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Design and Research of Propane Combustion Real Fire Training System

Guang Yang, He Zhang

School of Mechanical and Electrical Engineering, Southwest Petroleum University, Chengdu 637001, China

Abstract

According to the actual demand of the fire protection training of the domestic fire department, based on the oil and gas gathering technology and reference to relevant domestic and international standards, a set of propane real fire combustion training system for domestic fire rescue teams to conduct real fire training was designed and designed. In order to save fuel and improve the economics of propane combustion fire training system, the applicable air-fuel ratio algorithm was derived, using water bath combustion technology. Finally, the problems in the system design and the improvement direction of the next step are proposed.

Keywords

propane combustion real fire water bath combustion training system.

1. Overview

In recent years, production safety accidents in the petrochemical industry and hazardous chemicals fields have been frequent in the world, causing a large number of personnel and property losses. For example, an explosion occurred at the Westfield Fertilizer Plant near Wade City, Texas, USA on April 17, 2013, killing more than 50 people, including 15 firefighters, and direct economic losses of about $2.3 billion. Another example: On August 12, 2015, a major fire and explosion accident at the Tianjin Ruihai Company's dangerous goods warehouse caused 165 people, including 99 fire officers and soldiers, to die, and the direct economic loss was 6.866 billion yuan. After these accidents, the investigation and research departments of various countries have made in-depth analysis of the causes of accidents, improving production processes and improving safety production laws and regulations. They also proposed to increase the training skills of firefighters in combat, improve the efficiency of fire fighting, and reduce the risk of firefighters' casualties.

The current combustion fire training system has made great progress abroad, such as the German real fire training system of Dräger Company, the burning fire training system of HAAGEN of the Netherlands, etc. Its combustion fire training system has been widely used in fire protection, aerospace, In the military and other fields, corresponding national standards have also been issued, such as DIN 14097 - "Fire Training Facilities Standards", NFPA 1403 - "American Firefighters Practical Training Standards". However, the combustion of real fire training system is still a blank in China, and there is no large-scale combustion fire training system put into use, nor has it issued relevant national standards. Due to the huge investment in the imported burning fire training system, the engineering period is long, the training background is different from the domestic one, and the maintenance response is not timely. Therefore, based on the oil and gas gathering and transportation technology, this paper studies and designs real fire combustion training system of propane for domestic fire rescue teams to conduct real fire training, and deduces the air-fuel ratio algorithm applicable to the control system. The whole system is designed and put into use at a fire detachment training base.

2. Research and Design of Combustion Fire Training System

2.1. Carrier Design

According to the GA/T 623-2016 standard and the actual combat experience of the fire rescue team, the 40GP standard container is selected as the carrier of the real fire training system, as shown in Figure 1:

