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Free surface flow characteristics of multi-phase viscoplastic fluids on inclined flumes and planes

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ABSTRACT

Laboratory experiments were conducted to understand the dynamics of gravity-driven free surface flow of multi-phase viscoplastic fluids. Foam and sand–foam mixtures were employed to represent multi-phase yield stress fluids. Two different foam–water ratios of 0.1 and 0.2 were used and a wide range of sand concentrations from 0 to 0.82 were selected. A series of flume tests were conducted to model the two-dimensional flow of sand–foam mixtures for two slopes of 10° and 15°. Effects of sand concentration c_o on the dynamics of free surface flow were investigated. Three-dimensional spreading tests were carried out using an inclined plane with four bed slopes of $\alpha = 10°$, 12°, 15° and 18. Single and multi-discontinuity were observed in the spreading of foam mixtures. It was found that the number of discontinuities can be correlated with the bed slope and multi-discontinuity occurred for $\alpha \geq 12°$. Flow heights and frontal velocities were measured for different experimental conditions (slope angle, rheological parameter). The results of spreading tests were properly scaled using a non-dimensional time scale and Froude number. Experimental results were used to predict the rheological characteristics of sand–foam mixtures based on the Herschel–Bulkley constitutive law. Predictions were compared with independent measurements of the rheological parameter. The inclined plane test results showed that the shear stress predictions were independent of the bed slope and the uncertainty of the predictions was slightly higher than the rheometery results from the literature.

Introduction

The flow of multi-phase viscoplastic fluids on inclined surfaces is often encountered in engineering applications such as transport of mining products, fresh concrete and sewage sludge. (Coussot et al., 1996; Chambon et al., 2009; Chambon et al., 2011). Complex flow mixtures involve in natural catastrophic events and geophysical situations such as debris flows, lavas, and submarine slides are also belong to this class of materials (Coussot and Meunier, 1996; Coussot et al., 1998; Ancey, 2007). Foam and sand–foam mixtures are also categorized as multi-phase viscoplastic fluids and their rheological characteristics can be well predicted by the Herschel–Bulkley constitutive law (Azimi, 2015a; Azimi, 2015b).

Sand–foam mixtures can be made by the addition of either powders or liquid foaming agents and sand particles to water forming a uniform texture with a macroscopic continuous structure. These mixtures have many potential applications in underground mining and land stabilization (Abazari Torgabeh, 2013). A proper mixture of sand and foaming agent can be spread uniformly over unstable areas to prevent sand storm. Sand–foam mixtures can also be used in under-balanced drilling to enhance oil recovery in porous media (Edrisi et al., 2013) and to suppress underground fires in mining industry (Bobert et al., 1997). The performance of high-expansion fire-fighting foam has been tested in the past to control underground coal mine fires (Chasko et al., 2003).

Understanding the dynamics of multi-phase viscoplastic fluids is of particular importance to predict the flow behavior at different conditions for improving industrial processes and protect against hazard. Since conventional rheometrical tests deal with small scales, other practical techniques such as slump test, inclined flume and surface tests have been used in the past to study the dynamics of complex flows and mixtures in relatively larger scales (Clayton et al., 2003; Gawu and Fourie, 2004; Chanson et al., 2006; Cochard and Ancey, 2009). Those tests were used to identify the rheological characteristics and expansion rates of the mixtures in transient and steady state conditions. Gumati and Takahshi (2011) conducted experimental and numerical studies to evaluate the effect of foam–water ratio on the structure of foam-cuttings mixtures by measuring the pressure loss in horizontal pipes. Gawu and Fourie (2004) found that some rheological characteristics of different tailings can be measured by a slump test and the results showed a good agreement with the controlled-stress rheometery.

Rheological characteristics of foam mixtures to design pipeline network and pump operation were also studied using horizontal pipe

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and horizontal flume tests (Briceno and Joseph, 2003). Coussot and Boyer (1995) examined the accuracy of inclined surface test under a steady state condition to determine the yield stress of clay–water mixture whose yield stress ranged from 35 to 90 Pa. Coussot and Boyer (1995) used a 1 m long flume with a slope ranging from 10° to 30°. They showed a relatively good agreement between yield stress measurements from an inclined surface test and rheological measurements if the edge effects being considered. Coussot and Proust (1996) employed a mixture of fine mud suspension at different solid concentrations to model the expansion of mudflows in an inclined plane. They used the Herschel–Bulkley model to predict the longitudinal and lateral mean velocities and fluid depths of mudflows. The Herschel–Bulkley model can be defined as

$$\dot{\gamma} = 0 \Leftrightarrow \tau < \tau_o \qquad \dot{\gamma} \neq 0 \Leftrightarrow \tau = \tau_o + K\dot{\gamma}^n \tag{1}$$

where $\dot{\gamma}$ is the shear rate, and τ are the shear stress and τ_o is the critical shear stress. K is the consistency and n is an index of the model and both of them are positive numbers.

