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Shock-induced dust ignition in curved pipeline with steady flow

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Abstract

The ultimate objective of the research outlined in this paper is to determine the conditions governing shock-induced ignition of dusty flows in curved pipelines using analytical and computational approaches. The results of numerical simulation indicate that ignition of two-phase flows in curved channels is mainly conditioned by the shock-induced flow and is not very sensitive to the flow structure in front of the shock wave. The calculations of nonreactive shock propagation in the quasi-steady two-phase flow and in the uniform quiescent dust suspension revealed significant differences in the postshock flow structure downstream the channel corner. Nevertheless, ignition occurred in the region where the predominant role was played by reflected shock waves, i.e., in the vicinity to the channel corner. The results call for further studies dealing with shock-induced ignition and explosion build-up in curved channels.

Keywords: Dust ignition; Curved pipeline; Steady flow; Multiphase; Numerical simulation

1. Introduction

An explosion hazard of pneumatic dust conveyors is the issue of considerable concern for process industries (Bartknecht, 1987; Eckhoff, 1997). In case of accidental ignition of dust suspensions in feeders, cyclones, separators, filters, or other equipment attached to the dust conveyors, severe local explosions can occur and a danger of explosion transmission to other processing units through the conveyor manifolds exists. Physical mechanisms of explosion transmission and accident escalation include a possibility of flame propagation in the dust suspension and shock-induced ignition of a dusty flow leading to deflagration-to-detonation transition (DDT). The latter scenario is known to be most devastating.

Explosion hazards caused by flame propagation in the pneumatic dust conveyors were studied both experimentally and theoretically elsewhere (Bartknecht, 1987; Bielert & Sichel, 1997; Eckhoff, 1997; Vogl, 1996). The flame propagation velocity was shown to depend on many parameters including dust type and concentration in the flow, flow velocity, tube diameter and length, ignition location and ignition source, etc. Moreover, experiments of full-scale dust-conveying systems under realistic operating conditions were performed.

Shock-induced ignition and detonation of reactive dust suspensions were studied for simple initial configurations. Among them: (i) quiescent dust suspensions in channels of constant or variable cross-section (e.g., Korobeinikov, 1993; Kutushev & Shorohova, 2002), (ii) confined dust clouds with well-defined boundaries (e.g., Fedorov & Khmel, 2002), (iii) infinite-length, thin, dense dust layers (e.g., Kauffman, Sichel, & Wolanski, 1992; Korobeinikov et al., 2002), and (iv) finite-length, thin, dense dust layers with a definite shape of the upwind edge (e.g. Fedorov & Fedorchenko, 2005). In all cases, the two-phase flow was described by the set of governing conservation equations based on the formalism of interpenetrating continua (Nigmatulin, 1987), the applicability of which to dense dust layers still remains questionable. On the one hand, such studies revealed salient features of shock-induced ignition processes and provided useful information on characteristic time and length scales inherent in the ignition phenomenon. On the other hand, the dust cloud or dense layer formation process, which has a strong influence on

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the dynamics of dust explosion, is out of consideration in such studies. The ultimate objective of the research outlined in this paper is to determine the conditions governing shock-induced ignition of dusty flows in curved pipelines using analytical and computational approaches. It is implied that this study will provide information on possible similarity conditions for modeling large-scale explosions in pipelines using laboratory-scale installations.

2. Problem formulation

2.1. Flow configuration

As the starting point of the research, the flow configuration shown in Fig. 1 was considered. A gas uniformly laden with monodispersed spherical dust particles of diameter d entered at an inlet velocity U_{in} a curved planar channel of width H and total length L with the 90° corner. The lengths of the vertical and horizontal portions of the channel along its central section were L_1 and L_2, respectively, so that $L = L_1 + L_2$. The loading of the flow with the dust at the inlet of the channel was η. It was expected that the steady-state (or quasi-steady-state) flow pattern in the channel could exhibit pronounced stagnation and recirculation zones with dust particles accumulation, as shown schematically in Fig. 1. A shock wave, formed presumably due to accidental explosion outside the channel, could enter the channel either from the inlet or from the outlet. Depending on the incident shock wave strength and compression phase duration, ignition of dust particles could occur either in the free stream or due to complex interaction of the shock-induced flow with confining walls and dust deposits. The issue addressed in this study was to find out whether the steady-state flow pattern in the channel was important for shock-induced ignition of particle suspension or not. In the latter case, the analysis of the explosion hazards could be greatly simplified due to avoiding the necessity of simulating the steady-state flow pattern in the channel.

