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DYNAMIC AND STATIC WALL FRICTIONS FOR BULK SOLIDS

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Abstract

Wall friction is a critical material characterization parameter to understand when designing mass flow bulk solids storage and handling equipment such as silos/bins and hoppers. There are two wall friction coefficients, namely kinematic (dynamic) and static, to consider, each of which can be measured using standardized test methods. While kinematic wall friction is commonly of more interest for design purposes, static friction is also required for certain applications, such as after material has been held at rest (i.e., not flowing) in storage. This study compares the results of both dynamic and static friction measurements for three bulk solids materials on various wall liners. The results showed that the static wall friction coefficient measured was not consistently higher than the dynamic coefficient as expected. Reasons for this difference are outlined, and the dependence on the material and wall liner properties.

Keywords - Bulk solids handling, Kinematic wall friction, Static wall friction

1. Introduction

In the 1970s, Dr. Andrew Jenike defined the flow – no flow criterion for bulk solids in handling equipment, such as silos/bins and hoppers. The criterion states that a bulk solid will flow when the stress exerted on the solid material exceed its strength [1]. If this is not the case, flow problems may occur such as cohesive arching (blockage) and ratholing (piping). This criterion, when coupled with “flowability”, defined as the ability of a bulk solid to flow through a given piece of equipment reliably, considers the relationship of the bulk material itself and the equipment in which it is to be handled. Thus, the ability to achieve reliable flow of material, is a function of the bulk solid material’s properties (cohesive strength, particle size/shape, moisture content, temperature, etc.) and features of the handling equipment such as geometry, wall surface/liner material, and feeder type [2].

One half of the flowability matrix, the bulk material’s flow properties can be scientifically determined through a series of tests based on the pioneering work of Jenike [1]. Among these, quantifying the frictional between the bulk solid material and wall surface/liner of the equipment induced by material flow along the wall is essential to robust design. Carson discussed the vulnerability of relying on the tabulated values for wall frictions in design codes and explained the significance of conducting the wall friction tests for the material to be handled [3]. The testing results will be highly dependent on the properties of the bulk solids material and wall liner material of the handling equipment. Hancock et. al. [4] analgised the wall frictions for over 100 pharmaceutical powders on stainless steel surfaces with the most common finishes for pharmaceutical powder processing equipment. Ferreira et. al. [5] tested the frictions between different soils and retaining walls which are made of concrete and aggregates with various roughness.

This frictional resistance is often expressed as a wall friction coefficient, \( \mu \), or an angle of wall friction, \( \phi' \) (sometimes identified as \( \phi_w \)). These two values are related as given in Eq. (1).

\[
\mu = \tan \phi'
\]

Values of \( \phi' \) are typically determined using a Jenike Shear Tester or similar device, with the procedure standardised in [6, 7].

2. Testing Methodology

The tests in this study were conducted in accordance with Standard ASTM D6128-16. A Jenike direct shear tester was utilised in the study in conjunction with the associated wall friction test apparatus (see schematic in Fig. 1).

During a wall friction test, the bulk material is placed in a retaining ring on a sample of wall liner material which is compressed to a uniform bulk density. An actuator forces the material in the ring to slide along the stationary wall material at various applied vertical forces.
with the resulting shear force determined as a function of the applied normal force. Note that, in this arrangement, the ring does not contact the wall surface material to prevent additional friction from being generated during the test.

A typical wall friction test result is illustrated by Fig. 2. The abscissa represents the normal pressure exerted on the material, and the ordinate shows the shear force required to overcome the friction between the bulk material and the wall surface/liner material. The resultant curve is called a wall yield locus and is often slightly concave downward with a positive y-intercept.

From this, the wall friction angle can then be plotted as a function of normal pressure, as shown in Fig. 3. The results in this study are presented in this form.

As previously discussed, there are two coefficients of wall friction being kinematic (dynamic) and static. Kinematic wall friction is commonly measured for engineering design purposes, with static friction being required less. The methods for determination of both are outlined in ASTM D6128-16. As shown in Fig. 4, for dynamic friction measurements, the vertical load $\sigma_w$ is gradually decreased by removing weights from the material while the material continuously slides on the wall surface liner material. Thus, the test is conducted without stopping the relative movement between the tested bulk solid material and the wall surface liner. For static wall friction measurements, the material is in stationary position when each new load is applied before shear is induced. This process is repeated for each load.

Both test procedures utilise similar sample preparation methods.

