to accomplish this computationally demanding research.

PUBLICATIONS & DATA SETS

J. Davis, S. Ganju, and C. Brehm, "Direct Numerical Simulations of turbulence suppression in rotating pipe flows," in *Parallel CFD Conf. Proc.*, Indianapolis, IN, U.S.A., May 14–17, 2018.

C. Borchetta, C. Brehm, and S. Bailey, "On the development of an apparatus to examine rotating pipe flow at high rotation numbers," APS DFD, Atlanta, GA, U.S.A., Nov. 18–20, 2018.

J. Davis, S. Ganju, and C. Brehm, "Direct Numerical Simulations of rotating turbulent pipe flows at moderate Reynolds numbers," APS DFD, Atlanta, GA, U.S.A., Nov. 18–20, 2018.

C. Brehm, J. Davis, S. Ganju, and S. Bailey, "A numerical investigation of the effects of rotation on turbulent pipe flows," 11th Inter. Symp. Turbulence and Shear Flow Phenomena (TSFP11), Southampton, England, U.K., July 30–Aug. 2, 2019.

J. Davis, S. Ganju, N. Ashton, S. Bailey, and C. Brehm, "A DNS study to investigate turbulence suppression in rotating pipe flows," in *AIAA Aviation 2019 Forum*, Dallas, TX, U.S.A., June 17–21, 2019, doi: 10.2514/6.2019-3639.

N. Ashton, J. Davis, and C. Brehm, "Assessment of the elliptic blending Reynolds stress model for a rotating turbulent pipe flow using new DNS data," in *AIAA Aviation 2019 Forum*, Dallas, TX, U.S.A., June 17–21, 2019, doi: 10.2514/6.2019-2966.