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Computational fluid dynamics analysis of the Venturi Dustiness Tester

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ABSTRACT

Dustiness quantifies the propensity of a finely divided solid to be aerosolized by a prescribed mechanical stimulus. Dustiness is relevant wherever powders are mixed, transferred or handled, and is important in the control of hazardous exposures and the prevention of dust explosions and product loss. Limited quantities of active pharmaceutical powders available for testing led to the development (at University of North Carolina) of a Venturi-driven dustiness tester. The powder is turbulently injected at high speed ($Re \sim 2 \times 10^4$) into a glass chamber; the aerosol is then gently sampled ($Re \sim 2 \times 10^3$) through two filters located at the top of the chamber; the dustiness index is the ratio of sampled to injected mass of powder. Injection is activated by suction at an Extraction Port at the top of the chamber; loss of powder during injection compromises the sampled dustiness. The present work analyzes the flow inside the Venturi Dustiness Tester, using an Unsteady Reynolds-Averaged Navier-Stokes formulation with the k-ω Shear Stress Transport turbulence model. The simulation considers single-phase flow, valid for small particles (Stokes number $Stk < 1$). Results show that ~24% of fluid-tracers escape the tester before the Sampling Phase begins. Dispersion of the powder during the Injection Phase results in a uniform aerosol inside the tester, even for inhomogeneous injections, satisfying a necessary condition for the accurate evaluation of dustiness. Simulations are also performed under the conditions of reduced Extraction-Port flow; results confirm the importance of high Extraction-Port flow rate (standard operation) for uniform distribution of fluid tracers. Simulations are also performed under the conditions of delayed powder injection; results show that a uniform aerosol is still achieved provided 0.5 s elapses between powder injection and sampling.

1. Introduction

1.1. Dustiness

The measurement of dustiness has received renewed interest in the powder and occupational health communities as a test relevant for the assessment of exposure to particulates. Historically, dustiness tests were intended to simulate typical environmental and occupational settings so that an assessment could be made of exposure and a recommendation could be made as to a level of control [1–5]. Unfortunately, no clear relationship has yet been established linking inhalation exposure to dustiness as determined by any of these historical methods [1–2,4,6–11]. This may be due to the gentle nature of the tests employed, as well as to the variability of the external parameters, which influence the test.

Dustiness is relevant wherever powders are mixed, poured [12–13], transferred [14], handled, or conveyed [15] and is important in the control of hazardous exposures. Aerosol resuspension from dusty surfaces [16] is relevant for the prevention of dust explosions [17–19]. Sanding [20], grinding or milling of bulk materials generates and suspends small particles as airborne dusts [5]. Dust is also ubiquitous in mining and agricultural settings [21].

1.1.1. Dustiness testing

Dustiness quantifies the propensity of a finely divided solid to be aerosolized by a prescribed mechanical stimulus. The aerosolization process overcomes the adhesive binding forces within the powder and thus disperses pre-existing particles from the powder into the air [22–23]. A dustiness test is not intended to comminute the powder and generate new particles. This precludes the use of high shear critical orifices [24] and high impact processes [25] for dustiness determination.

Several attempts have been made at standardization [26–28], but these have not been widely accepted.

1.1.2. Historical dustiness test methods: falling powder and rotating drum

Historically [29–32], dustiness testing has utilized configurations (falling powder, rotating drum) that have imparted fairly gentle mechanical agitation to the powder. While these tests were devised to simulate various industrial procedures, their gentle agitation may be

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responsible for difficulties in reproducibility, as external factors must then be stringently controlled. The maximum velocities of the particles achieved are $v \sim 1$ m/s, and the aerodynamics tend to involve large-scale eddies. These techniques typically require the use of relatively large quantities of powder, e.g., 10^2–10^3 g per test [28].

In the falling powder method, a bolus of particles is released from a height [27]. The particles are aerosolized either by the countercurrents generated during the fall, or by the countercurrents generated by the impact of the bolus at the bottom of the fall [6,14,33–41].

In the rotating drum (Heubach) method, a powder is rotated within a drum with internal baffles; again, the particles are aerosolized by the countercurrents generated during the periodic avalanches [42–48].

These methods have been compared using a variety of powders [22, 49–53]. Modeling of the aerosolization and dust generation under these test conditions has also been attempted [54–56]. Dustiness measurement using a gas fluidization technique has also been proposed [57–58].

1.1.3. Venturi Dustiness Tester (VDT)

A qualitatively different method was introduced [59] in order to test pharmaceutical powders. Evans et al. [60] used this method to study a wide variety of nanoscale powders. The aim was to utilize small quantities (~5 mg) of powder under confined conditions (both for reproducibility and so as to limit exposure of the test operator to potentially toxic material) [61]. Similar measurements have recently been made on pollens and molds [62].

