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Hydrodynamic model for the flow of granular solids in the S-valve

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ABSTRACT

This article proposes a phenomenological model to predict the discharge of granular solids (group D in the Geldart classification) through a valve known as the S-valve (or spitting valve), which controls the flow of solids with the injection of a gas. The model predicts the flow of solids as a function of the density of the solid (ρ_s), the friction coefficient (f_s), the void fraction (ε), the gas flow (Q), the valve diameter (D_v), the pressure (P), and the spitting factor (SF). The friction coefficient, f_s, and the void fraction, ε, were estimated based on the surface velocity of the aeration gas using empirical relationships that were integrated into the model. The solids used were rice, lentils, and green coffee beans. The deviation from the model was ±3% for rice and lentil grains and ±2% for green coffee for a range of operation between 0.4 and 0.7 MPa.

1. Introduction

Granular material is one of the most common solid forms in the industrial world today. The treatment of granular materials involves 10% of the energy resources worldwide [1]. Weight estimates show that approximately 75% of raw materials and 50% of chemical industry products are manipulated in granular form [2]. Within the chemical industry, $61 billion is devoted to research on particle technology each year, and approximately 1.3% of the electric energy produced in the United States is expended in the pulverization of minerals [3]. Problems related to the poor handling of granular solids account for failures in approximately 1000 silos, containers and nozzles in North America each year [4]. In Mexico, 30% of the 5 million tons of corn stored in silos each year is lost due to poor handling of the grain [5].

Solid granular particles such as coffee, rice, mustard, salt, sand, and sugar grains will cling together due to their nature, which leaves gaps between grains that, in most cases, are filled with gas. Modeling the transport of two-phase gas and solid flows and calculating the loss in pressure is a complex task because of the different weight distributions in the mixture. These different weight distributions imply different types of flow, each with its own model [6]. Some techniques have been developed to treat the phenomenon of two-phase flows, such as empirical estimates and methodologies [4,7,8], semi-analytical estimates [9], and empirical models with reduced application ranges [10–12].

According to Zuriguel [13], the technology to manipulate and control granular materials is not yet adequately developed. Likewise, according to Huang et al. [14], the study of the hydrodynamics of non-mechanical valves is still deficient given the complex relationship between the gas and the solid that occurs within the valves. Of the many studies on non-mechanical valves (which mostly refer to the use of "group B" solids in the Geldart classification scheme), the studies of Matsumoto et al. [15], Geldart and Jones [8], Yang and Knowlton [16], Huang et al. [14], Kunii and Levenspiel [17], Daous and Al-Zahrani [18], and Hua et al. [9] stand out. These works omit the study of Geldart group D granular solids that occur frequently in industry.

To operate an experimental system of staged spouted beds, Arriola [19] designed and used a modified L-valve for the first time. The researcher dubbed this modified L-valve an "S-valve"—a device that has not yet been characterized and documented. In some of these experimental tests, the use of an oscillating pressure was observed to yield a more uniform flow of solids than when a stable pressure was used. Solids are continuously ejected from the system using pulses of compressed air that literally "spit" the solids (this is how the name "spitting valve" was derived). To prevent the problem of solids circulating uncontrolled toward the exterior of the pressurized system, the S-valve has an ingenious seal for these solids.

The S-valve (shown in Fig. 1) is a non-mechanical valve that controls the flow of granular materials with only the injection of a gas. Non-mechanical valves include the L-valves, the J-valves [20], the W-valves [17,21], the V-valves [22], and the N-valves [23].

The transport of solids takes place in a diluted stage when the solid particles move and are distributed throughout the section of the conduit that transports them, particularly the S-valves. In the diluted stage, the particles collide with each other or against the walls of the conduit; however, because contact between particles is minimal, it can be disregarded [24]. The void fraction (the space between particles) is

