Flame Propagation through Potato Starch/Air Mixture in Pipe of Interconnected Vessels

Wang Jian[1], Li Xinguang[1], Zhong Shengjun[2], S. Radandt[3], Wang Fuli[1], Ren Chunli[1]

1. School of Information Science and Engineering, Northeastern University, China

2. School of Materials and Metallurgy, Northeastern University, China

No.11, Lane 3, Wenhua Road, Heping District, Shenyang, 110004 China

3. Research Centre for applied System Safety (FSA), Germany

Tel. & Fax: +86-24-23891977, wangjian.1976@yahoo.com.cn

Abstract: Flame propagation through pipes of potato starch dust explosions in interconnected vessel was investigated by experimental and numerical approaches. The purpose of this research is to investigate the mechanism governing the acceleration of flame propagation through long pipe and thereby to provide valuable information for safety protection and design. The experimental equipment consists of two vessels linked by a long pipe. Explosions were initiated in one vessel and propagated to the other via the pipe. The Eulerian-Lagrangian approach was used for modeling propagation of dust explosions. The k-ε model was used to simulate the turbulence of the gas phase. In the particle combustion model, vaporization of water, decomposition of volatile, gas phase reaction and particle's surface reaction were taken into account. The EBU-Arrhenius model was used for gas turbulent combustion. The operator split method and FCT algorithm were applied for numerical simulation. The acceleration of flame propagation was relatively well represented in the simulation. The developed model is valuable for investigating flame propagation mechanisms of dust explosions.

Keywords: Dust explosions, Flame propagation, Long pipe, Numerical simulation, Potato starch

Introduction

The dust explosion hazard continues to represent a constant threat to process industries that manufacture, use and/or handle powders and dusts of combustible materials[1]. In the process industry there are many applications where process vessels with explosion potential are connected via pipes to other systems and the behaviors of accidental explosions in such systems is practically unpredictable. The question of dust explosions in large-scale linked equipments has been much less investigated; a probable reason is the difficulty and high costs of such experiments. Important contributions are those from some researchers[2-4]. Now that experimental investigation into explosions in connected vessels is not an easy task, another solution is the use of mathematical modeling and simulates the problem using a CFD code[5, 6]. They are gaining increased interest and it is likely that in the near future they will become the main source of information[7].

In present research, we investigated flame propagation through pipes of dust explosions in interconnected vessel by experimental and numerical approaches. The aim is to investigate the mechanism governing the acceleration of flame propagation through long pipe and thus to provide valuable information for safety protection and design. Moreover, another purpose is to improve and perfect the present numerical model by experimental validation.

1. Experimental investigation

1.1 Experimental setup

The experimental setup is shown schematically in Fig.1. A pneumatic conveying system was used consisting of a primary vessel with 9.63m^3 volume, a connecting pipe 29.3m in length and 0.3m in inner diameter, a secondary vessel with 4.4m^3 volume, a cyclone and a suction fan for establishing the air flow. Ten Flame detectors and two pressure transducers were located along the pipe. These were connected to data acquisition system to obtain transient results. The characteristics of potato starch are listed in Tab.1.

Tab.1 Main parameters of potato starch used in experiment

Fuel	Explosion characteristics		Residue Moisture
	K_{st}(bar·m·s^{-1})	P_{max}(bar)	
Dried potato starch	130	9	<4 wt%

In the experiments steady dust-air flow of 16m/s velocity was established and then suitable amount of potato starch were injected into the primary vessel to produced dust cloud with concentration of 1350g/m^3, after 1.15s suitable amount of potato starch were injected into the secondary vessel to produced dust cloud with concentration of 750g /m^3. The dust-air mixture in the primary vessel was then ignited in the center of the vessel after 0.15s using pyrotechnic igniters with ignition energy of 10kJ.

