Journal of Loss Prevention in the Process Industries 27 (2014) 89–98

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Numerical study of dust lifting using the Eulerian–Eulerian approach

Hanna Utkilen, Boris V. Balakin, Pawel Kosinski*

The University of Bergen, Department of Physics and Technology, Allegaten 55, 5007 Bergen, Norway

ARTICLE INFO

Article history:
Received 19 July 2013
Accepted 25 November 2013

Keywords:
Modelling
Particles
Two-phase flow
Dust-lifting
Dust explosions
Safety

ABSTRACT

The present paper shows a numerical investigation of dust lifting behind a moving pressure wave. The dispersion of combustible dust has previously been discovered to be a precursor to a potential dust explosion. Consequently, a growing interest on the subject has been observed in recent years. Numerous studies have been performed on dust lifting, however, very few investigations have focused on dust layers with high volume fractions. Therefore, the aim of this investigation was to provide additional data. The simulations were carried out in a three-dimensional duct with a dust layer dispersed along the lower wall. The Eulerian–Eulerian approach was selected as the modelling technique. At first, four simulations varying the initial pressure and volume fraction of the dust were performed. The former parameter was varied between 4 and 8 bar, while the latter varied between 0.4 and 0.6. The combination of high initial pressure and high volume fraction resulted in the greatest dispersion of dust. Subsequently, two different drag force models were compared: the Schiller–Naumann, and the Gidaspow. It was discovered through this research that the choice of model caused significantly different results. The former model was found to underestimate the drag in the diluted parts of the layer. Consequently, this led to a distinctly lower lifting of the dust than in the latter model. Finally, a validation of a particle–particle interaction model was performed. It was observed that in the case where the model was disabled, an unrealistically high maximum volume fraction of the dust layer occurred. Nevertheless, the model did not seem to improve the dispersion results, which indicates that the dust lifting in this research was solely due to fluid–particle interactions.

1. Introduction

When a combustible solid material is split into small particles, the combustion rate increases due to an increase of the total contact surface area between the material and the air. If the particles are suspended in an adequately large volume of air, providing each particle with enough space to burn unlimited, a very fast combustion rate is obtained. The creation of a particle cloud occurs from either a shock wave or a high pressure wave. The wave moving over the dust layer causes entrainment and lifting of the particles. In many factory facilities and process units, dust layers are found along the floors and other surfaces. A small, primary explosion may induce a pressure wave and thus lead to a dust cloud. In worst case scenario, if an ignition source is present, it may result in a dust explosion.

Early studies of dust lifting took place about 50 years ago when experimental investigations were carried out (Gerrard, 1963). Over the past years, there has been an increased interest to investigate the lifting of dust, both experimentally and numerically, which has improvements in measuring techniques and computational capabilities.

To fully understand the nature of dust lifting both experimental and numerical investigations are necessary. By studying it experimentally it becomes possible to physically observe and measure the behaviour of the lifting. However, the fast nature of this process makes it is difficult to obtain accurate measurements experimentally. Numerical modelling makes it possible to conduct experiments resulting in highly accurate data and to closely study what influence different parameters have on the process.

Until recently, investigations of dust lifting have mainly focused on dust layers of low volume fractions while in reality the volume fraction in dust layers is in many cases relatively high. When the volume fraction of the particles increases, collisions between them occur more frequently. Hence, the behaviour in the lifting process may be different from what is the case of a lower volume fraction. The lack of studies concerning this problem was a motivating factor for this research. The knowledge of how combustible particle clouds occur is very important in order to prevent hazardous situations that can lead to dust explosions.

A proper knowledge of multiphase flows is necessary when studying the process of dust lifting. In contrast to a single phase

---

* Corresponding author.
E-mail address: pawel.kosinski@ift.uib.no (P. Kosinski).

0950-4230/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jlp.2013.11.009

flow, which only consists of one fluid phase, a multiphase flow can have several phases within a domain. Sand in water, dust in air and air bubbles in water are all examples of this type of flow.

In the last decades, several studies have been devoted to the problem of dust lifting. In the following, a collection of relevant literature is presented.

2. Literature overview

About 50 years ago, Gerrard photographically studied the first few hundred microseconds after the passage of a shock wave in air over dust deposited on a horizontal surface in a shock tube (Gerrard, 1963). The Mach number, the type of dust and the depth of the deposit were investigated. A small delay between the passage of the shock wave and the raising of the dust at a point was discovered and this delay was found to be dependent on the depth of the deposit. The shape of the dust cloud depended upon the mode and type of deposit, but was independent of the depth of the deposit and the strength of the shock wave.

Some years later, Fletcher (1976) stated that the mechanism proposed by Gerrard could not be applicable. In Fletcher's studies no delays were observed between the passage of the shock past a point and the raising of the dust. Instead, the experiments showed that dust was raised due to the rapid flow that follows immediately behind the shock wave, instead of being the result of a pressure wave passing through the dust layer.

