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Experimental Studies on Fire for Offshore Structures and Its Limitations: A Review

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In past few decades a wide range of major accidents were reported due to oil & gas operation in offshore industry. Among of them hydrocarbon fire is the most frequently reported thread to offshore industry. It is an extremely costly and nearly impossible to conduct an experimental study on full scale offshore facilities under fire. But in order to understand the behaviour of fire and physically failure mode of structural member it is important to conduct an experimental study. For this purpose several studies focused just to understanding the behaviour of fire under expected fire scenarios. On the other hand, to maintain structure stability various structural members were tested under fire. In this review relevant studies will be presented to highlight and discuss the main studies based on experimental setup. Also the limitations of experimental studies will be highlighted in order to proposed comparison of experiment versus simulation. Although, simulation is considered to be the most economical and effect technique for modelling consequences before actual construction. It is recommended to validate simulation results obtained from computational fluid dynamics or nonlinear structural analysis which depends on the modelling techniques.

1. Introduction

Oil and gas industry is one of the most fragile industry due to involvement of heavy life and property risk. The highest risk is hydrocarbon fire and blast. Keeping this as a potential thread required careful considerations in designing structure, equipment layout or arrangement of the facilities to minimize the effects of these events. Despite of sophisticated technology and advance fire system accidents are still unrestrained. The great example of recent event is Deep water horizon in 10th April, 2010. The accident initiated with sudden explosion followed by uncontrolled hydrocarbon fire (Dadashzadeh et al., 2013). The incident caused world third largest oil spilled in oil and gas industry. Approximately five million barrel oil was spilled in gulf of Mexico due to failure of emergency shutdown valve as a result of sudden explosion and fire (Haidar., 2015). Hydrocarbon fires are extremely hazardous for offshore installations. They involve extreme heat flux which caused serious sever damage to not only for property but also human lives. Therefore, various studies focused on behaviour of fire under different scenarios. It was suggested to observe the complete effect of hydrocarbon fire through simulation (Kim et al., 2011), because limited factor can be considered during experimental study (Chatris et al., 2001). On the other hand, CFD based fire modelling and nonlinear structure analysis under fire require to validate through full scaled or scaled experiment setup.

Experimental studies have advantages as well as disadvantages. The advantages can be deal with the actual physical model with desired quantity. The measurement can be within the limits of experimental error and available facilities. Whereas, the disadvantages includes highly expensive, unrealistic compared to real model and time consuming. It is extremely costly and nearly impossible to conduct an experimental study on full scale platform. The analytical approach on the other hand is inexpensive and fast. The performance can be improved and examine before execution actual project. But in order to understand physically failure mode, it is important to conduct an experimental study. For this purpose previous studies

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focused on individual structural member under fire. It was also recommended to validate simulation results obtained from CFD simulations and nonlinear structural analysis because they are greatly depend on the modelling techniques (Paik and Czujko, 2011).

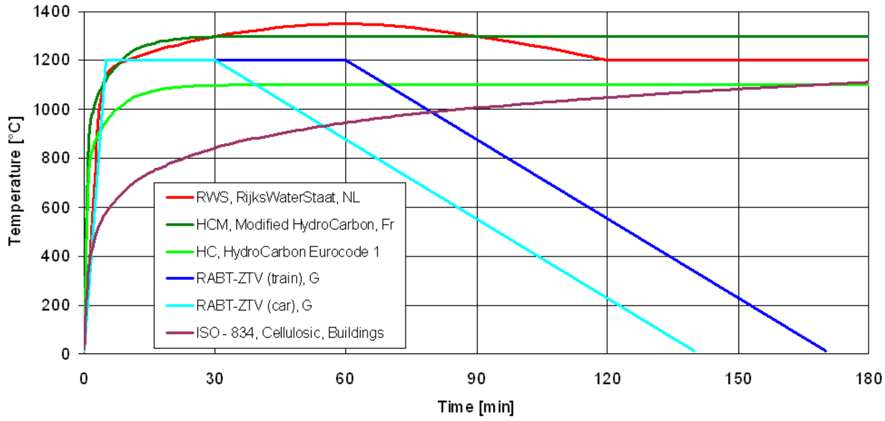

Figure 1: Cellulosic & Hydrocarbon Temperature vs Time Curve (Promat, 2014)

1.1 Study Objectives

- The main purpose of this review is to highlight the limitation of experimental study in order to analysis and understand the behaviour of fire and structural element under elevated temperature. In past studies due to the limitation of experimental setup only few parameters were selected in order to understanding the behaviour of fire and structural member using under various scenarios of fire.
- Secondly, in this paper previous studies were highlighted which were based on few selected parameters such as type of fire, wind effects, geometry of processing unit, intensity of heat and leak rate etc. To highlight the weakness and strength of predicted parameters this may or may not be present during accident.
- Finally the need of standard procedure for modelling and testing will be recommended at the end this paper based on past studies for further development in fire modelling and testing.

