Effect of Magnetic Field on Dynamics of 5% Propane/ Air Premixed Gases

Xigang YANG¹, Shoutao HU*¹,², Le WANG¹, Xu SUN², Zijin HONG¹, Ruxia LI¹, Huiwen SHI¹, Jiancun GAO¹,²

¹Beijing Institute of Petrochemical Technology, Beijing, 102617, China;
²Beijing Academy of Safety Engineering and Technology, Beijing, 102617, China

Corresponding author. Beijing Institute of Petrochemical Technology, Daxing, Beijing, 102617, China.
* Corresponding author.
E-mail addresses: hushoutao@bipt.edu.cn

Abstract. Under applying the gradient electromagnetic field of 2100Gs-3300Gs, the explosion pressure and the propagation velocity of the explosion flame of 5% propane/air premixed gases were studied experimentally. The experimental results showed that the gradient electromagnetic field suppressed the explosion overpressure and explosion flame propagation velocity. When applied the gradient electromagnetic field, the peak propane explosion pressure decreased by 26KPa and the explosion flame propagation velocity decreased by 1.54269m/s. In other words, the gradient electromagnetic field suppressed the increase of pressure shock waves and light waves. Through the numerical simulation of propane explosion reaction, it is inferred that electromagnetic field mainly inhibits propane explosion pressure and explosion flame propagation speed by affecting the reactions of ·H, ·O and ·OH radicals.

1. Introduction
China's annual Liquefied petroleum gas (LPG) consumption shows an increasing trend. Propane, the main component of LPG, is an important alternative fuel for engines and fuels because of its low boiling point and the high octane value it produces when burned and its ease of mixing with air. Propane explosions can also produce significant damage. 16:00, June 13, 2020, a major explosion of a liquefied petroleum gas tanker in the Shenhui Expressway in Wenling City, Zhejiang, caused 20 deaths and 175 injuries. The direct economic loss was 94.7781 million yuan. November 16, 2020, a trailer carrying propane lost control and crashed another vehicle on the highway from Tepic, causing a serial explosion, killing 13 people death. In order to reduce casualties, many explosion suppression techniques have been developed, such as adding water mist¹, inert gases², inhibitors³, other media⁴, carbon fiber explosion suppression materials⁵, HAN⁶, seven, different metal wires⁸, and other materials.

In 1847, Faraday⁹ observed a strong inhomogeneous magnetic field leading to deflection of candle flames and an increase in flame brightness. He argued that these changes are due to the presence of “magnetic” and “antimagnetic” gases in the flame. Since then, scholars in China and abroad have been studying the influence of magnetic field on combustion and explosion. P. Gillon et al.¹⁰ found that an upward increasing magnetic field inhibits methane combustion. A V Revanth¹¹ investigated that the repulsive magnetic field tends to suppress the flame. Shoogo Ueno¹² recognized that flows of gases
with different susceptibilities can be controlled by gradient magnetic fields using a gas with a high susceptibility such as oxygen. Shilpi Agarwal\textsuperscript{13} used the circular grating Talbot interferometer respectively found that the flame temperature increased under the influence of the upward decreasing magnetic field and the flame temperature decreased under the influence of the upward increasing magnetic field.

Strengthening the study of the basic data of the explosion is necessary to explosion prevention countermeasures. Explosion pressure and explosion flame propagation velocity both are the basic data of gas explosion.

