Journal of Loss Prevention in the Process Industries 45 (2017) 255–263

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Numerical analysis of factors influencing explosion suppression of a vacuum chamber

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ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form
9 November 2016
Accepted 9 November 2016
Available online 11 November 2016

Keywords:
Vacuum chamber
Gas explosion
Vacuum degree
BP neural network
Genetic algorithm

ABSTRACT

Vacuum chambers can effectively suppress gas explosion without relying on any explosion suppression material. The effect of explosion suppression by a vacuum chamber is correlated with the negative pressure of the vacuum chamber and flame front position when the diaphragm breaks. Accurate control of the experimental conditions of explosion suppression is challenging, and the use of experimental methods alone for analyzing their interrelation is difficult. This study analyzed considerable experimental data on explosion suppression by a vacuum chamber, investigated factors that influenced the explosion suppression, and evaluated parameters of the explosion suppression by using the *ΔP-I* principle. This study established a BP neural network optimized by a genetic algorithm, and discovered the non-linear relations among all parameters. The trained neural network was used to analyze the influence of vacuum degree and flame front position on explosion suppression when the diaphragm breaks. The results demonstrated that a good explosion suppression was achieved when a vacuum degree of P_0 *was* > 0.06 MPa and the optimal position of the flame front index *S* was 0 m. Explosion suppression of the vacuum chamber can be predicted by a fitting curve $I = 5.61e^{(-P0/0.028)} + 1.70$, which was obtained using the trained neural network and $S = 0.86$ m.

1. Introduction

Transmission pipelines are highly efficient when carrying flammable gases such as natural gas, coal bed methane, and gases produced from chemical plants. Unfortunately, pipeline failures are common. There are approximately 40,000 pipeline incidents in United States from 1968 to 2009 (Siler-Evans et al., 2014). Many causes can lead to pipeline failures, including construction errors, material defects, internal and external corrosion, operational errors, malfunctions of control systems, or relief equipment and outside force damage (Cunha, 2012). Failure of the pipeline can have several effects, and some of which can result in explosion. On June 22, 2014, a natural gas pipeline explosion occurred in India, which had 18 causalities and 40 serious injuries (Mishra and Wehrstedt, 2015).

Pipeline gas explosion is generally prevented by timely spraying explosion suppression materials on the reaction area of the explosion. As verified through experiments, the effective suppression materials known currently include water mist, inert gases, inert dust, and cellular materials. A significant decrease in H, O, and OH in the flame front can inhibit gas explosion caused by the presence of water (Liang and Zeng, 2010). The grain size of water mist influences its explosion suppression effectiveness (Chelliah et al., 2002). Several groups have investigated the effects of the density and distribution of water mist on its ability to suppress gas explosion (Ye et al., 2005; Catlin, 2002; Schwer and Kailasanath, 2007; Zhang et al., 2014). Ni, Ar, CO_2, and their mixtures influence the flameout effects of *n*-heptane and methane–air and propane–air mixtures (Saito et al., 1996). Wang et al. discussed the ability of He, Ni, vapor, and CO_2 to suppress explosions, and the detonation principle was further discussed by Wang et al. (Wang

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http://dx.doi.org/10.1016/j.jlp.2016.11.003
0950-4230/

and Duan, 2008). The explosion suppression principle and the effect of inert dust have also been explored (Linteris et al., 2002; Krasnyansky, 2006). Liu et al. investigated the explosion suppression effect of different inert dusts (Liu et al., 2013). Nie et al. investigated the effect and mechanism of foam ceramics used for suppressing gas explosions (Nie et al., 2011). Wei et al. reported that a porous material suppresses gas explosion flame waves (Wei et al., 2013). Luo et al. suppressed explosions by coupling CO_2 and ABC powder (Luo et al., 2014).

Our research team has recently developed an innovative method for suppressing pipeline gas explosion by using a vacuum chamber. In this method, a vacuum chamber is attached to the side of a gas explosion pipe and a diaphragm is placed in-between the vacuum chamber and the pipe. The vacuum chamber is evacuated to a vacuum state. When a gas explosion occurs, the diaphragm made of polytetrafluoroethylene film breaks and the flame of the explosion is extinguished because of the vacuum pumping action; therefore, the gas explosion is suppressed (Jiang et al., 2008; Wu et al., 2009, 2012; Shao et al., 2013). Based on this experimental method, a series of studies have been conducted to obtain sufficient experimental data. However, given the unpredictable factors and complicated mechanisms, ensuring the exact same experimental conditions for each gas suppression study is very difficult. This issue inevitably leads to varied results, which hinders accurate quantitative analysis of the factors influencing explosion suppression of the vacuum chamber. Up until now, only part of the experimental data were used to qualitatively analyze the influence of parameters such as break characteristics of diaphragm, volume of vacuum chamber, and vacuum degree on explosion suppression (Shao et al., 2014, 2015, 2016a,b).

