# Jet Fire Analysis of Highly Flammable Hydrocarbons Part I: High Pressure Natural Gas Transportation

Zekieni Robert Yelebe[1*] and Revelation Jacob Samuel[2]

1. Department of Chemical/Petroleum Engineering, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria
2. Department of Chemical Engineering, University College London, Torrington Place, WC1E 7JE

*Corresponding author: Phone: +2348035077979; E-mail: robert.yelebe@ndu.edu.ng

**Abstract**

This study is based on the analysis of predicted jet fire occurrence following the puncture or rupture of a high pressure natural gas pipeline. A case study of high pressure pipeline transporting natural gas at 8.9 MPa (89 bar) with pipeline diameter of 720 mm (0.72 m), and assumed puncture sizes of 0.1 m, 0.2 m and 0.3 m and a full bore rupture (FBR) are considered. The severity of a jet fire is dependent on the puncture size, flame length and its impingement on nearby equipment, accompanied heat fluxes and the distance between flame zone and target (humans/equipment). Research has shown that 6.3 kW/m$^2$ is the maximum bearable heat flux recommended for humans, buildings and other facilities. As such it is recommended that a safe distance be maintained between the pipeline facility and humans/equipment based on this bearable heat flux. Applying a modified Chamberlin's jet fire model, the results obtained from this analysis showed that for puncture sizes of 0.1 m, 0.2 m, 0.3 m and FBR, the minimum safe distances to receive 6.3 kW/m$^2$ heat radiations are 38.5 m, 60 m, 79.5 m and 95.5 m respectively. However, a highly busy major road with residential houses is 10 m away from our case study pipeline. Therefore, calculating the heat fluxes based on that distance for puncture sizes of 0.1 m, 0.2 m, 0.3 m and FBR. The results were 104.05 kW/m$^2$, 288.91 kW/m$^2$, 395.39 kW/m$^2$ and 593.09 kW/m$^2$ respectively.

**Keywords:** heat flux, jet fire, natural gas, pipeline, safe distance

## 1. Introduction

Nigeria has complex pipeline network within the country which transport crude oil, gas, condensate and other petroleum products from fields to flow stations to terminals and from refinery to depots and retail outlets. But sadly, the frequent occurrences of pipelines ruptures and explosions have cost the country so much fatalities and injuries, which indeed are preventable to some extent if proper research was done before the distribution of the pipeline network and understanding the jet fire effect of highly flammable hydrocarbons. The key motivation of this study is geared towards analysing and preventing the impact of accidental ruptures of natural gas high pressure pipelines by evaluating the length of the consequent jet released from pipe, initial release rate; heat radiating from the jet fire, volume of release etc.

Jet fires have been studied by a smaller number of authors probably due to the fact that they are smaller in size. They often occur in dense plants with compact layouts, and locally they can be very intense (Casal J et al. 2012). Jet fires bring about immense heat fluxes and if they were impinge on equipment such as a tank; they can create a catastrophic failure very quickly. "A turbulent diffusion flame resulting from the combustion of a fuel being released continuously with a significant momentum in a given direction is known as jet fire" (Snegirev & Frolov 2011). Source momentum and directionality gives the difference between a jet fire and other types of fire hazards such as pool fires (Casal Joaquim et al. 2012). An example is the pipeline ruptured by third party interference that caught fire in Lagos, Nigeria on December 2006 resulting in about 260 fatalities and another 700 people lost their life to an explosion in 2008 (History.com Editors 2009). San Juan Ixhuatepec company incident of 1984 in Mexico where a vapour cloud explosion occurred due to the release of flammable gas during maintenance leading to LPG jet fires in only 69sec when the first boiling liquid expanding vapour explosion (BLEVE) occurred (Pinhasi, Ullmann & Dayan 2007). The failure of the pressurized vessel was caused by a very short exposure time killing nearly 600 people. Therefore, jet fires are classified as high risk and hazardous incident.

In classifying jet fire as a hazard is important to understand that its occurrence;

- poses serious threat to human safety,
- can create a domino effect by impinging on surrounding equipment, causing a chain of explosions,

- causes damages to the environment worth millions of dollars,
- company halts operation and incurs losses and
- harms company reputation and prestige.

Jet fire modelling assists in carrying out a quantitative risk assessment by predicting the extent of the fire, the radiation emitted by the flame and the radiation received at a particular position. Calculating the safe distances for people and equipment when such an event occur helps with designing a new pipeline system or update an existing pipeline. Therefore, studying jet fire hazards and figuring out their basic parameters such as the flame radius, heat flux and its damage mechanism are of great significance for effective prediction of the failure risk of the natural gas pipeline, and effective protection for life and property (Zhang et al. 2014). Several semi-empirical models have been developed over the years to predict jet fires. However, most of them are designed for small scale jet fires involving natural gas and hydrogen (Tong et al. 2013).

