Experimental Thermal and Fluid Science 93 (2018) 1–10

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Effect of particle size and polydispersity on dust entrainment behind a moving shock wave

Amira Chowdhury[a], H. Greg Johnston[b], Chad V. Mashuga[a], M. Sam Mannan[a], Eric L. Petersen[b,*]

[a] Mary Kay O'Connor Process Safety Center and Department of Chemical Engineering, Texas A&M University, College Station, TX 77843-3122, USA
[b] Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843-3123, USA

ABSTRACT

To improve the fundamental understanding of dust dispersion with application to explosion safety, a series of experiments was conducted to elucidate the effect of particle size and size polydispersity on dust-layer dispersion behind moving shock waves. Aluminum samples of various average sizes ($D_{3,2}$ = 1.7–30.3 μm) with varying polydispersity (σ_D = 0.93, 1.52, 2.62) were the focus of this study. A 3.2-mm layer of Al dust was subjected to shock Mach numbers ranging from 1.23 to 1.52 in a shock tube. The effect of particle density on the dust-lifting process was also studied by comparing aluminum and limestone powders with similar average sizes. The results of the study confirm that particle size and size polydispersity have significant impacts on dust lifting as smaller particles lift higher and faster for a given shock speed. To the best of our knowledge, this work is the first to measure the effect of size polydispersity in a dust layer in a shock tube. New correlations were developed between the shock strength and the dust entrainment height as a function of time. Correlations were also developed to show the relation between dust entrainment height and particle size polydispersity. In summary, the results herein are in agreement with trends found in our previous work, where there is a linear relationship between dust-layer height growth rate and shock Mach number, and with the increase of particle size the dust entrainment height decreases. New data were collected for image analyses, where the longer observation time and higher camera framing rates led to the observation of a clear transition time between the early, linear growth regime of the dust-layer height and a much-slower average growth regime to follow. The dust particle size and polydispersity affected both the growth rate of the dust layer (*i.e.*, the change of dust-layer height with time) and the transition times between the two growth regimes.

1. Introduction

Research in the area of dust explosions has indicated that dust lifting caused by primary explosions acts as a catalyst for secondary explosions. It would be advantageous to gain insight into the dust-lifting process as well as quantitative parameters to define the process. When the shock wave passes over the stagnant layer of dust, it induces a velocity into the air medium behind it [1]. The air, with its induced velocity, starts lifting dust particles, leading eventually to a bigger dust cloud [1]. For simulating a secondary explosion scenario, it is necessary to identify the governing forces and also other fluid mechanic factors which will help in understanding the mechanism behind the formation of dust clouds that could eventually result in secondary dust explosion. It is also necessary to identify useful parameters for developing correlations that can be used in industrial-scale simulations of dust explosion. To this end, the authors have been utilizing a shock-tube apparatus to study the normal shock-dust layer interaction during the early times immediately after the passage of the shock wave [2,3].

All of the experiments in the present study used aluminum dust samples to investigate the effect of shock strength and particle size on the aluminum dust entrainment process behind a shock front. According to the National Fire Protection Association (NFPA) fire prevention standards [4], aluminum is graded as one of the most explosive metal dusts. The Chemical Safety Board stated that approximately one fourth of all dust explosions in the United States between 1980 and 2005 involved metal dusts [5–7]. Aluminum accounted for the majority of these metal dust explosions. Metal dusts are responsible for nearly 19% of dust explosions every year globally. As such, aluminum dust explosions have been the subject of active research [8–10]. Aluminum powder has a high explosivity measured using the deflagration

* Corresponding author.
E-mail address: epetersen@tamu.edu (E.L. Petersen).

https://doi.org/10.1016/j.expthermflusci.2017.12.002
Received 21 June 2017; Received in revised form 2 October 2017; Accepted 4 December 2017
Available online 13 December 2017

constant, K_{ST}[1] and ranked as a Class ST-3[2] dust [11,12]. As these data identified aluminum dust as imposing a dust explosion hazard in the current industry, aluminum was selected for the present study. An additional factor for choosing aluminum is that it is readily available in a variety of average, near-spherical particle sizes.

Results from an experimental program on dust lifting were first reported by Gerrard [13]. Gerrard investigated the process of lifting of small particles after shock wave passage (particle size 60 µm, Mach numbers of 1.1–1.28, observation time 100 µS). His experimental findings concluded that dust entrainment is a result of the action of a shock wave passing through the dust layer [13]. Borisov et al. [14] performed similar experiments and concluded that a compression wave created from a reflection of the shock wave from the shock-tube walls that extends through the dust layer is the main reason behind dust cloud formation. Fletcher [1] later argued both Gerrard's [13] and Borisov's [14] theory. His theory was based on experimental data and numerical analysis. According to Fletcher, the dust is lifted by the rapid flow behind the propagating shock wave [1]. Although Fletcher provided a hypothesis on the lifting mechanism, the governing forces for particle entrainment were still not identified.

