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Experimental study of monodisperse granular flow through an inclined rotating chute

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ABSTRACT

In blast furnaces, particles like coke, sinter and pellets enter from a hopper and are distributed on the burden surface by a rotating chute. Such particulate flows suffer occasionally from particle segregation during transportation caused by differences in density or size. To get a more fundamental insight into these effects, we started an experimental study to investigate the effect of rotation on such particulate flows.

Here, as a first step, we present an experimental study of granular flow of monodisperse 3 mm spherical glass particles flowing with a constant mass rate through a rotating smooth rectangular chute, which is inclined at a fixed angle. Experiments are performed for a sufficiently long time to study steady (but streamwise accelerating) flow. Particle image velocimetry (PIV), electronic ultrasonic height sensors, and a dynamic weighing scale are used to measure the surface velocity of the particle stream, the particle bed height and mass flow rate in the chute, respectively. The influence of rotation speed and angle of inclination of the chute is studied. We find an interesting interplay between the Coriolis force, which pushes the granular flow to the sidewall of the chute and tends to diminish the acceleration of the flow, and centrifugal forces that accelerate the flow. The velocity components display a complex dependence on the spanwise and streamwise position in the chute. The bed height in the chute is also influenced by these effects of system rotation. These measurements provide a well-defined set of observations for refining and validating computer simulations of granular flows, and point out some important limitations of physical experiments. We present preliminary three-dimensional discrete particle simulations, which show that the experimental measurements of bed height and surface particle velocity in a chute inclined at 30° can be predicted nearly quantitatively both without and with rotation of the chute.

1. Introduction

The flow behavior of dry granular materials is very important in many man-made and naturally occurring processes. Chemical, pharmaceutical, metallurgical and agricultural industries need to handle granular materials to produce their final products. Handling of granular materials involves the application of many solid processing devices such as mixers, chutes, hoppers, and other transfer equipment. An important example in the steel industry concerns the controlled charging of blast furnaces with coke, sinter and pellets, where the particles are finally delivered through open rotating channels.

Despite their common occurrence, fundamental knowledge about the dynamics of particulate flows through inclined open channels is still limited. Such particulate flows suffer occasionally from particle segregation during transportation caused by differences in density or size. The behavior of a granular flow through an inclined channel is partly determined by the wall surface characteristics, which can be either smooth or rough. Smooth surfaces lead to an ever-accelerating flow, see e.g. Augenstein et al. [1], Brennen et al. [2], Campbell [3], Johnson et al. [4] and Holyoake [5]. In case of a rough surface, for a range of chute angles a slow steady uniform granular flow can be produced. Such a rough surface is often generated by gluing particles to the surface, see e.g. Pouliquen [6], GDR MiDi [7], Holyoake [5] and Sheng [8]. It is of interest to mention that GDR Midi issues a phenomenological constitutive law for flows over uniform but rough chutes. In contrast to classical fluid mechanics, general constitutive laws for granular flows are largely unknown and experimental studies in these circumstances provide a key approach to the investigation of their dynamical behavior. Several experimental investigations and simulations have been carried out in the past on complex conveyer geometry and profiles to study the bulk flow behavior of granular materials, see Robert et al. [9,10]. Continuum-based methods have been used to predict the flow of granular cohesionless materials in chutes, see Roberts [11].

Different measurement techniques are used for measurement of granular flow based on force sensors (Savage and McKeown [12], Zenit et al. [13]), acoustic probes (Bennett and Best [14]), tracked transmitters (Dave et al. [15]), capacitance probes (Louge et al.

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List of symbols

Ro	Rossby number
Fr	(rotational) Froude number
V_p	particle velocity (m/s)
L	chute length (m)
W	chute width (m)
H	chute height (m)
Q	mass flow rate (kg/s)
m_p	mass of particle (kg)
d_p	particle diameter (m)
ρ_p	density of particle (kg/m^3)
Ω	rotation rate (rad/s)
ϕ	angle of inclination of the chute (rad)
G	gravitational acceleration (m/s^2)
g_n	gravitational acceleration in normal direction (m/s^2)
g_t	gravitational acceleration in tangential direction (m/s^2)
r	distance from the axis of rotation (m)
$\vec{a}$	acceleration of particle (m/s^2)
$\vec{F}_N$	reaction force from chute wall (kg m/s^2)
M	magnification of image (pixel/m)

[16]), optical sensors (Dent et al. [17]), and digital imaging (Guler et al. [18], Capart et al. [19], Bonamy et al. [20]). Variations on uniform granular flow pertaining to flow around obstacles and oblique granular jumps or shock waves at slight corners have also been studied in Gray et al. [21] and Hakonardottir and Hogg [22].