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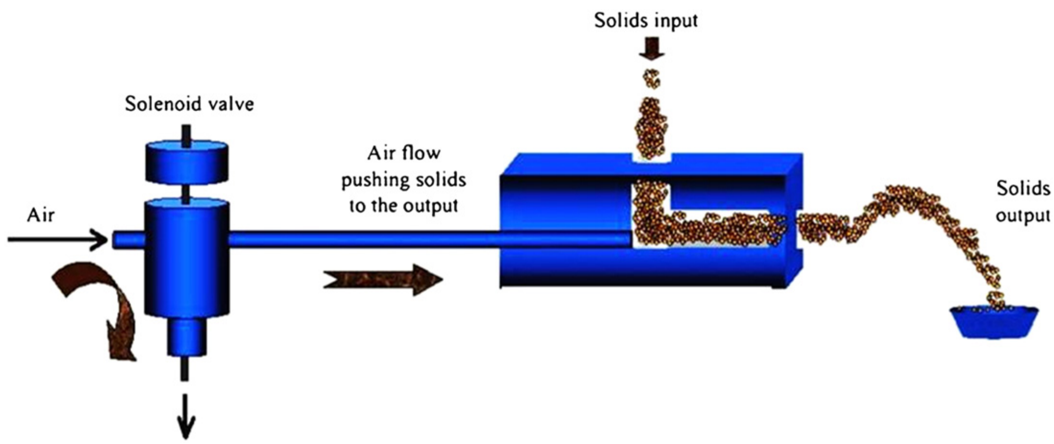

Fig. 1. S-valve [19] operated by a solenoid valve.

high (between 0.90 and 0.99 [25,26]), the ratio of solids to air is low, and the solids and the transporting fluid (air) are mixed within the same pipe and behave as "a single fluid," all of which helps to achieve an average density [27].

In the modeling of granular solids in the diluted stage, the particles interact only by so-called short-range forces (mechanical contact). Long-range forces, such as electrostatic forces, are not considered in these systems. The dynamics of group-D granular materials is therefore governed by Newton's laws of motion [28].

This article presents a mathematical model that permits the prediction of the discharge of group-D granular solids through the S-valve. The model is based on a balance of forces and theoretical considerations specific to the two-phase flow.

2. Materials and methods

2.1. Solids used

An experimental program was carried out with three types of grains in different sizes and shapes: rice, coffee, and lentils. The grains studied belong to the "Geldart group D" type [8]. The experimental design was based on multiple factors with different measurement levels. The "discharge" variable was left as a dependent variable, and air flow (Q), working pressure (P), valve diameter (D_v), and particle diameter (d_p) were used as *predicting* variables (Table 1). The experiments were executed in triplicate. The data were analyzed with Statgraphics Centurion XV (StatPoint, Inc., 2005).

The relevant properties of the solids used to design the S-valve were geometric particle diameter (d_p), density (ρ_p), sphericity (ϕ_s), and void fraction (ε) under the assumption of a fixed bed (Table 2). The characteristic dimensions (length, width, and height) of the grains were measured with a micrometer; the density was determined by the method suggested by Shoemaker et al. [29] and by Baryeh and Mangope [30]. The sphericity was measured using the method suggested by Baryeh and Mangope [30].

Table 1
Experiment design variables.

Variable	Measurement levels	Units
Q	0.07	m^3/s
	0.08	
	0.10	
P	7×10^5	Pa
	8×10^5	
D_v	0.04	m
	0.02	
d_p	0.00280	m
	0.00378	
	0.00646	

2.2. Equipment and procedure

The system in which the experiments were performed (Fig. 2) consists of a solids feeder built from stainless steel with a cone-shaped base and an output facing a transparent acrylic tube 0.04 m in diameter. The acrylic tube is connected directly to the horizontal tube that makes up the S-valve, which was also built with a transparent acrylic tube with a diameter D_1 (Fig. 3). The S-valve works with compressed air as a pulsing fluid; the pulses were regulated with the use of a solenoid valve.

The complete system also includes a compressed-air supply and a water trap from which two lines lead. The first line is connected to a pressure regulator, followed by a two-way ON/OFF solenoid valve, which in turn is connected to a time relay (with an adjustment accuracy of $\pm5\%$), a flow meter that operates on a 0 to 0.15 m^3/s scale, and a nozzle connected to the S-valve. The second line, with its own pressure regulator and flow meter, provides air to the solids feeder tank to provide the option of operating the system at a pressure greater than atmospheric pressure.

The feeding process requires the elimination of rods and/or large solids (trash) that could get stuck in the system, create an added resistance, and prevent the solids from flowing freely. The air filters and the water trap need to be checked and cleaned frequently. The precise flow of solids is determined by using a chronometer and a scale. All of the experiments were carried out at room temperature and in triplicate.

2.3. Development of the model

Fig. 3 presents a schematic diagram of the S-valve showing the four sections of the valve as used in this research; D_i and L_i represent the inner diameter and length, respectively, of each section i.

Table 2
Characteristic dimensions of the solids used.

Particle	d_p (m)	ϕ_s	ρ_p (kg/m^3)	ε
Rice	0.00280	0.76	1299	0.35
Lentil	0.00378	0.83	1283	0.33
Coffee	0.00646	0.78	1192	0.43