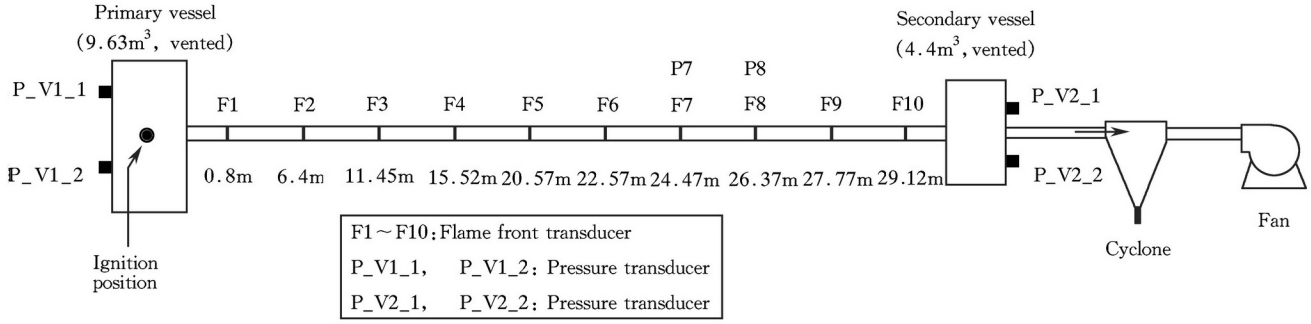

Fig.1 Schematic of the experimental setup

1.2 Experimental results

Experimental pressure development in the interconnected vessel system are shown in Fig.2, which clearly indicated that the primary explosions transmitted into the secondary vessel successfully via flame propagation through connecting pipe and induced a violent secondary explosions. Experimental maximum reduced overpressure Pred, max were 0.66bar and 0.83bar in primary vessel and secondary vessel, respectively. And explosion index K_{st} was 20.83(bar·m·s^{-1}) and 65.02(bar·m·s^{-1}) for primary vessel and secondary vessel, respectively. Experimental P_{max} is 0.82bar and 0.91bar at 22.57m and 24.47m position, respectively, it indicated that the explosions have developed into a much violent extent at the end of flame propagation.

Fig.3 shows the results of flame propagation through connecting pipe for potato starch/air mixture. The flame trajectories are deduced from flame front sensor records.

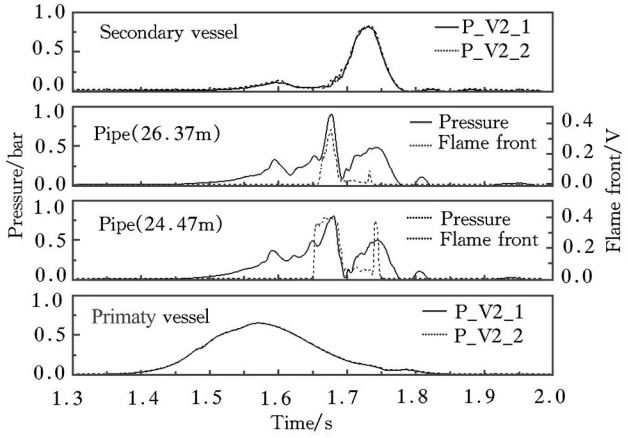

Fig.2 Experimental pressure development in the interconnected vessel system

From Fig.3 the auto acceleration of flames in connecting pipe can be clearly recognized. Towards the end of the combustion the flame front velocity is up to about 338m/s.