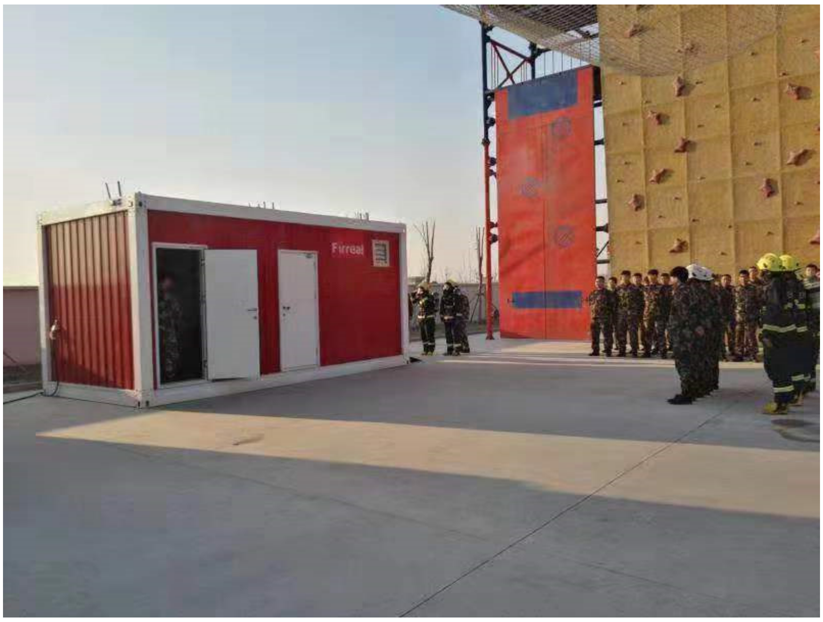

Figure 1. Propane combustion fire training system carrier

The inside of the container is made of 200×200 (H×W) wide-wing H-type weather-resistant steel to build the keel, and it is divided into three areas according to the function: training room, fuel room and control room. A 3mm thick weathering steel plate was placed on the ribs of the four walls of the training room and the top and bottom to make an inner partition, and then a 1.2 mm thick refractory steel plate was used as the inner wall. The inner wall and the inner partition, the inner partition and the outer corrugated board of the container are filled with refractory rock wool. In the training room, an explosion-proof flammable gas detector, an explosion-proof temperature sensor, an explosion-proof fire-resistant high-temperature axial flow inverter fan, and the like are installed. In order to prevent the water spray formed by the high temperature of the training water from corroding the fan blades, a wind tunnel is specially installed at the air inlet of the fan, and a wire mesh defogger is installed in the air duct. The electrical connections of all electrical equipment in the room are connected to explosion-proof hoses. Drainage holes are designed around the floor of the training room to drain the training water. Some equipment in the training room is shown in Figure 2.

Figure 2. Training indoor walls, drains and some equipment

2.2. Fuel Selection

Propane is a product of petroleum refining and natural gas purification, and is a commonly used fuel gas. When propane is fully burned, the flame is striking bright yellow. The main products when burning are carbon dioxide and water, which is beneficial to firefighters and environmental pollution. Liquid propane has a wide gasification temperature range. At -30 ° C, the saturated vapor pressure of liquid propane is still greater than the standard atmospheric pressure, which can be gasified and burned. Propane has a narrower explosion range and is relatively safe (lower explosive limit 2.1% LEL, upper explosion limit 9.5% UEL). Based on the above advantages, we chose six 40L bottles of liquid propane to act as fuel gas. A check valve and an anti-tempering device are installed on the cylinder, and then the iron chain is securely fixed on the cylinder bracket. In order to reduce the impact of cylinder replacement on training, we designed a two-way bus. Use one set of manual valves to close the other set of manual valves. When a group of cylinders needs to be replaced, it is only necessary to close the group of manual valves and open the other group of manual valves, thereby avoiding the disadvantages of troublesome operation and long downtime when the single group of busbars are replaced.

2.3. Gas Path Design

2.3.1. Gas Path Design

The fuel of the propane combustion fire training system is transported through the gas pipeline. The selection of the fuel gathering pipeline with the appropriate wall thickness and diameter is essential for the propane combustion fire training system. The formula for calculating the wall thickness of gas management is [1]:

$$\delta = \frac{PD}{2\sigma_S \phi F} \tag{1}$$

Where: δ is the wall thickness of the steel pipe, the unit is mm; P is the design pressure of the pipe, the unit is MPa; D is the outer diameter of the steel pipe, the unit is mm; σ_S is the lowest yield strength of the steel pipe; F is the strength design coefficient; ϕ is the weld system. Set the strength design coefficient F= 0.3 (four-level area); weld coefficient ϕ =1 (GB / T 9711.2); 20 steel pipe minimum yield strength σ_S = 245 MPa; DN32 pipe outer diameter D = 42.4 m; P = 2 MPa.