1.2 Types of Fire

Hydrocarbon is the organic compound that contained carbon and hydrogen only. They can explode through ignition as they mixed with an oxidiser (such as air). At that point when hydrocarbon molecules react due to temperature with an oxidizer spontaneous combustion with high pressure take place. They can cause fire or explosion by rapidly increasing in temperature and pressure (Jerzy and Paik, 2012).
There is always a highest chances of hydrocarbon fire on offshore platform due to presence of hydrocarbon gases on board depending upon the type of leakages. Hydrocarbon fire is more dangerous than natural fire or Cellulosic in which the temperature increment is slow compared to hydrocarbon fire (API, 2000). The temperature of Hydrocarbon fire is more severe. Hydrocarbon fire can reach up to 1,000 °C in few minutes after ignition whereas cellulosic can reach up to 600 °C as shown in Figure 1 (Promat, 2014). There are four major types of fire pool of fire, jet fire, flash fire and fireball (Pula et al., 2006) which will discuss further in details in section 2.

1.3 Behaviour of Structural Member under Fire

In order to reveal the steel behaviour under elevated-temperature and observed the response of mechanical properties of steel numerous experimental studies were conducted at various temperatures by different researchers (Wang and Davies, 2003). The elevated-temperature reduced axial forces (Zhang et al., 2013), elastic modulus or stiffness (Al-Jabri, 1999), yield strength (Ming Rui, 2006) and ultimate strengths of the steel (Qiang et al., 2013). The major causes of failure for any structural member are due to interruption of internal balancing force. Heat flux entirely responsible of this behaviour which is highly depends on structural steel grades. Experimental testing deals with the physical system with desired quantity to determine the limits of structural steel. Whereas, the experimental studies are highly expensive, unrealistic compared to real model and time consuming. Analytical approach on the other hand is inexpensive and fast, but have high chances of error. The performance can be improved by examine the stimulation and comparing with an experimental study before execution actual project.

2. Experimental Studies on Behaviour of Fire

There are various types of fire occurred in O&G industry depending upon nature of incident, such as pool of fire, jet fire, fire ball and fire flash etc. Pool fire is caused by high turbulence diffusion and burn above pool of vaporizing fuel Figure 2(a). The probability of pool of fire on offshore platform are high due to presence of hydrocarbon gases on board. They may release accidentally due to different processing operation on platform. The major cause of pool of fire is overflow of tanks, pipeline leakage, and ship collision accidentally (Pula et al., 2005). A jet fire is a high flame caused by combustion of fuel continuously Figure 2(b). Jet fire ignites immediately with high pressurised hydrocarbon gas. It possessed high risk caused significant life losses and damage to property (Zárate et al., 2014). Flash fire on the other hand, caused by ignition of highly flammable vapour cloud Figure 2(c). These formed due to sudden release of hydrocarbon gases or develop vapour cloud and suddenly blowout. The occurrence of fireballs in O&G industry is extremely common Figure 2(d) and can lead to sequence of disaster. Fireballs are caused by rapid combustion of hydrocarbon gases or fuel with high turbulence and expending radiant ball of fire. Despite of characterizing types of hydrocarbon fire it is essential to understand the behaviour fire under various conditions. The behaviour fire is highly dependent on type of leakage, fuel supply, congestion, and wind speed etc. In order to understand the behaviour of fire under different condition different experimental studies were conducted.