2. Experimental facility and procedures

The schematic diagram of the experimental device is shown in Figure 1. The experimental pipe is a cylindrical pipe of acrylic material designed by independent processing, with a Max pressure of 2 MPa, a length of 1000 mm, a diameter of 100 mm, a thickness of 6 mm, and a volume of 8L. The experimental pipeline is made into a black box, in order to the fiber optic sensor to better receive the light signal. Explosion velocity meter is multi-segment high-precision explosion velocity meter and based on the flame light waves through the two optical fiber sensor time difference measurement, the multi-segment distance of the explosion flame propagation velocity are tested. Its accuracy is 0.01us($10^{-8}$ s), which is more accurate than the high-speed camera. The first fiber optic sensor is horizontally 300 mm away from the left end of the pipe. The fiber optic sensors and the transient pressure sensors are corresponding to each other up and down, and the horizontal distance between the sensors are both 300 mm. The transient pressure sensors are Kistler-211B3 with an acquisition frequency of 100Hz. The ignition energy of the ignition system are 500mJ, at this energy the premixed combustible gases can be ignited stably. The DC magnetic field has a voltmetr and three sets of magnetic poles, the voltage is 150V, the current is 24A, and the magnetic field strength is measured with a Tesla meter with an accuracy of 1Gs. The magnetic field strength is 2100Gs at the center of the pole and 3300Gs at the ends of the pole. The experimental pipes do not have effect the magnitude of the magnetic field strength. The horizontal distance of the first group of magnetic poles is 140 mm from the left end of the pipe, and the horizontal distance of each group of magnetic poles is 300 mm.

![Figure 1. Schematic diagram of the experimental system.](image)

The purity of propane is 99.99% and the synthetic air consists of 79% nitrogen and 21% oxygen with a purity of 99.999%. The experiments are divided into control group and electromagnetic group, the control group was 5% propane/air premixed gas explosion. All experiments were conducted at room temperature and atmospheric pressure. Each set of experiments was repeated three times to ensure reproducibility. The experimental steps were as follows:
Attaching fiber optic sensors to fixed regulators and then mounting them to the experimental pipeline, where the fiber optic sensors can extend a little beyond the inside of the pipeline to allow for better reception of the light signal;

Checking the gas tightness of the device, a vacuum of <667 Pa (according to Method of test for explosion limits of combustible gases in air (GB/T 12474–2008)) was established in the reaction cylinder. The drop of vacuum was no greater than 267 Pa in 5 min, which indicated the seal of pipeline is proper for experiment. Then a vacuum of <0.07MPa was established in the reaction cylinder where the partial pressure method was used to create the required gas mixture. Injection of 400ml of propane, then supplement synthetic air to 1 atm state, the rapid closure of the intake valve; Circulating the gas in the pipeline for 60s using a circulation pump and standing 2min to ensure that the gas is well mixed. After standing still, the voltage regulator and the ignition device were opened. After the explosion, turning off the voltage regulator and the ignition device, respectively. The pressure data and blast flame propagation velocity data are collected after explosion, and harmless treatment of exhaust gas.

3. Experimental results and analysis

3.1  5% propane - air premixed gas explosion flame propagation speed
Since the gas explosion each time it is not possible to be the same pressure and speed, take the average of the results of three experiments on the propagation speed of the explosion flame for analysis.

| Serial Number | Fiber Optic Sensor | Distance(mm) | Time(us) | Velocity(m/s) |
|---------------|--------------------|--------------|----------|---------------|
| 1             | P1-P2              | 300          | 176470.59| 1.70000       |
|               | P2-P3              | 300          | 40415.21 | 7.42352       |
| 2             | P1-P2              | 300          | 175320.84| 1.71115       |
|               | P2-P3              | 300          | 36576.71 | 8.20194       |
| 3             | P1-P2              | 300          | 161050.05| 1.86278       |
|               | P2-P3              | 300          | 36414.90 | 8.23839       |
| Mean          |                    |              | 170650.41| 1.75798       |
|               |                    |              | 37713.93 | 7.95462       |

Table 2 1m Pipeline 5% Propane/Air Explosion Flame Propagation Velocity under Electromagnetic Field

| Serial Number | Fiber Optic Sensor | Distance(mm) | Time(us) | Velocity(m/s) |
|---------------|--------------------|--------------|----------|---------------|
| 1             | P1-P2              | 300          | 183961.05| 1.63078       |
|               | P2-P3              | 300          | 47546.75 | 6.30958       |
| 2             | P1-P2              | 300          | 181135.68| 1.65622       |
|               | P2-P3              | 300          | 46095.98 | 6.50816       |
| 3             | P1-P2              | 300          | 181791.74| 1.65024       |
|               | P2-P3              | 300          | 46743.17 | 6.41805       |
| Mean          |                    |              | 181135.35| 1.65622       |
|               |                    |              | 46787.78 | 6.41193       |