From the formula (1), choose DN32, seamless galvanized steel pipe with a wall thickness of 3.25mm as the main pipe to meet the design requirements. The gas output from the main gas path passes through the manual valve, the pressure gauge, the filter, the release valve and the two shut-off valves, and is divided into a burner gas path and a fuel gas path through a three-way. The gas in the burner gas path is passed through a pressure reducing valve, a pressure gauge, a burner solenoid valve, and finally to the ignition burner. The gas in the fuel gas path passes through the fuel valve, the servo valve, and finally to the fuel nozzle. The gas path design is shown in Figure 3:

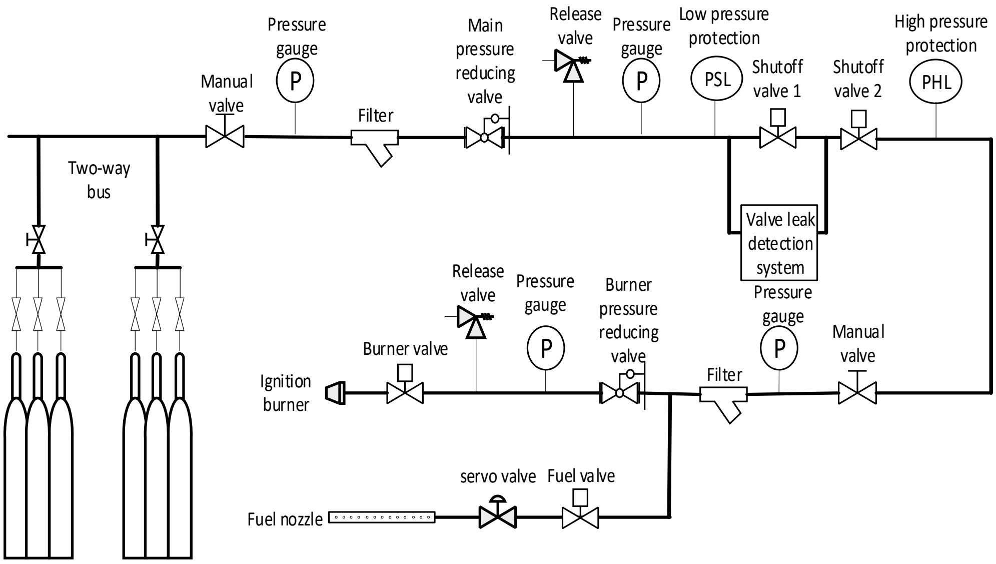

Figure 3. Gas circuit design

2.3.2. Pipeline Pressure Drop

When propane is used as the fuel gas, the technical parameters of the ignition burner require that the absolute pressure range of the propane gas in the burner should be up to 40-80mBar. In order to determine the decompression range of the main gas path, the pressure loss of the gas line must be calculated. With the pressure loss value of the gas line, the selection of the main gas line pressure reducing valve has a basis. Because the total length of the gas line of the propane-burning real fire system is only 10 meters and the number of tees and elbows is small, the pressure drop caused by the tee and the elbow is negligible when calculating the pressure loss. The formula for calculating the line pressure drop is as follows:

$$\frac{P1^2 - P2^2}{L} = 1.27\times10^{10}\lambda\frac{Q^2}{d^5}\rho\frac{T}{T_0}Z \tag{2}$$

$$\frac{1}{\sqrt{\lambda}} = -2\lg[\frac{K}{3.7d} + \frac{2.5L}{\mathrm{Re}\sqrt{\lambda}}] \tag{3}$$

$$\mathrm{Re} = 0.354\times\frac{Q_V}{dV} \tag{4}$$

Where: P1 is the absolute pressure of the gas after decompression of the main gas path, in units of kpa; P2 is the absolute pressure of the gas in the ignition burner, unit KPa; Q is the gas flow, the unit is m^3/h; Z is the compression factor; T is gas temperature, unit K; T0=273.15K; L is the length of gas pipeline, unit km; λ is the friction coefficient of gas pipeline; K is the absolute roughness of gas pipeline; Re is dimensionless of Reynolds number, unit m^3 / h; D / d is the

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inner diameter of the gas pipeline, the unit is mm; V is the kinematic viscosity of the gas, the unit is m^2 / s.