(a) (b) (c) (d)

Figure 2: Types of hydrocarbon fire (a) pool of fire (Paik et al. 2013), (b) jet fire, (c) flash fire (Promat, 2014) and (d) fireball (Paik et al. 2010)

Chatris et al. (2001) identified the effects of larger diameter of pool fire with 1.5 m, 3 m, and 4 m under natural wind condition. Experiments were involved two different types of fuels: gasoline and diesel oil. The results revealed that the influence of wind speed on burning rate was negligible up to 2 m/s, but it had a certain effect for the largest pool at a wind speed higher than 2 m/s (Chatris et al., 2001). This factor is important to consider for the high risk area on platform to avoid fire spread. Another study was conducted by Kim et al. (2011) on the effects of wind from heat source at FPSO topside structure. An experimental study was conducted under wind-tunnel & simulated using ANSYS CFD. It was observed that wind has a significant effect on the thermal-diffusion characteristics. In some case temperature tend to decreased whereas in other cases it tend to increase with the wind speed. The effects were highly dependent on the type of congestion and wind direction from heat source at FPSO processing area (Kim et al., 2011). Schalike et al. (2013) conducted experiments to understand the limits of the distances for merging flame of multiple pool fires. It was observed that merging distance of pool of fire is highly dependent on diameter of fire. The merging of hydrocarbon fuel started from 0.12H where ‘H’ is height of flame (Schälike et al., 2013). Ibrahim and Masri, (2001) focused on the interaction of the propagating flame front with various obstructions. Observed parameters were venting pressure, pressure-time history, effects of blockage ratio and obstruction, geometry. The outcome of the research was quite supportive in planning platform. For example as the blockage ratio increased maximum overpressure increased, meanwhile the venting pressure remains unchanged. Whereas, increase in maximum overpressure depends on the geometry of obstruction as well as its size (Ibrahim and Masri, 2001). To understand the behaviour obstruction further, Park et al. (2007) studied the behaviour of fire under different shapes of hindrance. The used shapes were circular, square, rectangle, and triangle. Experimental results have shown high turbulence with hindrance having edges compared to circular hindrance. The behaviour of fire varies with obstacles tested under local flame propagation speed during the interaction with different shape of hindrances. This local fire speed increase even becomes larger when passing from circular, triangular and square obstacle. The fastest increase in the averaged flame speed with time was observed for the rectangular plate. The study is quite supportive to arrange layout of platform (Park et al., 2007).

These discussed studies are limited according the test arrangement and availability of resources. There are several types of wind that can blow during fire accident with various intensities. Similarly, the shape, configuration and congestion cannot measure during experimental studies. It is highly recommended to focus on simulation by modelling actual platform with complete configuration of processing unit under various wind and leak rate for fuel in order to minimize the risk of hydrocarbon fire.

3. Experimental Studies for Structural Member under Fire

Offshore structure is made up of massive structural steel. Steel is an excellent heat conductor compared to concrete. The thermal characteristics of steel are the main factors affecting structural integrity in fire. The specific heat of steel varies with temperature. At temperatures above 400 °C assumed to be critical temperature as the mechanical properties of steel significantly decrease (HSE, 2007). The heat flux in previous studies assume to be uniform throughout the section that cause conservative design (Holmas and Amdah,(Bergan et al., 2005). They criticised the Myths of industrial steel that assume 400 °C critical. During nonlinear analysis author found 50 % of initial strength of steel at temperature of 600 °C whereas in old degradation curve it was assumed 20 % only which was no uniform (Bergan et al., 2005). There are several studies presented that deal with individual structural members using both experimental under various type of fire in past few decades. In order to ensure safety and stability of offshore platform individual structural members were tested and analysed before construction. Al-Jabri (1999) conducted an experimental study on steel beam-column connection under fire. The results revealed that steel beam-column connection under fire can effect both stiffness and strength of the connection (Al-Jabri, 1999). The strength can significantly reduce between the ranges of 400 °C - 600 °C. An experimental study was presented by Yuli et al. (2005) conducted test on loaded I-shaped steel girder under elevated temperature in furnace. It was observed that the temperature was not uniform though out the section despite of testing under uniform temperature (Yuli, 2005). The beam experiment data was used to validate different nonlinear structural analysis models (Kim et al., 2012). Normally it is often difficult to maintain uniform temperature throughout furnace (Paik et al., 2013). Similarly, during actual incidence distribution of temperature is not uniform which cause heavy part to lose its internal balance and cause heavy loses.