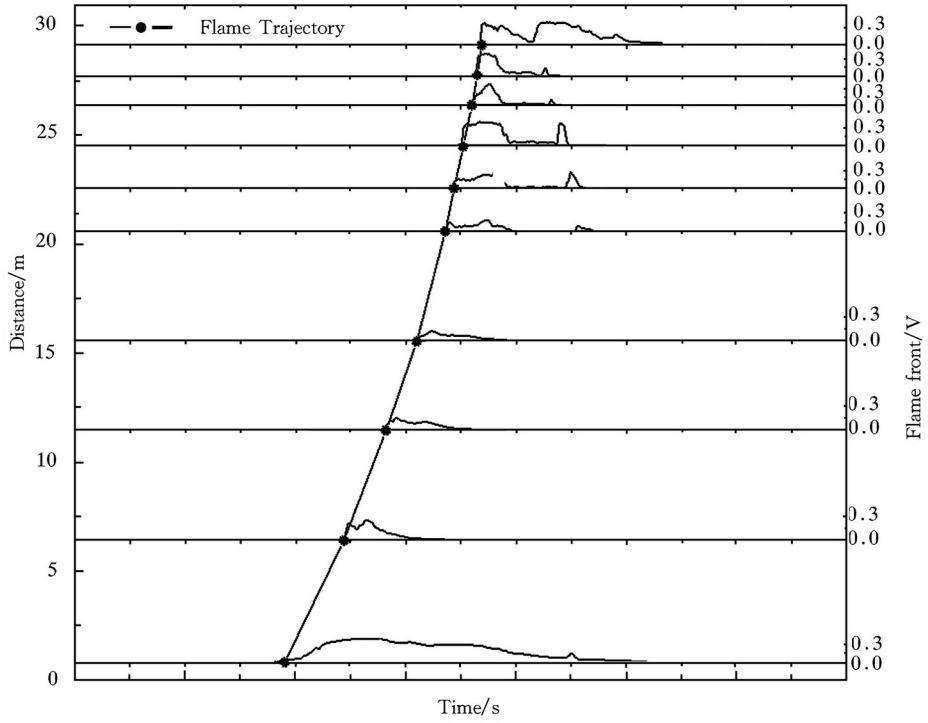

Fig.3 Experimental flame trajectory

2. Mathematical model

Currently there are two approaches for the numerical calculation of multiphase flows: the Eulerian-Eulerian approach and the Eulerian-Lagrangian approach. The Eulerian-Lagrangian approach is used in this paper.

2.1 Gas phase equations

$$\frac{\partial(\alpha\rho Y_s)}{\partial t}+\nabla\cdot(\alpha\rho Y_s\vec{u})=-\nabla\cdot I_s+\alpha_s S_p-w_s \quad (1)$$

$$\frac{\partial(\alpha\rho\vec{u})}{\partial t}+\nabla\cdot(\alpha\rho\vec{u})=-\nabla(\alpha p)+\nabla\cdot\vec{\vec{\tau}}+M_p \quad (2)$$

$$\frac{\partial(\alpha\rho E)}{\partial t}+\nabla(\alpha\rho\vec{u}E)=-\nabla\cdot(\alpha p\vec{u}-\nabla\cdot(I_q+I_\sigma)+\nabla\cdot(\vec{\vec{\tau}}\cdot\vec{u})+E_p \quad (3)$$

where

$$I_s=-\alpha\rho D_s\nabla Y_s=-\alpha\rho\left(D_l+\frac{\nu_t}{\sigma_s}\right)\nabla Y \quad (4)$$

$$\vec{\vec{\tau}}=\alpha\rho(\nu_l+\nu_t)\left(\nabla\vec{u}+(\nabla\vec{u})^{\mathrm{T}}-\frac{2}{3}\nabla\cdot\vec{u}\vec{I}\right)-\frac{2}{3}\alpha\rho k\vec{I} \quad (5)$$

$$I_q=-\left(\lambda_l+\frac{\alpha\rho C_p\nu_t}{Pr}\right)\nabla T \quad (6)$$

$$I_\sigma=-\left(\frac{16}{3}\frac{\sigma_B}{c_\sigma}T^3\right)\nabla T \quad (7)$$