ASTM D6128-16 describes, in section 8.3.7, the process by which static friction can be measured as below:

“static angle of wall friction can be determined as follows: A [wall friction] test is performed as previously described, but when the shear force has passed through the maximum the stem is retracted. After the shear force has fallen to zero, the weight on the hanger is reduced and the motor is stared again, the shear force will again pass through a maximum, and the procedure of retracting the stem and reducing the weight is repeated.

The peak values of $\tau_w$ are used to evaluate the static angle of wall friction.”

There is another type of static wall friction test, which is often referred as wall friction time test or adhesion test, being required frequently to assess the flowability of a material after being held storage for a while. But it is not included in the scope of this study.

### 3. Results and Discussion

Friction tests were undertaken for three iron ore fines materials, at different moisture contents on various wall surface liner materials. The properties of the materials and the details of this test program are listed in Table 1. The selected wall liners were ceramic (Liner 1) and metal (Liner 2 and Liner 3).

| Table 1 | Testing Program |
|---------|-----------------|
| Material | P50, mm | P90, mm | Tested Moisture (wet basis), % | Wall Liner Materials |
| Iron Ore Fines 1 | 2.4 | 6.9 | 8, 16 | Liner 1 |
| Iron Ore Fines 2 | 1.9 | 6.1 | 8, 15 | Liner 2, Liner 3 |
| Iron Ore Fines 3 | 2.5 | 9.7 | 8, 10, 12 | Liner 1 |

The comparisons between the dynamic and static wall frictions for the three bulk solid materials and wall liners tested are presented in Fig. 6, and Fig. 7 respectively.
As can be seen, the dynamic coefficient of wall friction is higher than the measured static values for the Iron Ore Fines 1 material at both tested moistures on the selected wall liner which is contrary to the authors’ expectations. The differences between the dynamic and static friction results for the other two iron ore fines materials, at the same tested conditions, were noted to be trivial. While it seems that the results shown in this study contradict the conventional understanding that the peak static friction is normally higher than the dynamic friction between two solid objects, it can be explained.

To understand a potential cause of the phenomenon observed, it is important to note the difference between an incompressible solid object and the bulk solid material tested. The sample placed in the test rig (see Fig. 1) is a sample of bulk solids consisting of many small particles. Given the particle size distribution and the void spaces between the particles, the specimen in the ring is often quite compressible and will consolidate to different levels depending on the magnitudes of the external forces. While sliding on the wall liner the individual particles are also able to move relative to each other and to rearrange themselves. During consolidation induced by the normal pressure, the bulk density of the material will increase, and the material will become more compact until the bulk density reaches a steady state. The shear force (friction) generally follows a similar trend as the bulk density.

In accordance with the standard, the dynamic wall friction is recorded when the shear force reaches a steady state value. For static wall friction measurements, a “peak” at the onset of sliding is expected; see Case (a) as shown in Fig. 8. It is generally accepted that this peak value corresponds to static wall friction, however, Case (b) which shows no peak at the beginning often occurs. This can make the selection of the static wall friction value challenging.

In this study, based on the definition of the static friction, the values of static wall friction were determined at the moment that the bulk material started to move relative to the wall liner. As such, the values may be less than those measured, at the steady state condition, for the dynamic friction.

Prescott suggests that the peak, at the beginning of shear, is attributable to particle realignment rather than being a true static friction [9]. However, the authors believe that this may reflect a combination of particle re-orientation within specimen in the ring as Prescott stated and the initialization of the movement of those particles which are in direct contact with the wall (which contributes to the static friction).

4. Wall Friction Impact Factors

Many factors can influence the friction between two solid objects and are dependent on the mechanisms
which cause it. Recent research conducted by Person [10], who developed a model of friction for rubber on a hard road surface, suggests that kinematic friction can be higher than static friction.

Friction between bulk solids and a wall liner is governed by the type of bulk solid material (i.e. its flow properties) and the specific wall liner surface; a comprehensive discussion is provided by Prescott [9]. As a summary, the physical and chemical properties of the bulk solid material, such as chemical composition, moisture content, temperature, and particle size distribution etc., will affect wall friction results. Depending on the mechanism of the friction, particle size can have opposite influences on friction results for different materials. Wall liner surfaces’ coatings, roughness, and composition play important roles in determining friction along with the specific bulk material.

5. Conclusion

Wall friction measurements based on the standard (ASTM D6128-16) differ from the conventional determination of friction between two incompressible solid objects. The results in this study show that the static friction between a bulk solid material and a wall liner surface is not always higher than the dynamic friction. Due to the complex nature of bulk solids, the mechanisms that cause friction between bulk solid materials and wall liner surfaces are complicated [11]. More attention should be paid to the development of the testing program to ensure the right information is attained before designing the bulk solids handling equipment.

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