Cochard and Ancey (2009) studied the spreading of viscoplastic fluids (i.e., Carbopol Ultrez 10) on a plane surface, whose inclination ranged from $\alpha = 0°$ to 18°. It was found that the front position of the flow varied as a power function of time and an empirical formulation was developed to predict the front position of the flow. The proposed formulation was a function of time and plane inclination. Chanson et al. (2006) conducted a series of laboratory experiments using a tilting flume with a slope of 15° to study the flowability of Bentonite suspension. They developed an empirical formulation to predict the frontal position and velocity of the Bentonite clay flowing in the flume. Variations of the frontal position and velocity with time were found to be a function of the initial flume height H_o and the bed slope α. They reported that the proposed formulation provide reasonable accuracy for $[t(gH_o)^{1/2}] < 6$ where t is time and g is the gravitational acceleration. Recently, Chambon et al., (2014) presented a series of experimental studies on the hydraulic properties of free-surface flow of viscoplastic fluids. Two types of Herschel–Bulkley fluids (i.e., Kaolin slurries and Carbopol microgels) with different microstructure were employed. They found an excellent agreement between the results of rheometrical tests and theoretical predictions for Kaolin slurries. For Carbopol microgel, a systematic discrepancy was reported between experimental results and analytical predictions due to larger microstructure of Carbopol samples.

This paper aimed at understanding the free-surface flow dynamics and spreading of multi-phase viscoplastic fluids on inclined flumes and planes. Sand–foam mixtures with different foam–water ratios and sand concentrations were selected as an example of multi-phase viscoplastic fluids. The foremost objective of this study is to correlate the dynamics of multi-phase viscoplastic fluids with different fluids characteristics such as density and rheological parameters. Density and rheological characteristics of sand–foam mixtures are controlled by foam–water ratio and sand concentration. Experimental results of this study can be used to validate numerical models and improve general understanding on the dynamics of multi-phase viscoplastic fluids.

Experimental studies began with two-dimensional flume tests. The flow positions and frontal velocities were measured and the results scaled based on the non-dimensional time scale and Froude number. Spreading of the flow mixtures were tested by conducting inclined plane tests. A more empirical point of view was adopted in order to describe the intermediate flow of sand–foam mixtures. The simplified one-dimensional momentum equation and the discharge equation using the Herschel–Bulkley constitutive law were employed to predict the rheological characteristics of the flow.

This paper is structured as follows. Section two of this paper describes the theoretical background on the free-surface flow of complex fluids on inclined surfaces. Section three describes the experimental design and procedures. Section four is devoted to experimental results followed by proposed empirical formulations. Section five discusses about the performance of the theoretical models to predict the dynamics of sand–foam mixtures. The conclusions of the experimental studies are drawn in section six.

Theory and background

Flow of viscoplastic fluids on inclined flumes

The averaged critical shear stress in an inclined flume can be estimated using one-dimensional force balance between the gravitational force and the resistance shear force as

$$\rho g h_o (\sin\alpha) x_F = \tau_o (x_F + 2h_o) \tag{2}$$

where u_F is frontal velocity, x_F is frontal position and h_o is the asymptotic depth of the mixtures when $u_F \to 0$ (see Fig. 1). Neglecting the wall effects on the force balance, Eq. (2) can be simplified as

$$\tau_o = \rho g h_o (\sin\alpha) \tag{3}$$

Frontal velocity of the two-dimensional granular flow on inclined flume can be predicted using dimensional analysis. Pouliquen (1999) found a linear relationship between the normalized depth and Froude number as

$$\frac{u_F}{\sqrt{gh}} = \beta \frac{h}{h_{stop}(\theta)} \tag{4}$$

where h is the flow depth, $h_{stop}(\theta)$ is the critical depth of flow at specific angle θ and $\beta = 0.136$. The steady-state gravitational flow of a Herschel–Bulkley fluid in an open channel and in laminar flow condition was studied by Coussot (1994). He showed that the flow can be described by the non-dimensional fluid depth G and the non-dimensional shear stress H_b (i.e., Herschel–Bulkley number) as

$$G = \frac{\rho g h (\sin\alpha)}{\tau_o} \tag{5}$$

$$H_b = \frac{\tau_o}{K}\left(\frac{h}{u_F}\right)^n \tag{6}$$

Coussot and Boyer (1995) defined the asymptotic depth h_o corresponding to rest state when G drops to 1 (i.e., $h = h_o$). Using the discharge equation established for the Herschel–Bulkley fluids Coussot (1994) showed that the following correlation can be written if the edge effects and surface tension assume negligible.

$$H_b^{-1/n} = \frac{1}{(1/n+1)(1/n+2)} G^{-2} (G-1)^{(1/n+1)} ((1/n+1)G+1) \tag{7}$$

Eq. (7) shows a non-dimensional stress–strain rate relationship and it has been extensively used to predict the free surface flow of the Herschel–Bulkley fluids on inclined flumes (Chambon et al., 2014).

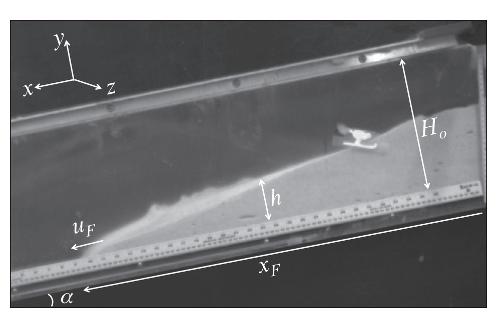

Fig. 1. Image of flow of sand–foam mixture in flume experiment (Test T6-10 at $t = 45$ s) with the coordinate system.