The turbulence model adopted widely used k-ε model and the kinetic turbulent viscosity is got by:

$$\nu_t=c_\mu k^2/\varepsilon \quad (8)$$

2.2 Particle phase equations

$$\frac{\mathrm{d}m_p}{\mathrm{d}t}=\dot{m}_w+\dot{m}_v+\dot{m}_c \quad (9)$$

$$m_p\frac{\mathrm{d}\vec{u}_p}{\mathrm{d}t}=\vec{f}_d+m_p\vec{G} \quad (10)$$

$$\frac{\mathrm{d}\vec{x}}{\mathrm{d}t}=\vec{u}_p \quad (11)$$

$$m_pC_p\frac{\mathrm{d}T_p}{\mathrm{d}t}=Q_{sr}+Q_v+Q_w+Q_{cv}+Q_{rd} \quad (12)$$

where

$$\vec{f}_d=\frac{1}{8}c_d\alpha\rho\pi d_p^2(\vec{u}+u^{\sim}-\vec{u}_p)|\vec{u}+\vec{u}'-\vec{u}_p| \quad (13)$$

2.3 Combustion model

The chemical structure of potato starch is rather complicated; the chemical formula of the main composition in potato starch is $(C_6H_{10}O_5)_n$. The reaction mechanism of potato dust is not clear yet. The combustion process of potato starch consists of the following stages:

- water vaporization from the particle
- volatile decomposition from the particle
- volatile combustion in the gas phase
- surface reaction of the particle

All of the above-mentioned processes are taken into account in the combustion model. Water vaporization is modeled using the droplet vaporization model. Two-equation method is used to model particle devolatilization process. It is assumed that CH_4 and CO extracted from volatile and CO generated by surface reaction of solid carbon combusting with oxygen in the gas phase and the EBU-Arrhenius model is used for modeling gas turbulent combustion. The main reactions of particle surface are considered as follows:

$$C+0.5O_2\rightarrow CO \quad (14)$$

$$C+CO_2\rightarrow 2CO \quad (15)$$

An extension form of "Single Reaction Theory" is used to describe the reaction rates of the above reactions. Details of combustion model used here are presented in literature[8].

3. Numerical simulation

The system considered in the numerical simulation is shown schematically in Fig.4. A dust-air mixture flows through a straight tube and is ignited at left end. Limited to the available computational resources, vessels connected to both end of the long pipe are not included in the model. In the numerical simulation, the ignition end and exit end were treated as inflow and outflow boundaries respectively. A jet flame of 1m length with 0.5bar pressure is introduced in the left boundary.

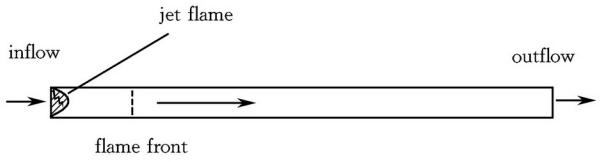

Fig.4 Schematic representation of numerical simulation

Operator splitting method[9] is used to solve the conservation equations of gas and particle phase. Flux Corrected Transport(FCT) scheme[10] is used to solve the convective parts of the governing equations, and implicit scheme is used to solve the diffusion parts. The source items are solved using an anti-stiff ordinary equation solver[11].

4. Numerical results and discussion

The time histories of numerical pressure at different locations along the tube are shown in Fig.5, which indicated the development of pressure waves due to flame acceleration while propagating through the connecting pipe. Compared with Fig.2, the agreement between the shape of the calculated and measured curves is reasonable and the entire process of combustion is well predicted.

It is shown from Fig.5 that close to the ignition location only a small and slow pressure rise is observed. With increasing distance from the ignition location the rate of pressure rise increases and the maximum pressure reaches higher levels. The numerical simulation shows a pressure maximum