All collected experimental results of explosion suppression by the vacuum chamber are valuable. This study focuses on how to effectively use all experimental data to quantitatively and accurately analyze the factors influencing explosion suppression.

The BP neural network can solve the complex non-linear problem and has been extensively used in fault diagnosis, feature extraction, and prediction (Rumelhart et al., 1986). This study used the BP neural network optimized by a genetic algorithm to analyze the experimental data, and determined non-linear relations among factors influencing explosion suppression.

2. Experimental apparatus and results

2.1. Experimental apparatus

The experimental explosion system primarily comprises a straight pipe, vacuum chamber, circulating pump, flammable gas ignition system, dynamic data acquisition system, pressure test system, flame speed test system, and diaphragm. Fig. 1 shows the framework of this system and Fig. 2 shows a photograph of the experimental system.

The experimental pipe is 11.5 m long, and its cross section is an 80 mm × 80 mm flat square. The ignition end of the experimental pipe is sealed, while the outlet end is completely open. A vacuum chamber is installed in the pipe. Fig. 3 shows the schematic of the experimental pipe with the vacuum chamber attached.

One end of the vacuum chamber is sealed, and a diaphragm is positioned at the other end. A polytetrafluoroethylene film with various thicknesses (i.e., 0.1, 0.2, 0.25, and 0.3 mm) is used as the diaphragm (Fig. 4).

The flame arrival time and the flame signal strength are recorded using photodiodes (referred to herein as flame transducers). Overpressure is monitored using an array of piezoresistive pressure transducers. This procedure was detailed in Shao et al.'s (Shao et al., 2014, 2015) study. Equal numbers of flame and pressure transducers are inserted and sealed into the experimental pipe. The position of each transducer is shown in Tables 1 and 2 and Fig. 3.

2.2. Experimental results

The experiments using 0.1-mm-thick polytetrafluoroethylene films were conducted with a vacuum degree of 0.02–0.05 MPa, whereas those using 0.2-, 0.25-, and 0.3-mm-thick polytetrafluoroethylene films were conducted with a vacuum degree of 0.01–0.08 MPa. Thirty groups of experimental results were obtained. Meanwhile, comparison experiments, without the vacuum chamber, were also conducted. The experimental procedure and results were detailed in Shao et al.'s (Shao et al., 2015) study.

3. Establishment and analysis of BP neural network used for explosion suppression by a vacuum chamber

3.1. Procedures of optimization of BP neural network using a genetic algorithm

The BP neural network was optimized using a genetic algorithm following the procedures below (Rumelhart et al., 1986; Sexton, et al., 1999; Gupta and Sexton, 1999):

(1) Determination of BP neural network structure: The input and output parameters are used to determine the number of input, hidden, and output layers.

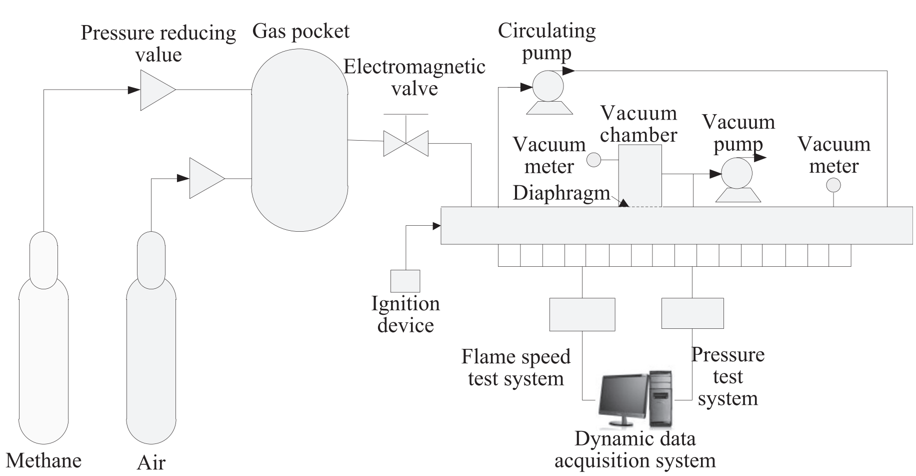

Fig. 1. Experimental components.