As shown in Table 1, 5% propane-air premixed gas in 1m pipe in the first section of the explosion flame propagation velocity of 1.75798m/s, with 170650.41us, the second section of the explosion flame propagation velocity of 7.95462m/s, with 37713.93us. As shown in Table 2, the average propagation velocity of the explosion flame in the first section of the 1m pipe was 1.65622m/s in 181135.35us, and in the second section was 6.41193m/s in 46787.78us under the 2100Gs-3300Gs gradient electromagnetic field.
3.2. 5% propane/air premixed gas explosion pressure

Three transient pressure sensors are used distributed along the axial direction to monitor the pressure changes at three different locations in the pipe. In the figure 3-4, the abnormal signal corresponding at the zero position of the pressure curve is the ignition signal.

![Figure 2. 5% propane/air premixed gas explosion overpressure.](image)

![Figure 3. 5% propane/air premixed gas explosion overpressure under electromagnetic field.](image)

Under 2100Gs-3300Gs gradient electromagnetic field, compared with the control group, there was little change in the first two pressure peaks and the third pressure peaks reduced by 26KPa, decreased by 13.20% from Figure 2 and Figure 3. The time for the pressure shock waves to reach transient pressure sensor No. 1 was 45.71ms, the time to reach sensor No. 2 was 97.90ms, and the time to reach sensor No. 3 was 181.64ms. The time for the pressure shock waves to reach transient pressure sensor No. 1 was 48.10ms, the time to reach sensor No. 2 was 105.10ms, and the time to reach sensor No. 3 was 194.03ms under the gradient electromagnetic field. Application of gradient electromagnetic field can extended the propagation time of pressure shock waves.

4. Numerical simulation

A closed reactor with no heat exchange with the surrounding environment and constant volume and solve energy equation, was modeled in CHEMKIN-18.2.

The species equation is defined as:

\[
\frac{dY_i}{dt} = \nu \omega_i M_i (i = 1, 2, \ldots, k_g)
\]  

(1)

The energy equation is as follows:

\[
c_v \frac{dT}{dt} + \nu \sum_{i=1}^{k_g} e_i \omega_i M_i = 0
\]

(2)

where \(Y_i\) and \(M_i\) are the mass fraction and molecular weight of species \(i\), respectively; \(t\) is time; \(\nu\) represents the mixture’s specific heat capacity; \(T\) is temperature; \(c_v\) is constant volume specific heat; \(k_g\) is the total number of species; \(e_i\) denotes the internal energy of species \(i\); and \(\omega_i\) and \(K_{fk}\) are given by:

\[
\omega_i \sum_{k=1}^{N_g} \nu_k K_{fk} \prod_{j=1}^{k_g} (x_j)^{v_{rik}} (i = 1, 2, \ldots, k_g)
\]

(3)

\[
K_{fk} = A_k T^{b_k} \exp \left( \frac{-E_k}{RT} \right) (k = 1, 2, \ldots, N_g)
\]

(4)

where \(N_g\) stands for the total reaction steps; \(x_j\) is the mole fraction of species \(j\); \(A_k\), \(b_k\) and \(E_k\) are the pre-exponential factor, thermal constant and activation energy of reaction \(k\), respectively; \(P\) represents pressure; and \(R\) is the universal gas constant.
Figure 4. Rate of C₃H₈ in the progress of gas explosion.