Yu et al. (2011) also tested steel tubular T-joint to compare with and without impact loading under elevated temperature. The results have shown that the joints were the weakest region under fire. Impact loading would cause serious effect depending upon the type of loading, but the effect is not significant (Yu et al., 2011). Jin et.al. (2011) later on simulated same steel tubular T-joint under using finite element program ABAQUS to overcome limitations of experiment and understand and validate the behaviour of joint and validate model with experimental study (Jin et al., 2011). Similarly, Kim et al. (2010) conducted a study on concrete and steel tubular member under elevated temperature (jet fire) to observe the fire load characteristics. The specimen was tested under jet fire with 100 % methane gas released with the flow rate of 10, 15 and 20 L/min. The observed temperature from steel tubular member was lower than from concrete tubular member. The behaviour resulted by transferring of heat energy by conduction, which gave a lower temperature distribution (Kim et al., 2010). Chen and Zhang, (2011) performed an experiment under pool of fire for mechanical behaviour of steel truss scaled structure. Result has revealed the balance of the internal force effected due to consequence of fire. The chances were high for upper story to fall on lower when temperature due to higher heat flux on loaded structure (Chen and Zhang, 2011). These effects highlight the need of fire analysis to maintained stability of structure during fire. Liu et al. (2010) conducted an experimental and numerical study for mechanical behaviour of two full-scale steel planar tubular trusses without any fire-proof coating under real fire conditions. The loading was applied gradually, and then fire was ignited. The specimens failed due the local buckling of the diagonal brace and necking phenomenon was observed in the bottom diagonal brace (Liu et al., 2010). The behaviour was verified through nonlinear FEM analysis (Jin et al., 2011). Scullion et al. (2011) tested elliptical shaped steel columns under hydrocarbon fire. Most common failure mode observed to be bulking failure due to load and elevated temperature (Scullion et al., 2011).

Qiang et al. (2012) focused on residual strength of the high strength structural steel. Results concluded that elevated-temperature cause reduction in elastic modulus, yield and ultimate strengths of steel. The results were obtained and compared with current design standards and available literature. The results also discovered that the design standards are not applicable to high strength structural steels. It was also testified that the deterioration of mechanical properties of structural steels at elevated temperature was highly dependent on steel grades (Qiang et al., 2012). Under uniform heat the loaded member bend as the temperature of steel increase as reported by different researchers. Therefore, it is important to identify the heat propagation within the steel member to improve stability and integrity of structural steel.

Careful considerations should be taken in designing of the structure, equipment layout or arrangement of the facilities to minimize the effects of mishaps (API, 2000). Hydrocarbon explosions and fires are extremely hazardous for offshore installations. They involve extreme explosion and heat flux, which have hazardous consequences for safety, health and the surrounding environment (Paik and Czujko, 2011). To observe complete effect of hydrocarbon fire simulation is best solution. However, it is also essential that fire modelling and nonlinear structure analysis should validate through full scaled or scaled experiment. But usually it requires high resources and advance facilities to conduct fire testing. These test are highly sophisticated and required special arrangement (Cļengel, 2007). The analytical approach on the other hand is inexpensive and fast. The performance can be improved and examine before execution actual project. Under various scenarios by keeping simulation and experimental studies parallel. Therefore it is suggested to conducted and experimental study with relevant modelling technique. As the results obtained from computational modelling could be totally wrong depending upon the modelling techniques (Kim et al., 2010).

4. Conclusions

The purpose of this review paper is to highlight the available major experimental studies on the behaviour of fire and structural member under elevated temperature at one podium. The limitations of experimental studies are examine in this paper to highlight the need of modelling parallel with experimental studies and vice versa for economical and safe design for offshore facilities. The following conclusions have been drawn from this review study:

- In most of the cases experimental study cannot predict the entire behaviour of the fire and behaviour of structural member under elevated temperature due to presence of various factors that are affecting the fire scenarios. Extensive studies were focused just to observe the wind effects, congestion ratio, heat flux and fire response, but results varies with different missing variables.
- It is revealed that the behaviour of fire depend upon the incident type leak rate, wind direction and available testing facility. Similarly, individual structural members that were tested under different fire condition or elevated temperature presented different results. The response differed due to steel type and mechanical properties. In general, the mechanical properties are highly affected under elevated temperature for most of the steel type ranges from 400 – 700 °C.
- The fire facilities are extremely limited due to testing setup limitation and size of testing furnaces. The individual structural element cannot represent the entire behaviour of structure under fire. Therefore, it is recommended to simulate fire scenarios using commercial software that can cover a wide range of parameters which is difficult to observe during experimental study. But a part of experimental study must be included for validating these results and increasing the confidence on modelling selected parameter.
- For future studies the structural behaviour should be conducted under standard fire condition such as hydrocarbon fire to form hydrocarbon curve. The behaviour of structure under hydrocarbon fire can be used to improve passive fire protection and maintaining structural stability under hydrocarbon fire

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