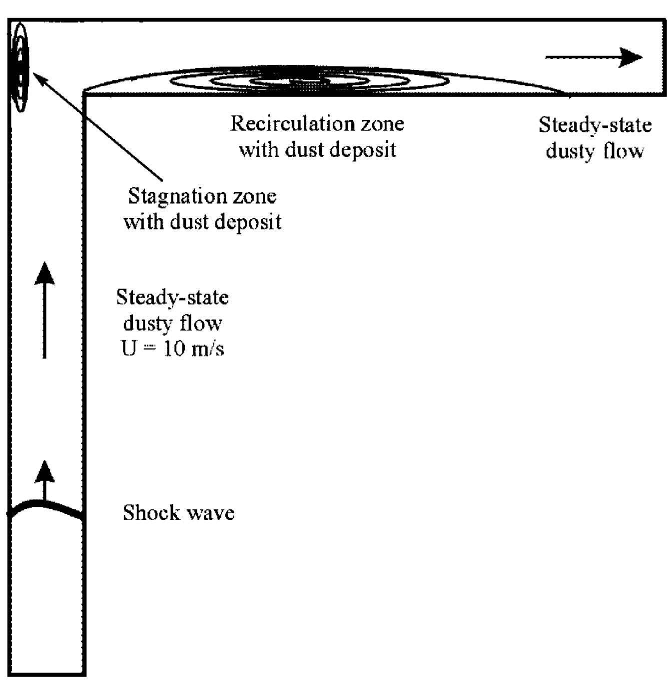

Fig. 1. Flow configuration.

2.2. Mathematical model

The mathematical statement of the problem was based on two-dimensional equations of two-phase, viscous, reactive, compressible flow within a coupled two-velocity and two-temperature formulation (Nigmatulin, 1987). The set of governing equations is given below

$$\rho_1 = \sum_{k=1}^{NGSP} \rho_{1,k}, \quad \rho_2 = \sum_{k=1}^{NSSP} \rho_{2,k},$$

$$\partial_t \rho_{1,k} + \partial_m \rho_{1,k} u_{1,m} = -\partial_m J_{k,m} + \tilde{\omega}_{1,k}, \quad k = 1, \ldots, NGSP,$$
$$\partial_t \rho_{2,k} + \partial_m \rho_{2,k} u_{2,m} = \tilde{\omega}_{2,k}, \quad k = 1, \ldots, NSSP,$$

$$\partial_t(\rho_1 \mathbf{u}_1) + \partial_m(\rho_1 \mathbf{u}_1 u_{1,m}) + \nabla p = -\mathbf{F} - \tilde{\omega}_2 \mathbf{u}_2 + \partial_m \mathbf{T}_m,$$
$$\partial_t(\rho_2 \mathbf{u}_2) + \partial_m(\rho_2 \mathbf{u}_2 u_{2,m}) = \mathbf{F} + \tilde{\omega}_2 \mathbf{u}_2,$$

$$\partial_t E_1 + \partial_m (E_1 + p) u_{1,m} = -\mathbf{F}\mathbf{u}_2 - Q_T - Q_R - 0.5\tilde{\omega}_2 \mathbf{u}_2^2 - \sum_{l=1}^{NSSP} \tilde{\omega}_{2,l} e_{2,l} - \dot{\omega}_{1,1} Q_v - \dot{\omega}_{2,2} Q_s - \partial_m \left(\sum_{k=1}^{NGSP} h_{1,k} J_{k,m} + \mathbf{q} - \mathbf{T}\mathbf{u}_1 \right),$$

$$\partial_t E_2 + \partial_m E_2 u_{2,m} = \mathbf{F}\mathbf{u}_2 + Q_T + Q_R + 0.5\tilde{\omega}_2 \mathbf{u}_2^2 + \sum_{l=1}^{NSSP} \tilde{\omega}_{2,l} e_{2,l},$$

$$E_1 = 0.5\rho_1 \mathbf{u}_1^2 + \sum_{k=1}^{NGSP} \rho_{1,k} e_{1,k},$$

$$E_2 = 0.5\rho_2 \mathbf{u}_2^2 + \sum_{k=1}^{NSSP} \rho_{2,k} e_{2,k},$$

$$e_{1,k} = c_{1,k} T_1, \quad k = 1, \ldots, NGSP,$$
$$e_{2,k} = c_{2,k} T_2, \quad k = 1, \ldots, NSSP,$$

$$p = \sum_{k=1}^{NGSP} \rho_{1,k} R_{1,k} T_1,$$

$$h_{1,k} = e_{1,k} + R_{1,k} T_1, \quad k = 1, \ldots, NGSP,$$

where t is time, $m = (x, y)$, x and y are the coordinates, ρ is the density, p is the pressure, T is the temperature, c is the specific heat, R is the gas constant, $\mathbf{u}$ is the velocity vector, $\mathbf{J}$ is the diffusion mass flux in the gas, $\tilde{\omega}$ is the rate of mass variation, $\mathbf{F}$ is the interphase force vector, $\mathbf{T}$ is the stress tensor in the gas, $\mathbf{q}$ is the heat flux vector in the gas, Q_T and Q_R are the interphase heat fluxes due to convection and radiation, Q_s and Q_v are the chemical