Table 3 The key reaction of C₃H₈.

| Reaction | Equation                      | Coefficients |
|----------|-------------------------------|--------------|
| R325     | C₃H₈(+M)=CH₃+C₂H₅(+M)         | Negative     |
| R330     | H+ C₃H₈=H₂+iC₃H₇             | Negative     |
| R331     | H+ C₃H₈=H₂+nC₃H₇             | Negative     |
| R332     | O+ C₃H₈=OH+iC₂H₅             | Negative     |
| R333     | OH+ C₃H₈=H₂O+iC₃H₇           | Negative     |
| R335     | CH₃+ C₃H₈=CH₄+iC₂H₅          | Negative     |
| R343     | O+ C₃H₈=OH+nC₃H₇             | Negative     |
| R344     | OH+ C₃H₈=H₂O+nC₃H₇           | Negative     |
| R346     | CH₃+ C₃H₈=CH₄+nC₃H₇          | Negative     |
| R929     | C₃H₈=H₂+C₃H₆                | Negative     |

The top 10 elementary reactions about rate of product (ROP) of C₃H₈ were shown Figure 4. As seen in Table 3, the critical reaction affecting rate of C₃H₈ in the explosion process was R325, R330, R331, R332, R333, R335, R343, R344, R346 and R929. Most of the elementary reactions to generated propyl and consume ·H, ·O and ·OH. R325 was the fastest reaction of propane consumption which generated ·CH₃ and C₂H₅. R331, R330 were also faster reaction of propane consumption. ·H radical was beneficial to propane consumption.
Figure 5. Sensitivity analysis of elementary reactions that are key to free radical.

Table 4 Key elementary reactions affecting the free radical concentration.

| No. | Reaction                      | ·H, ·O, ·OH Coefficients | O₂ Coefficients |
|-----|-------------------------------|--------------------------|-----------------|
| R5  | H+O₂= ·O+OH                  | Positive                 | Negative        |
| R37 | HO₂+CH₃=O₂+CH₄              | Negative                 | Positive        |
| R68 | O₂⁺CH₃=OH+CH₂O              | Positive                 | Negative        |
| R75 | HO₂+CH₃=OH+CH₂O              | Positive                 | Negative        |
| R154| CH₃+CH₄(+M)=C₂H₆(+M)         | Negative                 | Positive        |
| R208| OH+C₂H₆=H₂O+C₂H₅             | Positive                 | Negative        |
| R325| C₃H₈(+M)=CH₃+C₂H₅(+M)        | Positive                 | Negative        |
| R331| H+C₃H₈=H₂+3C₃H₇             | Negative                 | Positive        |
| R344| OH+C₃H₈=H₂O+nC₃H₇           | Negative                 | Positive        |
| R415| HO₂+C₃H₈=O₂+3C₃H₇           | Positive                 | Negative        |

The O₂, ·O and ·OH radicals are paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.

Shinsuke Itoh, Eisuke Yamada and Masahisa Shinoda established an analysis method for various gas species in flames and obtained that different magnetic field intensities had the greatest influence on OH density. So the sensitivities of ·H, ·O and ·OH radicals were chosen to analyze.

The ·H, ·O and ·OH and O₂ displayed opposite sensitivities. Sensitivity analyzed the degree to which the free radicals changes with the elementary reaction. There were some elementary reactions not directly influenced the sensitivity of free radicals rather indirectly influence the sensitivity of free radical by chain reaction. So the top 10 elementary reactions of each substance were the same, and the pathways that affect the substance were different. The greater the sensitivity changes, the greater the effect of this elementary reaction. Sensitivity coefficients were positive indicating that elementary reactions promote the formation of this free radicals. The O₂, ·O and ·OH radicals were paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.

Shinsuke Itoh, Eisuke Yamada and Masahisa Shinoda established an analysis method for various gas species in flames and obtained that different magnetic field intensities had the greatest influence on OH density. So the sensitivities of ·H, ·O and ·OH radicals were chosen to analyze.

The ·H, ·O and ·OH and O₂ displayed opposite sensitivities. Sensitivity analyzed the degree to which the free radicals changes with the elementary reaction. There were some elementary reactions not directly influenced the sensitivity of free radicals rather indirectly influence the sensitivity of free radical by chain reaction. So the top 10 elementary reactions of each substance were the same, and the pathways that affect the substance were different. The greater the sensitivity changes, the greater the effect of this elementary reaction. Sensitivity coefficients were positive indicating that elementary reactions promote the formation of this free radicals. The O₂, ·O and ·OH radicals were paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.