Lebecki et al. performed a large scale grain dust explosion research (Lebecki, Cybulski, Sliz, Dyduch, & Wolanski, 1995). The experiments were carried out in a surface gallery, with a length of 100 m and a cross-section of 2.9 m^2, and in an underground entry, with a length of 400 m and a cross-section of 7.5 m^2. The investigation aimed at showing how critical dust parameters influenced the course of the explosion, the development of the explosion and also the suppression.

The process of dust lifting from a layer behind a propagating shock wave was investigated by Fletcher (1976). Experiments were performed using two different types of dust: black coal dust and silicon dust. The initial conditions varied between three shock wave velocities and three dust layer thicknessess. It was discovered that the delay in the dust lifting decreased when the thickness of the dust layer and the shock wave propagation velocity increased. The vertical velocity of the lifted dust usually increased when moving away from the particle layer, but after a certain distance the velocity decreased. The dust lifting process was observed at some distance behind the shock wave. This indicates that the cause of the lifting was due to the flow behind the shock wave.

Over the past years, also numerical studies have become an important tool for fluid dynamic research. Some of the advantages of these compared to experimental studies are that they are less costly and easy to reproduce.

Kosinski, Hoffmann, and Klemens (2005) did numerical simulations of dust lifting behind shock waves using two different approaches, namely the Eulerian–Eulerian (E–E) and the Eulerian–Lagrangian (E–L) approach. The results from the E–E approach showed that the lifting process was caused by the interaction with the shock wave in the beginning of the dust layer. The particles further down in the layer did not seem to be affected by the pressure wave passing over them. By comparing the results of both of these approaches it was concluded that the E-L approach is the most accurate method to simulate this problem.

Fedorov and Fedorchenko (2005) used the E–E approach to derive an equilibrium model of mechanics of heterogeneous media. The model was developed to describe dust lifting from a layer during the action of a rectangular or triangular shock wave. The model was compared with experimental dependence of pressure on the surface versus the time in one- and two-dimensional geometry. Computations were executed with and without turbulence modelling in the mixture. The results demonstrated that in the turbulent mixture, at the leading edge of the layer, a high-velocity trickle was formed near the wall. Turbulence increased also made the number of shock waves reflected from the substrate. Besides, this lead to a more significant lifting of the dust.

Klemens et al. have performed several studies to investigate the dust lifting problem. Zydak and Klemens (2007) investigated how the implementation of three improvements of the Eulerian–Eulerian approach would affect the results of 2D simulations of dust lifting behind a propagating shock wave. These simulations were executed to upgrade an earlier model that showed weaknesses when compared to experimental research (Klemens, Zydak, Kaluzny, Litwin, & Wolanski, 2006). Three modifications were made to improve this model. Firstly, the Saffman force was implemented secondly, the Magnus force and thirdly, particle–particle interactions. The results showed that neither the implementation of the Saffman or the Magnus force gave any significant improvement. However, the particle collisions did improve the model. The results from the last improvement showed good correlation to the experimental investigations.

In another study, Klemens et al. (2001) investigated the lifting of dust in a channel with vertical obstacles. Several numeric computations of multiphase flows were done in a channel with complex geometry. The investigation concluded that the presence of vertical obstacles may lead to critical change in the process and should not be neglected.

Previous research of the dust lifting problem has normally been conducted in two dimensions. Ilea, Kosinski, and Hoffmann (2008a) compared results of dust lifting between two-dimensional and three-dimensional simulations. The E–L method was used for these simulations. The number of particles varied throughout the simulations. In both cases, the results showed that an increasing number of particles gives a less intensive lifting effect. The comparison of the 2D and the 3D models showed that the 2D simulations overestimated the lifting process and the 3D model is therefore preferable.

Ilea, Kosinski, and Hoffmann (2009) investigated the lifting process of polydisperse particles behind a shock wave. The E–L approach was used to model this problem and the simulations were three dimensional. Simulations of monodispersed particles were compared to simulations of the polydispersed particles. The investigation concluded that the simulations of the layer containing polydispersed particles gave results that were quite different from the layer containing monodispersed particles. The particles with smaller sizes than the mean value of the distribution were found to contribute the most to the lifting effect. The overall lifting appeared more intense in the case of polydispersed particles. The influence of gravity was also investigated in this article. In the beginning of the simulations, when the drag force acting on the particles is weak, the influence of the gravity was visible. However, for the remainder of the simulations, gravity had a negligible effect as the drag force was much greater.

The effect of rough walls was presented by Ilea, Kosinski, and Hoffmann (2008b). The E–L approach was used for the simulations that were run in a two-dimensional domain. Simulations were done for smooth and rough walls with varying thickness of the initial dust layer and numbers of particles. The results were compared concluding that the rough wall model gave significantly different results compared to the smooth wall model. As the average lift height values corresponding to this model were bigger the general lifting effect appeared more intense. Finally, similar modelling strategy was used by Kosinski (2008) for studying explosion suppression by inert particles.