In this paper we consider specifically the effect of chute rotation on the granular flow of monodisperse particles down a smooth inclined chute. The novelty of our investigation lies in the fact that state-of-the-art experimental methods have been used to obtain a well-defined reference data set of particles flowing down an inclined chute at different rotation rates. The rotation leads to additional Coriolis and centrifugal forces on the particles (Fig. 1), which in turn lead to flow paths and particle distributions in a rotating chute which deviate considerably from those in a non-rotating chute. The key parameter that classifies the relative effect of the inertial and the Coriolis forces is the so-called Rossby number, defined as

$$\mathrm{Ro} = \frac{V_p}{2\Omega \mathrm{L} \cos\phi} \tag{1}$$

where V_p is the particle flow velocity (within the co-rotating frame), Ω is the rotation rate of the chute and L is the chute length and ϕ is the angle of inclination. This is an important dimensionless parameter also in geophysical flows when comparing typical flow time scales L/V_p with the background rotation of earth the Earth. When $\mathrm{Ro} \gg 1$, the effects of rotation are unimportant and can be neglected, whereas $\mathrm{Ro} \ll 1$ signifies a system which is strongly affected by the Coriolis force.

The relative importance of the centrifugal force compared to the gravitational force can be quantified by a (rotational) Froude number defined as [23]

$$\mathrm{Fr} = \frac{\Omega^2 \mathrm{L} \cos\phi}{\mathrm{g}} \tag{2}$$

where g is the gravitational acceleration. When $\mathrm{Fr} \ll 1$ the gravity dominates the centrifugal effects.

The paper is organized as follows. In Section 2 we present the experimental setup and the measurement techniques. In Section 3, we present the experimental results of the effects of rotation on the flow behavior of a monodisperse granular flow through an inclined chute for three different inclination angles $\phi = 30$, 40 and 50°. In

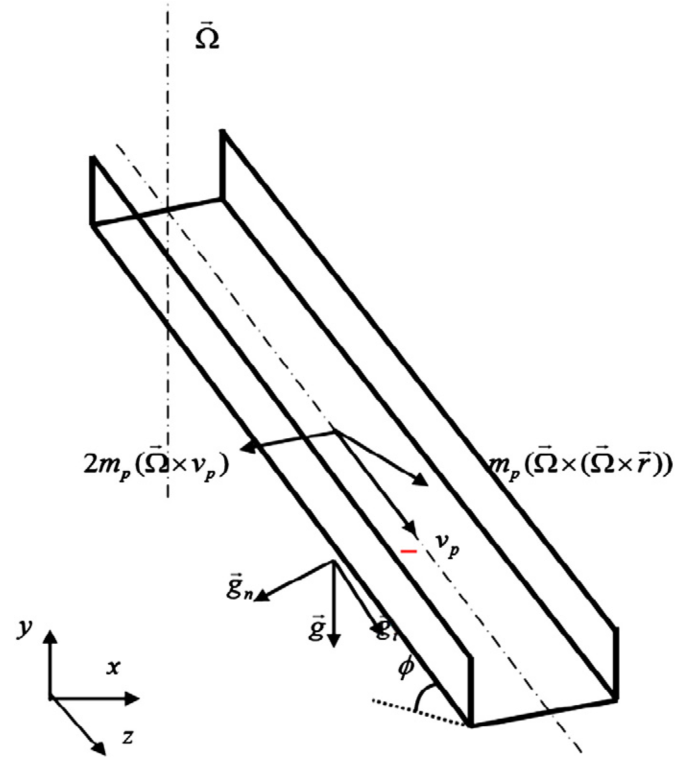

Fig. 1. Orientation of gravitational, centrifugal and Coriolis forces experienced by particles flowing down a rotating inclined chute.

Section 4, preliminary discrete particle simulation results are compared with experimental measurements of a rotating chute inclined at 30°. We will show that pronounced effects of rotation occur in granular flows for which $\mathrm{Ro} < 1$. We give our conclusions in Section 5.

2. Experimental setup and techniques

In this section we describe the experimental setup and measurement techniques, including use of electronic ultrasonic height sensors and particle image velocimetry (PIV). We outline experimental settings and the experimental protocol followed in the experiments.

2.1. Experimental setup

In Fig. 2 we give a schematic representation of the side view of the experimental setup. The chute is made of plexiglass for optical accessibility. The experimental equipment includes a hopper for storage of particles and a collection tank. A vacuum pump is attached to the top of the hopper to recycle the granular material from the collection tank. The mass rate is measured through a dynamic weighing scale, the particle bed height is measured at selected locations through an ultrasonic sensor, and the surface particle velocity field is measured through a PIV camera and basic PIV tools.

The granular material is stored in a hopper at the top end of the chute. To minimize rotational flow of the granular material inside the hopper prior to deposition on the chute, the rotation axis passes through the center of the hopper. The bottom end of the hopper is connected with different mouthpieces in order to get different flow rates at exit of the hopper.

The flow region of the experimental setup consists of a rectangular Plexiglas chute with transparent sidewalls though which the moving granular material can be photographed. The interior of the chute is 1 m in length, 10 cm in height, and 8 cm in width. The bottom wall of the chute is black to achieve a better contrast in the photographs. The inclination angle of the chute (defined with respect to the