Shinsuke Itoh, Eisuke Yamada and Masahisa Shinoda established an analysis method for various gas species in flames and obtained that different magnetic field intensities had the greatest influence on OH density. So the sensitivities of ·H, ·O and ·OH radicals were chosen to analyze.

The ·H, ·O and ·OH and O₂ displayed opposite sensitivities. Sensitivity analyzed the degree to which the free radicals changes with the elementary reaction. There were some elementary reactions not directly influenced the sensitivity of free radicals rather indirectly influence the sensitivity of free radical by chain reaction. So the top 10 elementary reactions of each substance were the same, and the pathways that affect the substance were different. The greater the sensitivity changes, the greater the effect of this elementary reaction. Sensitivity coefficients were positive indicating that elementary reactions promote the formation of this free radicals. The O₂, ·O and ·OH radicals were paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.

Shinsuke Itoh, Eisuke Yamada and Masahisa Shinoda established an analysis method for various gas species in flames and obtained that different magnetic field intensities had the greatest influence on OH density. So the sensitivities of ·H, ·O and ·OH radicals were chosen to analyze.

The ·H, ·O and ·OH and O₂ displayed opposite sensitivities. Sensitivity analyzed the degree to which the free radicals changes with the elementary reaction. There were some elementary reactions not directly influenced the sensitivity of free radicals rather indirectly influence the sensitivity of free radical by chain reaction. So the top 10 elementary reactions of each substance were the same, and the pathways that affect the substance were different. The greater the sensitivity changes, the greater the effect of this elementary reaction. Sensitivity coefficients were positive indicating that elementary reactions promote the formation of this free radicals. The O₂, ·O and ·OH radicals were paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.

Shinsuke Itoh, Eisuke Yamada and Masahisa Shinoda established an analysis method for various gas species in flames and obtained that different magnetic field intensities had the greatest influence on OH density. So the sensitivities of ·H, ·O and ·OH radicals were chosen to analyze.

The ·H, ·O and ·OH and O₂ displayed opposite sensitivities. Sensitivity analyzed the degree to which the free radicals changes with the elementary reaction. There were some elementary reactions not directly influenced the sensitivity of free radicals rather indirectly influence the sensitivity of free radical by chain reaction. So the top 10 elementary reactions of each substance were the same, and the pathways that affect the substance were different. The greater the sensitivity changes, the greater the effect of this elementary reaction. Sensitivity coefficients were positive indicating that elementary reactions promote the formation of this free radicals. The O₂, ·O and ·OH radicals were paramagnetic substance and ·H radical not only is diamagnetic substance but also occupy an important position in rate of C₃H₈ in the progress of gas explosion.
5. Discussion
As seen in Figure 6, the 2100Gs-3300Gs gradient electromagnetic field had negligible effect on the peak propane explosion pressure at the first two measurement points, and caused the peak explosion pressure at the third measurement point to decrease by 26KPa compared with without the electromagnetic field. As can be seen from Figure 7, the application of the gradient electromagnetic field had a suppressive effect on the gas explosion flame propagation velocity, the first section explosion flame propagation velocity reduced by 0.10176m/s, diminished by 5.8%, and the time increased by 10484.94us; the second section explosion flame propagation velocity decreased by 1.54269m/s, diminished by 19.4%, and the time increased by 9073.85us. The average propagation velocity of the explosion flame was 4.85630m/s in the control group, and 4.03409m/s when the magnetic field was added, which decreased by 0.82221m/s and reduced by 16.9%.

Different from the influence of the propagation velocity of electromagnetic field to explosion flame, electromagnetic field on the explosion pressure in the first two points of measurement was not obvious, in the third point of measurement was particularly obvious. This is because the propagation velocity of pressure shock waves was the propagation velocity ahead of the disturbance of the airflow, higher than the propagation velocity of explosion flame.

