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Experimental study of the grain-water mixture flow past a cylinder of different shapes

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ABSTRACT

This paper reports on the experiments of the flows of a mixture of grains and water around a circular or triangular cylinder, where the two-dimensional flow is driven by the internal cylinder of a Taylor–Couette cell. The working conditions during tests are such that instabilities do not appear. Velocity measurements of the mixture at the external surface are carried out using the PIV technique. The flow field is very different from that of a Newtonian fluid. However, the streamline patterns look similar, if the flow directions are ignored, as it happens for a dry granular stream. A limited recirculation zone behind the triangular cylinder is present, whose size is much less than that for a Newtonian fluid and is absent for dry granular stream. Upstream of the triangular cylinder, a zone of sediments almost at rest is present, with a semi-circular shape and an extension independent on the Reynolds number. It seems that the flow is controlled by factors downstream the location of interest. Vorticity scales with both the size of the obstacle and the free stream velocity, and is confined near the vertices at the base of the triangular cylinder. Compared to the vorticity field for the Newtonian fluid case, it spreads more upstream. The normalized energy of vortices has a probability distribution function with a peak and a steep reduction, but does not scale with the Reynolds number. The contribution of clockwise and counter-clockwise vortices is roughly balanced.

1. Introduction

The granular flow around an obstacle is of interest in the study of the complex rheology of a fluid, as well as in practical applications. There are numerous industrial processes, where solid objects are present in the stream as heat exchanger or are used as weld lines in polymer processing applications. They are also relevant in food manufacturing, chemistry and pharmacy, and in measurements instrumentation, where the vortex shedding flow meter is based on the detection of shedding frequency of eddies generated by an obstacle inserted in the stream.

The literature includes several references on Newtonian fluid flows around a circular cylinder (see [1]), and the potential flow theory of infinitely long wings that uses conformal mapping of flow around a circular cylinder. [2] present a detailed analysis of the flow of water and polymer additive around a circular cylinder, while [3] analyze the gravity-driven flow of mustard seeds around a cylinder, adopting a kinematic description based on a stochastic model. Other more detailed analyses refer to the kinematics of complex fluids flows around bodies [4].

Despite the widespread use of cylindrical and non-circular obstacles in many applications, the studies on this geometry effect are scant, especially for triangular cylinder with a vertex facing downstream.

There are limited experimental and theoretical analyses for Newtonian fluids with the numerous possible conditions (orientation respect to the incoming flow, characteristics of the incoming flow, aspect ratio of the obstacles, etc.), let alone non-Newtonian fluids. [5] numerically analyzed the flow of incompressible Newtonian fluids around a triangular cylinder with the apex facing upstream, while [6] made an extensive numerical simulation for the 2-D laminar flow of power-law fluids over an equilateral triangular cylinder in both configurations, i.e. with apex facing upstream and downstream. A few experimental investigations about the shedding vortices from the triangular cylinders or prisms in cross flow have been reported in high Reynolds-number turbulent flows, e.g. [7–10].

The present experiments deal with a mixture of grains and water — a fluid with a complex rheological behavior. A crude analogy can be made between this flow with the dry granular flow, with air as inter particles fluid. Usually, numerical simulation is

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Nomenclature

$\ldots^*$	Non dimensional operator
δ	Thickness of the gap
Γ	Shear rate, circulation
λ	Linear concentration of the solid phase, eigenvalue
μ	Dynamic interparticle fluid viscosity
ν	Kinematic viscosity of the interparticle fluid
$\nu_{mixture}$	Apparent kinematic viscosity of the mixture
ρ_s	Mass density of the solid phase
σ	Standard deviation
ω, ω_z	Rotation rate, vorticity component along z
$\mathbf{\Omega}$	Tensor, antisymmetric part of the velocity gradient tensor
$a_1, b_1, c_1, d_1, e_1, a_2, b_2, c_2, d_2, e_2, c$	Coefficients
b	Length of the edge of the base of the triangular cylinder
Ba	Bagnold number
C, C_0	Void concentration of the grains (ratio between the volume of sediments and the bulk volume), maximum void concentration of the grains
CCW	Counterclockwise
CW	Clockwise
d	Grain diameter
D	Diameter of the circular cylinder, of the cylinder of the cell (internal or external)
E	Energy
FOV	Field of view
l_k	Length of the kernel
L	Length of the recirculating zone
$L_{x,y}(\cdots)$	Polynomials for spatial correction along x, y
LDA	Laser Doppler Anemometry
NDH	Nedderman R.M., Davies S.T., Horton D.J. (1980), Powder Technology 25 215–223
pdf	Probability density function
PIV	Particle Image Velocimetry
PMMA	Polymethyl methacrilate
POD	Proper Orthogonal Decomposition
R, r	Radius of the cylinder (internal, external) $r$adius of the eddies
rpm	Revolutions per minute
Re, Re$_c$	Reynolds number, critical Reynolds number
$\mathbf{S}$	Tensor, symmetric part of the velocity gradient tensor
s	Wall thickness
t, dt	Time, time increment
Ta, Ta$_c$	Taylors number, critical Taylors number
U_0	Reference asymptotic velocity
U_x, U_y	Horizontal, vertical instantaneous velocity
U, V	Horizontal, vertical instantaneous velocity
U'_x, U'_y	Horizontal, vertical fluctuating velocity
U', V'	Horizontal, vertical fluctuating velocity
x, y	Spatial co-ordinates
$\boldsymbol{x}$, $\boldsymbol{x}'$	Position vector, dummy position vector
x_c, x_m, y_c, y_m	Spatial co-ordinates measured, corrected

