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Reynolds number scaling of the influence of boundary layers on the global behavior of laboratory quasi-Keplerian flows

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We present fluid velocity measurements in a modified Taylor-Couette device operated in the quasi-Keplerian regime, where it is observed that nearly ideal flows exhibit self-similarity under scaling of the Reynolds number. In contrast, nonideal flows show progressive departure from ideal Couette as the Reynolds number is increased. We present a model that describes the observed departures from ideal Couette rotation as a function of the fluxes of angular momentum across the boundaries, capturing the dependence on Reynolds number and boundary conditions.

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I. INTRODUCTION

That the global properties of an extended system may be mapped to the boundaries is an idea that has found success in holographic theories of general relativistic systems [1,2] and in magnetically confined plasmas [3,4]. We report on a similar behavior observed in incompressible hydrodynamic flows in a Taylor-Couette (TC) apparatus where it is observed that certain characteristics of the global flow are largely dictated by the boundaries. This finding is particularly relevant for experiments that examine quasi-Keplerian (QK) flows, that is, rotation satisfying $0 < q < 2$, where $q = -d \ln \Omega / d \ln r$, Ω is the fluid angular velocity, and r is the radial coordinate, as models of astrophysical systems, namely accretion disks. Numerous recent studies have commented on the hydrodynamic stability of such systems [5–8], with extensions to magnetohydrodynamics in electrically conducting fluids [9–13].

While there is some disagreement between studies as to whether hydrodynamic turbulence can be induced in QK flows, the balance seems to lean toward the negative, at least insofar as incompressible turbulence is considered, and points to the important role of magnetohydrodynamic effects in astrophysical systems. However, while it is known that QK flows are linearly stable it remains unknown whether there exists a nonlinear transition to turbulence, even for incompressible hydrodynamic systems. Some experiments [5–7] and simulations [14] indicate that such a transition is not likely, while others present evidence that suggests that a subcritical transition may exist [8] and some simulations find significant transient growth of perturbations that may allow for nonlinear effects to enter [15]. Fluid experiments in other regimes of operation that are not astrophysically relevant have observed bistability [16,17], suggesting that should a similar mechanism exist for QK systems then a subcritical pathway to turbulence may explain angular momentum transport in accretion disks [18]. We show in this work that the influence of the boundaries is intimately connected to the global structure of flows in Taylor-Couette experiments and, by extension, is also related to the tendency of these systems to generate and sustain turbulence.

One of the long-standing challenges of Taylor-Couette experiments in the quest to understand angular momentum transport in astrophysically relevant flows has been the parasitic presence of Ekman circulation (secondary circulation) induced by the mismatch between the fluid velocity and the solid body rotation of the axial boundaries. A significant reduction in Ekman circulation has been realized in experiment by using axial boundaries that are split into multiple rings capable of differential rotation. Under particular boundary conditions, azimuthal velocity profiles of the fluid can be generated that very nearly match that of ideal Couette rotation [5,7,19,20], the rotation profile that is expected in the absence of axial influences for a constant radial flux of angular momentum, and has been observed to hold over a wide range of Reynolds numbers [20]. In contrast, studies in the "classical" configuration where the axial boundaries corotate with the outer cylinder have shown performance that further deviates from ideal Couette as the Reynolds number is increased [21]. Such trends are revealing of whether these systems are dominated by boundary interactions or internal dynamics, a distinction with important consequences for the applicability of such experiments to interpretation of astrophysical systems, especially at large Reynolds numbers. First, through the experiments reported here we identify two necessary criteria that define constraints on the boundary configurations that allow near-ideal flows to develop. We then discuss the competing roles of radial (Stewartson) boundary layers and axial (Ekman) boundary layers, from which we develop a model that describes the quantitative departure of the rotation profiles from ideal Couette flow as a function of the angular momentum fluxes through the boundaries.

II. EXPERIMENTAL APPARATUS

A TC device is a system of coaxial cylinders that rotate independently of each other with the experimental fluid region between. The TC apparatus used in these studies, called the hydrodynamic turbulence experiment (HTX), is a modified version of the classical device in that the axial boundaries in HTX are segmented to allow differential rotation across the boundaries [7]. The inner cylinder radius is $r_1 = 6.9$ cm and the outer cylinder radius is $r_2 = 20.3$ cm. The inner radius and outer radius of the independent rings are defined by the parameters r_3 and r_4, respectively. The axial length of the experimental volume is $L = 39.8$ cm, giving an aspect

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