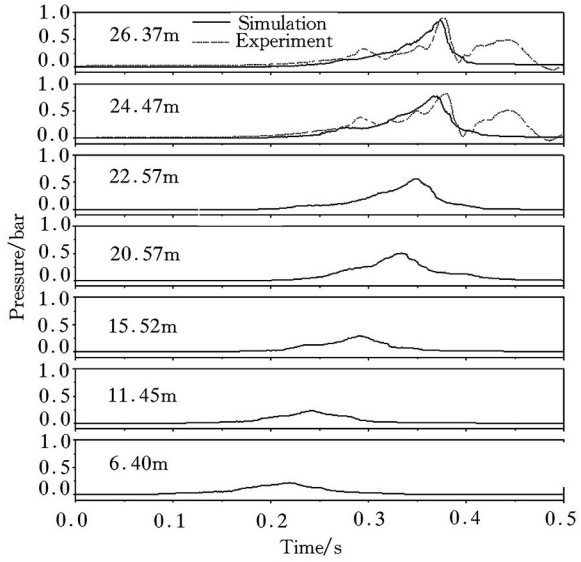

Fig.5 Calculated pressure history along pipe and measured pressure history at two location

which is moving downstream and becoming narrower with higher peak values. The location of this maximum coincides with the pronounced pressure rise observed in the experiment.

Fig.6 shows the comparison of calculated and measured flame trajectory in the connecting pipe. Experimental data are denoted as symbols, data from the numerical simulation as continuous curves. From Fig.6, it is evident that flame velocity become faster and faster along the pipe, the calculated maximum flame speed is about 330m/s, the simulation results is similar to that of experiments. Early in the combustion process there are some differences between simulation and experiment. For later times closer to the end of the tube the numerical curves are in good agreement with the measured results.

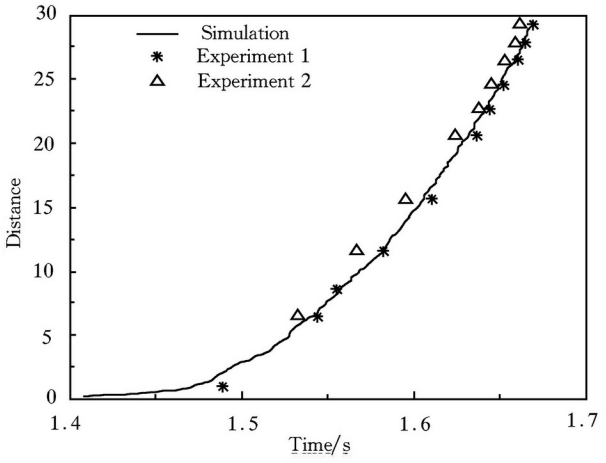

Fig.6 Comparison of calculated and measured flame trajectory in connecting pipe

Compared comprehensively from Fig.5 and Fig.6, the simulation results reproduced experimental results comparatively well and both of them are in reasonable agreement.

5. Conclusion

The experimental results indicate that, for linked vessels, dust explosions initiated in primary vessel can translate into the other vessel via connecting pipe and cause subsequent severely secondary explosions. Therefore, safety protection measures, such as explosion disengagement or explosion interruption must be taken to prevent other equipment from being affected by the explosion in such equipments. And, understanding of underlying mechanism for flame propagation is essential for safety protection and design.

A numerical model was applied to the study for flame propagation in the connecting long pipe. The comparison of numerical and experimental results showed that simulation result captured major characteristics of flames propagation in long pipe and simulated results are in good agreement with experimental results. The present numerical model is good in use for investigation of flame propagation through long pipe. And the code should be extended so that such a model would then allow simulations of dust explosions in equipment with complex geometries.

Nomenclature

Latin letters

c_d drag coefficient

C_p specific heat capacity of constant pressure, J/(kg·K)