When calculating: P2=6KPa, the volume flow of gas is measured by gas flow meter, Qv=25.3m3/h; T=288.15K; compression factor Z=0.098; ρ=1.83kg/m^3;kinematic viscosity of propane V=4.507 mm^2/S (20°C, atmospheric pressure); DN32 gas pipe with a wall thickness of 3.25 mm, d = 35.9 mm; length 10 m; Re =0.062 ; gas pipe absolute roughness K = 0.15; gas pipe friction resistance coefficient λ=0.02; After calculating P1=229Kpa, the inlet pressure is 0-2.5Mpa, and the main gas pressure reducing valve with adjustable outlet pressure 1-3Bar meets the design requirements. Since P2=6KPa, the pressure reducing range of the pressure reducing valve of the burner gas passage is 1-3 Bar for the inlet pressure and 0-10Kpa for the outlet pressure.

2.4. Control Design

Propane combustion fire training systems must ensure a reasonable air-fuel ratio during combustion. In the process of combustion, the low supply of air will result in insufficient propane combustion, which wastes both propane and black smoke. Long-term use can easily block the ignition burner and cause tempering. On the contrary, when the air supply is too high, a large amount of harmful substances such as NO_X will be generated. In the training process of firefighters, NO_X encounters water vapor to generate acidic substances, which pollutes the environment and corrodes the combustion equipment. For long-term use, it reduces service life of the propane combustion fire training system. In addition to the air-fuel ratio control, another method is to use the water bath combustion technology. The water bath combustion technology effectively improves the utilization of propane during training, greatly reduces the ablation of the fuel line and the burner by the flame, and reduces the harmful substances such as NO_X. The amount generated. The propane combustion fire training system uses an air-fuel ratio control algorithm and a water bath combustion technique in the control design.

2.4.1. Air-fuel Ratio Control

GB13271-2014 stipulates that the excess air coefficient of gas equipment is 1.2, that is, the air-fuel ratio of propane should be 1.2 times the theoretical air-fuel ratio. Set the air density = 1.29Kg / M^3, propane density = 1.83Kg / M^3, and the system is in a standard environment, then the air-fuel ratio calculation method is as follows:

$$\alpha = \frac{SR_{M_0}}{SR_{M_1}} \tag{5}$$

Where: SR_{M0} is the actual air-fuel mass ratio; $SR_{M1}$is the theoretical air-fuel mass ratio.

It is known from formula (5) that the air-fuel volume ratio specified by the national standard is $1.2\times\frac{\rho_2}{\rho_0}$ =1.7, The formula for calculating theoretical air-fuel ratio is following:

$$SR_V = \frac{\frac{5\times 32}{\rho 1}\times\frac{100}{21}}{\frac{44}{\rho 2}} \tag{6}$$

Where: the volumetric content of oxygen in the air is 21%; the oxygen density in the standard environment is ρ1 = 1.43Kg/m^3; The alkane density was 1.83 Kg/m^3. SR_V = 22.16, so the air-fuel volume ratio specified by the national standard is: 22.16 × 1.7 =37.67. The air-fuel ratio feedback value of the actual combustion is measured by the on-line flue gas measuring instrument, and the volume fraction of carbon dioxide is calculated by the following formula. [2]

$$\alpha_m = \frac{21}{21 - 79\frac{V_{O2}}{100-(V_{O2}+V_{co_2})}} \tag{7}$$

Where: 21 is the volume content of oxygen in the air; 79 is the volume content of nitrogen in the air; is the volume fraction of oxygen in the flue gas after combustion; V_{co_2} is the volume fraction of carbon dioxide in the flue gas after combustion.