![Figure 6. 5% propane/air premixed gas explosion overpressure.](image)

![Figure 7. 5% propane/air premixed gas explosion flame propagation velocity.](image)

| Types of waves | Distance | Control group | Electromagnetic field | Increased time(μs) |
|---------------|----------|---------------|------------------------|-------------------|
| Pressure shock waves | a | 52190 | 57095 | 4815 |
| | b | 83740 | 88930 | 5190 |
| Light waves | a | 170950 | 181135 | 10185 |
| | b | 37714 | 46788 | 9074 |

a represents the distance between the first sensor and the second sensor.
b refers to the distance from the second sensor to the third sensor.

Propagation of pressure is essentially the propagation of pressure shock waves. Light has wave-particle duality and is both a particle and an electromagnetic waves. Explosion flame propagation speed is essentially the propagation of light waves. In the Table 5, under the influence of the gradient electromagnetic field, the transmission time of the pressure shock waves increased by 4815us at section a and at section b, the transmission time extended by 5190us. And the communication time of the light waves during section a increased by 10185us and the time during section b extended by 9074us compared with the control group. The gradient magnetic field not only suppresses the propagation of pressure shock waves but also light waves.

The process of light propagation was due to the movement of the light source object, which drove the electrons to change their motion transitions, and the interconnected electrons interacted with each
other. The magnetic field was able to act on these electrons and thus affect the propagation of light waves. The application of an external magnetic field lead to some of the extranuclear electrons that produced a paramagnetic field to jump in the direction that produced an inverse magnetic field. In other words, this phenomenon is called chemical shift, i.e., an energy shift of the extranuclear electrons. Magnetic fields may change the energy of some paramagnetic radicals, thus affecting the reaction rate of combustion practice. The wall effect was an effective way to stop radical elementary reactions. The gradient electromagnetic field produced an effect on paramagnetic free radicals and antimagnetic free radicals, promoting free radical movement to make it collide with the pipe, or reducing free radical activation energy. The gradient electromagnetic field mainly inhibits the explosion reaction kinetics by influencing the key free radicals such as ·H, ·O, ·OH and so on to produce the wall effect. The more free radicals destroyed by the wall effect, the stronger the inhibition effect on the combustion explosion reaction. The combustion explosion reaction was weakened thus bringing the explosion pressure and explosion flame speed became smaller.

6. Conclusion
Through the experimental study of 5% propane/air premixed gas in the length of 1m length-diameter ratio φ=10 closed pipe explosion flame propagation speed and explosion pressure, under the 2100Gs-3300Gs gradient electromagnetic field the conclusions are summarized as follows: When applying the gradient electromagnetic field, the explosion pressure and explosion flame propagation velocity both were suppressed. The peak explosion pressure reduced by 26 KPa and the average explosion flame propagation velocity reduced by 0.82221 m/s.

The gradient electromagnetic field suppressed the propagation of pressure shock waves and light waves, extending the propagation of pressure shock waves by 10010us and light waves by 19259us from the first sensor to the third sensor.

In the whole propane combustion reaction, ·H plays an important role in ROP, the sensitivity of ·O changes most, and the electromagnetic field has the greatest influence on the inhibition of the reactions of ·OH radicals.

The gradient electromagnetic field mainly inhibits the explosion reaction kinetics by influencing the key free radicals such as ·H, ·O, ·OH and so on to produce the wall effect.

The influence of electromagnetic field on chemical kinetics is through Lorentz force, gradient magnetic field force, magnetic electrophoresis force, extranuclear electron chemical shift and so on. Electromagnetic field inhibits the propagation of light waves by changing the rotation of electron motion. Gradient electromagnetic field has an inhibitory effect on combustion and explosion, however the effect of electromagnetic field on chemical kinetics is a complex subject.

Acknowledgements
This research is supported by the science and Technology Plan Project of Beijing Municipal Education Commission (KM201910017001), the innovation Training Program for University Students(2020J00081) and Beijing Natural Science Foundation, Youth Project (No. 2214071).