used for studying granular flows, and in most analysis the drag of obstacles in the granular stream is of major interest. [11] used discrete element simulations to investigate a two-dimensional dilute dry granular flow around an immersed cylinder (no interparticle fluid) in order to evaluate the drag coefficient. They found that the drag coefficient depends on the Mach number, expressed as the ratio of the asymptotic velocity and the celerity of sound, and on the Knudsen number, expressed as the ratio between the mean free path of particles and the diameter of the cylinder. They also depicted some properties of the granular flow, including velocity, temperature (a measure of the velocity fluctuations) and the solid fraction field. [12] experimentally studied the flow around a fixed cylinder immersed in a uniform dry and dense granular flow, including the vorticity and the granular temperature fields. They found that the drag force is independent of the mean flow velocity and scales with the asymptotic stress.

The drag behaves differently between the obstacles moving in the granular medium at rest and the obstacles at rest placed in a granular stream. In both cases, the presence of grains at high concentrations near the obstacles induces stress transmission through contact forces and leads to a jammed state. This jammed state is a character of granular flows, different from classical Newtonian fluid flows. Jamming can be caused by the gravity force and compressive stress. The main kinematic effect of jamming is the need for a proper re-organization of the flow pattern around obstacles inside a granular medium. The length scale of the re-organization pattern is different in the two extreme situations and generally enhances the disturbances by the obstacles, which subject strong fluctuations of the drag force. If the granular medium is at rest (on average), the drag usually depends little on the speed or on the form of its cross-section [13], except at low velocities. If the obstacle is at rest, a much stronger dependence on granular velocity is expected, with a low resistance similar to that for a usual fluid (a quadratic law at high velocities). These results can be drastically different if a lubricant interstitial fluid is present. Some numerical experiments on the interaction of a stream of granular particles with a resting obstacle in two dimensions [14] show that, at low velocities, the drag is proportional to the 3/2 power of the velocity, whereas at high velocities, the drag recovers its usual quadratic dependence on velocity.

Compared to other flows, granular flows are often characterized by significant variations in bulk density. Experiments by [15] show that a granular stream impacting an obstacle or being regulated by a wall has different zones of compression and expansion with shocks and discontinuities. In these experiments, it is very difficult to measure fluid velocity. It is possible to use Laser Doppler Anemometry (LDA) [16] and Particle Image Velocimetry (PIV) [17] through a transparent wall. While PIV exactly displays the particle motion, results usually underestimate the real velocity due to the wall boundary layer (unless it is used for measuring a free granular surface), but fortunately, this error is limited due to slip of granular flows at the boundary.

The flow of a fluid–granular mixture is characterized by three main regimes: (i) a macroviscous regime with essentially Newtonian behavior, (ii) a dilatant regime with interparticle collisions dominant, and (iii) a quasi-static regime, with stresses transferred mainly as frictional stresses. Several models have been developed and tested for dry grain rapid granular flows, mainly based on the assumption of an isotropic granular temperature, small dissipation and low to mid grain void ratio. Significant progress has also been made regarding the granular temperature anisotropy. However, little has been done to include the effects of interstitial fluid since Bagnold's pioneering work [18]. Bagnold was interested in the rheology of the mixture, and developed a model widely used for its simplicity that makes it an excellent tool for practical computations or simplified approaches. Despite several critics [19] and the limitations of the model (e.g., the evidence that it does not develop a constitutive equation, lacking a tensorial formulation), Bagnold's model is still adopted at least for concentrated suspensions of grains in water at low shear rates (Bagnold's macroviscous regime). However, Bagnold's model does not consider the interaction between the mixture and solid boundaries.

The aim of the present experiments is to provide information on the kinematics of the flow fields past a circular cylinder and a