After the air-fuel ratio setting value and the air-fuel ratio feedback value are determined, the air-fuel ratio control system can be approximated as having a hysteresis loop.The first-order inertial system of the section [3]. According to Darling's algorithm, the control function of the air-fuel ratio control system is [4]:

$$D(Z) = \frac{0.0134 - 0.012Z^{-1}}{1 - 0.78Z^{-1} - 0.22Z^{-3}} \tag{8}$$

The equation of state for the air-fuel ratio control system is:

$$Y(K) = \begin{bmatrix} X_1(K) \\ X_2(K) \\ X_3(K) \end{bmatrix} \begin{pmatrix} 0.78 & 1 & 0 \\ 0 & 0 & 1 \\ 0.22 & 0 & 0 \end{pmatrix} \begin{bmatrix} X_1(K-1) \\ X_2(K-1) \\ X_3(K-1) \end{bmatrix} + \begin{bmatrix} -0.0000076 \\ 0 \\ 0.0035 \end{bmatrix} + 0.0134u(k) \tag{9}$$

The MATLAB software simulation diagram of the air-fuel ratio control system is shown in Figure 4.

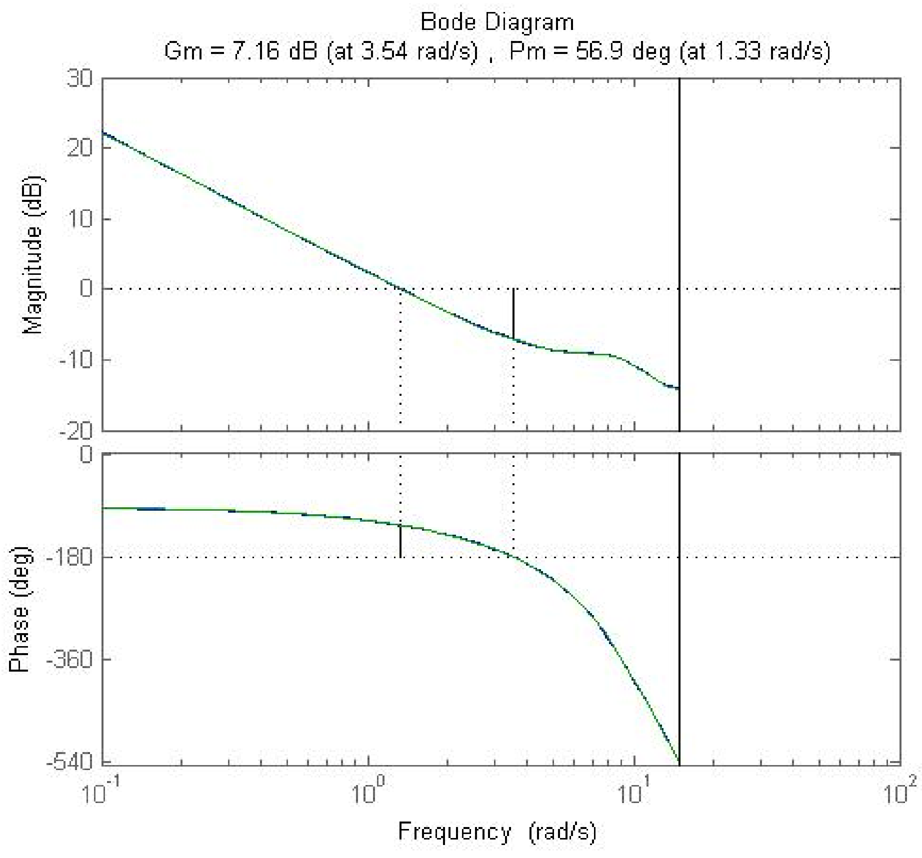

Figure 4. MATLAB simulation diagram of air-fuel ratio control system

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According to the figure: the amplitude margin of the air-fuel ratio controller of propane combustion real fire system is 7.16db; the phase angle margin is 56.9deg, and the system performance meets the design requirements

2.4.2. Water Bath Burning

In field applications, propane is sprayed from a fuel nozzle of a fuel gas path (injection pressure of 2.3 Bar) and then ignited by an ignition burner flame. This type of combustion causes some ablation at the fuel nozzle. As time accumulates, the degree of ablation gradually deepens, and under certain pressure there is a risk that the fuel nozzle will be damaged and fly out of injury. In order to avoid this danger, we have specially designed a water bath to burn. The specific process is as follows: the fuel gas path is arranged at the bottom of the water bath. When training, the water bath is first filled with water, and then the ignition burner is ignited. After the ignition is successful and the flame is stabilized (after the ignition is successful, the ignition controller will feedback the ignition success signal) Then open the valve corresponding to the fuel gas path. At this time, the propane gas emerges as a bubble from the opening of the fuel line and reaches the water surface, and is then ignited by the burner flame. As shown in Figure 5:

Figure 5. water bath burning

Since the water in the water bath does not exceed 100 ° C in the training room environment, and the fuel nozzle is not in contact with the fire, the water bath combustion mode effectively avoids the ablation of the fuel line by the high temperature generated by the propane combustion. We have calculated the fuel consumption in the case of water bath combustion and waterless bath combustion at different ambient temperatures, see Table 1.

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Table 1. Water bath combustion fuel consumption test statistics

NO	Temperature ℃	Pool size mm×mm	Water Injection Depth mm	Fuel consumption m^3	NO_X Mg/M^3
1	10	1800×500	300	2.23	122
2	10	1800×500	0	2.32	138
3	15	1800×500	300	2.55	132
4	15	1800×500	0	2.72	151
5	23	1800×500	300	2.82	167
6	23	1800×500	0	3.23	173

In order to prevent too many openings, the pore spacing is too large, so that propane can not be ignited by the burner flame in time and the stacking causes detonation. During the test, only 5 Φ3 round holes are opened in the fuel pipeline, the hole spacing is 150mm, and the training room is opened at the same time. ventilation system. In order to prevent high temperature damage to the water bath, each test time is 4 minutes. Fuel consumption is measured by a turbine flow meter.

Figure 6. Water bath burning test site map (left water bath, right water bath)

From the visual point of view, since the water in the water bath slows down the fuel injection speed, the flame is relatively flat when the water bath is burned, the flame height is low, and the fire area on the surface of the water bath is large. When there is no water to burn, the flame is strong when burning, the flame is high, and the fire area on the surface of the water bath is small. From the statistical data, the average volumetric consumption rate of the fuel in the water bath combustion is about 7.27% lower than the average fuel consumption rate in the waterless bath combustion, and the average NOx content is about 9.05% lower. It can be seen that the use of water bath combustion technology can reduce the ablation of the fuel nozzle, extend the service life of the equipment, and reduce the NOx emissions, which is more beneficial to the environment.

3. Conclusion

After the propane real fire combustion training system was put into use for a period of time, according to the fire department statistics, when the fuel servo valve opening degree is 100%, the average consumption rate of the water bath combustion technology is about 7.72% lower than that of the waterless bath combustion; when the fuel servo valve opening degree is used At 75%, the average consumption rate of the water bath combustion technology is about 6.74% lower than that of the anhydrous bath. When the fuel servo valve opening is 50%, the average consumption rate of the water bath combustion technology is about 6.23% lower than that of the anhydrous bath. It can be seen that the energy saving effect is obvious when the water bath is burned. When the water bath is burned, the fuel servo valve opening is kept constant. When the portable heat radiometer is used to measure the heat radiation value of the flame, it is also found that the fluctuation of the flame heat radiation value is not large. It can be seen that since the combustion is relatively stable, the heat release rate of the fuel is relatively average. However, some problems have also been exposed in actual use. The most important problem is that the saturated vapor pressure of propane changes with the change of ambient temperature. When the ambient temperature is high, the saturated vapor pressure of propane is relatively large, and the propane gasification amount is large. The combustion control efficiency is high and the combustion effect is good. When the ambient temperature is low, the propane gasification amount is low, the control efficiency is low, and the combustion effect is unsatisfactory. When the combustion control efficiency is low and the combustion effect is poor, the operator is often required to manually adjust the needle valve, which is inconvenient to use. The next step is to continue the on-site test to understand and master the control law of the propane combustion system at different ambient temperatures, and further improve from both hardware and software. In software, it is ready to use improved control algorithms to improve control accuracy at different temperatures. On the hardware, prepare a propane gas tank and add a vaporizer to reduce the effect of temperature on propane gasification efficiency.

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