A powder is introduced into a dispersion chamber under energetic turbulent airflow conditions; typical nozzle airflow $v \sim 70$ m/s. Aerosolization presumably occurs via aerodynamic lift and pneumatic drag mechanisms acting on the powder; particulate velocities are one to two orders of magnitude larger than in the gentler falling powder and rotating drum methods. Aerosolization proceeds under turbulent conditions, whereas in the gentle tests, the airflows are larger scale and laminar. The reproducibility [59] of the method has been criticized [63] but has been defended [64]. The method involves more aggressive air flows than those typically encountered in large-scale workplace activities (however, the use of compressed air to clean contaminated worker clothing or work surfaces approximates the aerodynamic conditions of the VDT).

Each of these methods is under consideration [65] as a potential ISO standard test method of dustiness (falling powder and rotating drum [Annex C], and the Venturi method [Annex E]).

1.2. Geometry of the Venturi Dustiness Tester (VDT)

Fig. 1 is a schematic of the VDT. It consists of a 5.7 L glass dispersion chamber with a square base and a tapered top. The horizontal end of an inverted tee-shaped injection tube ($d = 0.44$ cm) pierces the midsection of the front wall (Nozzle Inlet); powder is aerosolized within this tee-shaped tube and enters the VDT as an aerosolized jet. The VDT has three outflow ports: an Extraction Port, a Sampler Port (Dust Sampler), and a Cyclone Port (Respirable Mass Cyclone). During the Injection Phase, air is drawn out of the VDT through the Extraction Port; this is closed during the Sampling Phase. In both the Injection and Sampling Phases, the Dust Sampler collects powder particles of all sizes on its filter cassette, and the Cyclone collects respirable dust (particles < 4.25 μm in diameter) on its filter.

1.3. Experimental operation of the VDT

Prior to the start of the experiment, the powder, mass M_{t}, is loaded in the Inlet Nozzle. Operation of the VDT consists of two phases, Injection and Sampling. During the Injection Phase, at $t = 0$, flow is set up in the Extraction Port, Cyclone, and Sampler, at the rates of $Q_{ep} = 53.8$ L/min, $Q_{cp} = 4.2$ L/min, $Q_{sp} = 2.0$ L/min, respectively. These flow rates are continued until $t = 1.50$ s. The balanced replacement flow enters through the Nozzle at $Q_{in} = 60.0$ L/min, giving rise to an inlet velocity $v = 65.80$ m/s, corresponding to a Reynolds number $Re_d = 19.900$ (based on the hydraulic diameter of the nozzle). During the Sampling Phase ($t > 1.50$ s), the Extraction Port is closed (while the inlet and the Cyclone and Sampler ports remain open), reducing the total replacement flow to $Q_{in} = 6.2$ L/min. This is continued for 240 s, during which the inlet flow rate corresponds to an inlet velocity $v = 6.79$ m/s and $Re_d = 2050$.

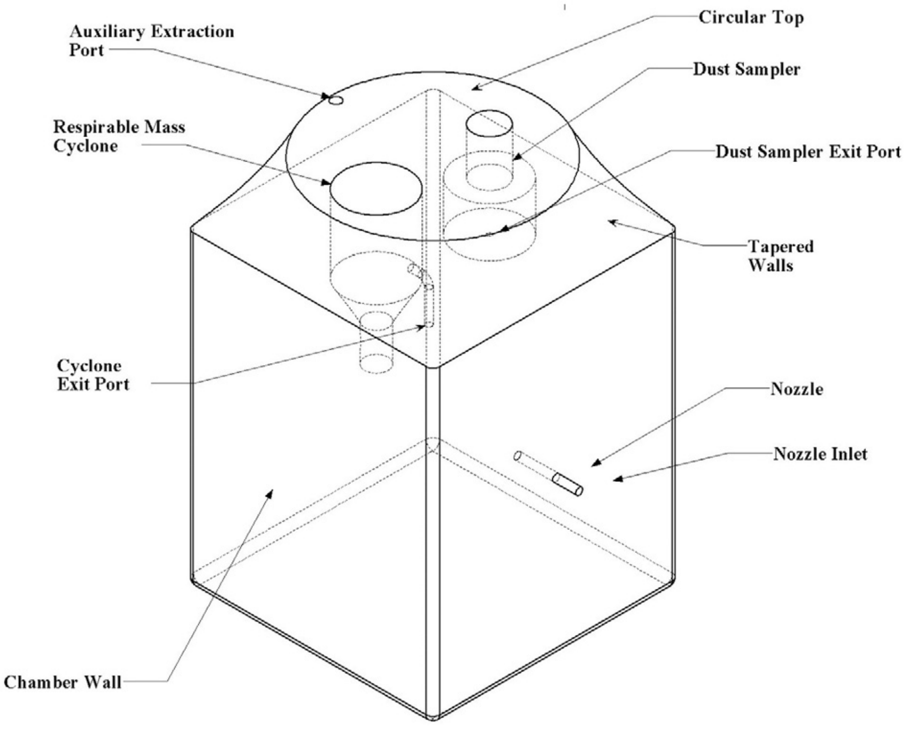

Fig. 1. Schematic of the Venturi Dustiness Tester.