c_σ Rosseland mean absorption coefficient

c_μ constant used in k-ε model

D_s mass transfer diffusion coefficient of s th specie, m^2/s

d_p diameter of a particle, m

E specific mixture energy, J/kg, activation energy, J/mol

E_p energy flux from particulate phase, $J/(m^3 \cdot s)$

$\dot{e}$ energy flux from a particle, J/s

$\vec{f}_d$ drag force, N

$\vec{G}$ gravity acceleration constant, $kg \cdot m/s^2$

$\vec{\vec{I}}$ unit tensor of second order

I_q Heat flux of thermal conduction in gas phase

I_s Mass diffusion flux, $kg/(m^2 \cdot s)$

I_σ Heat flux of thermal radiation

J_q heat flux due to heat transfer, $J/(m^2 \cdot s)$

k kinetic turbulent energy, J/kg

$\dot{k}$ momentum flux from a particle, $kg \cdot m/s^2$

M_p momentum flux from particulate phase, $kg/(m^2 \cdot s^2)$

m mass of a particle and its composition, kg

p pressure, Pa

Pr Prandt number, 0.7

Q rate of heat transfer, $J/(s \cdot m^3)$

S_p net mass flux from particle phase, kg/(m^3·s)
T temperature, K
$\vec{u}$ velocity vector of gas phase,
w_s net reaction rate of sth specie in gas phase, kg/(m^3·s)
$\vec{x}$ position of a particle, m
Y_s mass fraction of sth specie in gas phase

Greek letters

α volume fraction of gas phase
ρ density of gas, kg/m^3
$\vec{\vec{\tau}}$ stress tensor of second order, N/m^2
λ thermal conductivity coefficient, J/(s·m·K)
σ Prandt/Schmidt number
σ_B Stefan Boltzmann constant, 5.67×10^{-8} J/(s·m^2·K^4)
μ dynamic viscosity, kg/(m·s)
ν kinetic viscosity, m^2/s
ε turbulent energy dissipation rate, J/(kg·s)

Superscripts

T matrix transpose
$\cdot$ rate of change
$'$ fluctuation of a parameter

Subscripts

c carbon
l laminar properties
p particle properties
r radiation, radius
s species index
t turbulent properties
v volatile
w water
sr surface reaction
cv convective
rd radiation

References

[1] Eckhoff, R.K., Current status and expected future trends in dust explosion research, Journal of Loss Prevention in the Process Industries, 2005, 18(4-6): 225-237.
[2] Lunn, G.A., et al., Dust explosions in totally enclosed interconnected vessel systems, Journal of Loss Prevention in the Process Industries, 1996, 9(1): 45-58.
[3] Holbrow, P., Andrews, S., and Lunn, G.A., Dust explosions in interconected vented vessels, Journal of Loss Prevention in the Process Industries, 1996, 9(1): 91-103.
[4] Roser, M., et al., Investigations of flame front propagation between interconnected process vessels. Development of a new flame front propagation time prediction model, Journal of Loss Prevention in the Process Industries, 1999, 12(5): 421-436.
[5] Skjold, T., Review of the DESC project, Journal of Loss Prevention in the Process Industries, 2007, 20(4-6): 291-302.
[6] Kosinski, P., Klemens, R., and Wolanski, P., Potential of mathematical modelling in large-scale dust explosions, Journal De Physique Iv, 2002, 12(7): 125-132.
[7] Kosinski, P. and Hoffmann, A.C., Dust explosions in connected vessels: Mathematical modelling, Powder Technology, 2005, 155(2): 108-116.
[8] Zhong, S.J. and Deng, X.F., Modeling of maize starch explosions in a 12 m^3 silo, Journal of Loss Prevention in the Process Industries, 2000, 13(3-5): 299-309.
[9] Smirnov, N.N., Nikitin, V.F., and Legros, J.C., Ignition and combustion of turbulized dust-air mixtures, COMBUSTION AND FLAME, 2000, 123(1-2): 46-67.
[10] Boris, J.P., et al., LCPFCT-A Flux-Corrected Transport Algorithm for Solving Generalized Continuity Equations. Naval Research Laboratory, 1993: NRL/MR/6410-93-7192.
[11] Kee, J.R., et al., CHEMKIN-III-A FORTRAN Chemical Kinetics Package for the Analysis of Gas-Phase Chemical and Plasma Kinetics. Sandia National Laboratories, 1996: SAND 96-8216.