Reference
[1] Greenberg, J. and Sahar Shpitz. 2020. Micro-explosion effects in a laminar water-in fuel spray diffusion flame J. Combustion Theory and Modelling, 1-24. DOI: 10.1080/13647830.2020.1847329.
[2] Torikai, H.. 2020. Extinguishing Characteristics of a Pool Fire with a Rubber Balloon Filled with Inert Gases J. Fire Technology 56, 385-399.
[3] Yu, M. et al. 2020. Investigation of methane/air explosion suppression by modified montmorillonite inhibitor J. Process Safety and Environmental Protection 144, 337-348.
[4] Azam, S. and D. P. Mishra. 2019. Effects of particle size, dust concentration and dust-dispersion-air pressure on rock dust inertant requirement for coal dust explosion suppression in underground coal mines J. Process Safety and Environmental Protection 126, 35-43.
[5] Kim, Young-O et al. 2020. Recyclable, flame-retardant and smoke-suppressing tannic acid-based carbon-fiber-reinforced plastic. *J. Composites Part B-engineering* **197**, 108173.

[6] Wang L et al. 2020. A product analysis-based study on the mechanism of inflammable gas explosion suppression. *J. Journal of Loss Prevention in The Process Industries*, 104311. doi: https://doi.org/10.1016/j.jlp.2020.104311.

[7] Zhou, S.; Gao, J.; Luo, Z.; Hu, S.; Wang, L.; Su, B.; Li, R., 2021. Effects of mesh aluminium alloy and aluminium velvet on the explosion of H2/air, CH4/air and C2H2/air mixtures. *J. International Journal of Hydrogen Energy* **46**, 14871-14880.

[8] Zhuang, C., Wang, Z., Zhang, K., Lu, Y., Shao, J., & Dou, Z. 2020. Explosion suppression of porous materials in a pipe-connected spherical vessel. *J. Journal of Loss Prevention in The Process Industries* **65**, 104106.

[9] Faraday, M. 1847. LXIV. On the diamagnetic conditions of flame and gases. *J. Philosophical Magazine Series 1* **31**, 401-421.

[10] Gillon, P.; Blanchard, J. N.; Gilard, V., 2010. Methane/Air-Lifted Flames in Magnetic Gradients. *J. Combustion Science and Technology* **182** (11-12), 1805-1819.

[11] Revanth, A. V. et al. 2020. On the effect of repulsive magnetic field on partially premixed flames. *C. 240th. The Electrochemical Society*, **912** doi:10.1088/1757-899X/912/4/042020

[12] Ueno S and K Harada. 1987. Effects of magnetic fields on flames and gas flow. *J. IEEE Transactions on Magnetics* **23**, 2752-2754.

[13] Agarwal S, Kumar M and Shakher C, 2015. Experimental investigation of the effect of magnetic field on temperature and temperature profile of diffusion flame using circular grating Talbot interferometer. *J. Optics and Lasers in Engineering* **68**, 214-221.

[14] Itoh Shinsuke et al. 2001. Spatially resolved elemental analysis of a hydrogen–air diffusion flame by laser-induced plasma spectroscopy (LIPS). *J. Microchemical Journal* **70**, 143-152.

[15] Yamada E, Shinoda M, Yamashita H and Kitagawa K, 2002. Numerical analysis of a hydrogen-oxygen diffusion flame in vertical or horizontal gradient of magnetic field. *J. Combustion Science and Technology* **174** (9), 149-164.

[16] Yamada E, Shinoda M, Yamashita H and Kitagawa K. 2003. Influence of Four Kinds of Gradient Magnetic Fields on Hydrogen-Oxygen Flame. *J. AIAA Journal* **(8)**, 1535-1541.

[17] Shinoda M, Yamada E, Kajimoto T, Yamashita H and Kitagawa K, 2005. Mechanism of magnetic field effect on OH density distribution in a methane–air premixed jet flame. *C. Proceedings of the Combustion Institute* **30** (1), 277-284.

[18] Kajimoto T, Yamada E, Shinoda M, Desmira N, Kitagawa K and Gupta A K, 2013. Analysis of flame structure by isotope shift-planar laser induced fluorescence spectrometry of trace OH and OD Radicals. *J. Microchemical Journal* **106**, 334-339.