Many later experiments focused on identifying the forces responsible for dust lifting. Merzkirch and Bracht [15] demonstrated experimental and theoretical investigations and decided Saffman and drag forces contribute significantly to the dust-lifting phenomenon. Magnus force was found to have significant effects as well [16]. Also, turbulent mixing of the particles within the air medium behind the shock wave was analyzed using mathematical models [17–21]. Tateuki and Takashi [19] focused on the effect of particle sizes on the lifting phenomenon. According to Tateuki and Takashi [19], smaller particles tend to lift faster than larger particles [19]. Gelfand et al. [22] used a vertical shock tube for understanding the dust-lifting phenomenon; their experiment pointed out the effects of bulk density of layered particles on the lifting mechanism. Manjunath and Kurian [23] conducted experiments on dust lifting in an air flow behind the shock front in the formulation for higher Mach numbers of 1.92–2.48 and focused on the delay time in dust lifting behind the shock wave. Klemens et al. [24] experimentally investigated the interaction of coal dust and silica dust with a shock wave and monitored important parameters such as delay time and the dust concentration gradient behind the moving shock. Most of the experiments related to this study had limited observation time.

Another very important factor of interest in the current study is the high frame rate of the visual diagnostic, as that allowed the collection of much data within a very short period of time. In most cases, this type of information was not made available from the literature. However, based on the available data, it is fair to assume that mostly low-frame-speed cameras were used in the previous experiments.

Considerable attention has also been given to the numerical analysis of the dust-lifting process, although no mathematical model has been developed which can define every stage of dust entrainment. Modeling studies on this subject include the works of Skjold et al. [25], Fedorov et al. [26], Kuhl et al. [27], and several others [28–30].

Although there have been experiments to understand the aerodynamics of particle lifting in uniform aerodynamic conditions, comparatively there are very limited experimental studies of dust lifting behind a shock front, which is necessary in secondary dust explosion investigations. From the literature survey, it is evident that not many experimental works have been carried out in recent years using modern techniques such as high-speed cameras which give more data than earlier studies. As most of the studies in this field generated fewer data over very short experimental time periods, no conclusions on the boundary-layer phenomenon have been derived. As a result, no numerical model is able to portray all stages of the dust-lifting phenomenon, including shock-wave propagation, possible turbulent mixing, and precise features of force interaction of the phases. In addition, there have been no studies using a shock tube that have investigated in a targeted manner the effect of particle size and the effect of particle size polydispersity.

Presented in the following sections are the results of the present study that focused on the varying metal dust size and polydispersity on the rate of dust lifting over a range of shock Mach numbers. Details of the experimental setup and procedure are described first, including characterization of the dust samples. The results of the experiments are discussed at length over the range of parameters investigated, followed by a presentation of the results as they pertain to process safety aspects of secondary dust explosions.

2. Experiments

This section provides a short description of the shock-tube facility followed by summaries of the operating conditions and dust-sample characterization. Further details are provided in the thesis of Chowdhury [31].

2.1. Shock-tube facility

The authors modified an existing shock-tube facility so that it can be used for the study of shock waves over dust layers [2]. Fig. 1 presents a schematic of the test facility. The shock tube has a 1.86-m-long driver section which is circular in cross section (7.6-cm diameter). The driven section is approximately 10.8 cm square and 4.1 m long. To this existing shock tube, a modified test section was introduced. As the main purpose of this test section is flow visualization, it has windows on the top, left, and right sides. Further details on the design and construction of the test section can be found in Chowdhury et al. [2,3].

Parabolic and flat mirrors were arranged relative to the side windows to establish a shadowgraph imaging technique. Along with the mirrors, a Photron Fastcam SA1.1 high-speed camera (with 15,000 frames per second) and an Oriel 70-W Hg-Ze lamp light source were used. An easily removable dustpan is inserted at the bottom surface of the windowed test section, with a dust deposit area of 6.9 × 27.3 cm. The dustpan can be adjusted to provide various dust-layer thicknesses in 3.2-mm increments, between 3.2 mm and 12.7 mm.

2.2. Operating conditions

The experimental variables of interest for the present study included particle size, particle size polydispersity, and strength of the shock wave as described by the incident-shock Mach number, M_s. The initial driven section pressure was maintained at 67 kPa. This slightly sub-atmospheric initial condition was mainly for the safety of the facility, to maintain reflected-shock pressures at a safe level [2,3]. Nitrogen was used for both the driver and driven gases. The reason for using nitrogen as the driven gas was to ensure an inert atmosphere inside the shock tube while running experiments with combustible dust particles while otherwise representing an air-like environment gas dynamically. For this study, the shock Mach numbers ranged from 1.23 to 1.53. Dust-layer thickness was kept constant at 3.2 mm (or 1/8 in.) for convenience and to conform with this particular depth used by the authors in earlier studies. Note that the dust-layer depth is controlled by fixed-thickness plates that can be stacked or removed as needed for an adjustable depth [2]. Table 1 summarizes the different experimental conditions for all the experimental studies, including the thickness of the polycarbonate diaphragms employed to achieve the conditions indicated. However, for this specific study special care was given in monitoring P_5. As the pressure (and hence temperature) behind the

[1] KST = (dP/dt)max × $V^{1/3}$; (dP/dt)max is the maximum pressure rise rate from the explosion, and V is the volume of the confinement.

[2] ST-1, ST-2, and ST-3 are hazard classifications of dusts ranked by NFPA and used to determine the relative explosiveness. ST-3 dusts are the most explosive.