Carsley (1995) developed a general model for the spatial probability distribution of a jet fire. The model was based on image analysis data of both large-and small-scale flame tests. It was shown that, for all the flames examined, the mean flame can be represented by a simple, two-parameter model. The spatial probability distribution for a flame has been built around the mean flame with the tail of the distribution along the flame centre-line. Cook et al (1997) also developed a numerical model capable of predicting the structure of, and heat transfer from, jet fires resulting from high pressure, sonic releases of natural gas. The accuracy of the model was assessed by comparing its predictions with experimental velocity data obtained in the near field, shock containing regions of such releases, and with observed flame lift-off heights. More recently, Youbo Huang et al (2017), You-bo Huang et al (2018) Tong et al (2013) and Zhou (2018) conducted jet fire related works. Youbo Huang et al (2017), You-bo Huang et al (2018) conducted experiments on temperature distribution during jet release while Tong et al (2013) and Zhou (2018) modelled the jet release and analysis of fire consequence using a MATLAB aided jet fire flow model.

This study is very critical and important with regard to the safety and risks associated with the operation of high pressure natural gas and their proximity to human settlements and other facilities such as roads and rail networks. In the case of pipeline failures it become imperative to predict precise safe distances from the rupture point based on the recommended maximum heat flux of 6.3 kW/m$^2$ humans and buildings can bear while steel structures can bear up to 35 kW/m$^2$. This study is of great importance as it provides the reader with required safety knowledge and accurate risks assessment in the case of high pressure natural gas pipeline failure and its associated jet fire when ignited. The study demonstrates an application of a jet fire model to a real life natural gas pipeline along Tombia – Amassoma road, Bayelsa State, Nigeria.

## 2. Development of mathematical model

Figure 1 gives the flame shape that best describes a jet fire as proposed by (Chamberlain 1987). Where $L_b$, $b$, $R_L$, $R_w$, $W$, $\alpha$, and $\theta$ represent flame length, jet lift-off, length of frustum, ratio between exit jet and wind speed, jet diameter (width of frustum), angle between the axis of the hole and the axis of the flame, and angle between the hole axis and the wind axis respectively.

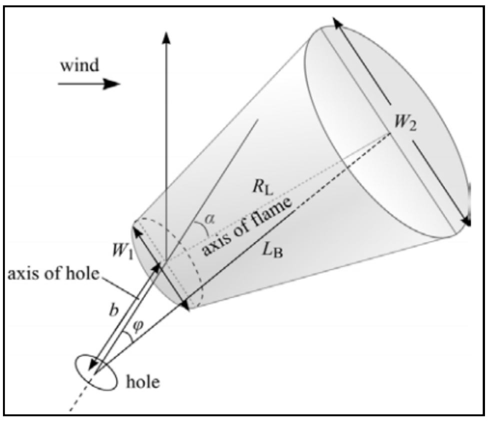


Figure. 1: Flame shape represented as a frustum (Chamberlain 1987)

We begin by calculating the mass flow rate q for the studied leak sizes using.

$$q = \sqrt{\frac{AMP}{2RT} \mathrm{X} \frac{K}{K-1}\left[\left(\frac{P_{atm}}{P}\right)^{2/K} - \left(\frac{P_{atm}}{P}\right)^{K+1/K}\right]} \tag{1}$$

where
$q$ is the flow rate of gas leakage in kg/s.
$A$ is the area of the frustum in $m^2$.
$M$ is the molecular weight of gas in kg/mol (usually 0.016 kg/mol for $CH_4$)
$R$ is the gas constant (8.314 J/mol).
$T$ is the temperature of the gas inside the pipeline in $^{o}K$.
$K$ is the adiabatic index or the ratio of the isobaric specific heat capacity to the volumetric specific heat capacity (1.28 for natural gas).
$P_{atm}$ is the atmospheric pressure.
$P$ is the pressure inside the gas pipeline in Pa

The flame length is calculated using Chamberlain's model (Chamberlain 1987).

$$L_b = L_{bo}\left(0.51e^{-0.4u_j} + 0.49\right)[1 - 0.00607(\theta - 90)] \tag{2}$$

The length of the jet flame in still air ($L_{bo}$) is calculated using;

$$L_{bo} = 6.73\, Re^{0.27} \mathrm{x}\, d \tag{3}$$

where
$d$ is orifice exit diameter (puncture size) = 0.1m
$Re$ is the Reynold's number which is given as;
$Re = \rho ud/\mu$
$\rho$ is density of natural gas = 0.68kg/$m^2$
$v$ is velocity of natural gas which is given as $q/A$
$\mu$ is viscosity of natural gas = 0.1083x$10^{-4}$

The jet lift-off is calculated in m using;

$$b = L_b \frac{\sin \kappa\alpha}{\sin \alpha} \tag{4}$$

where $\kappa = (0.185 \text{ x } e^{-20R_L}) + 0.015$ is a factor relative to the wind.

The length of the frustum $R_L$ is calculated in m, using Richardson correlation (Yang & Renken 2003)

$$R_L = \sqrt{L_b^2 - b_l^2(\sin^2\alpha)} - b_l \cos\alpha \tag{5}$$

Also, the frustum widths $W_1$ and $W_2$ can be calculated using;

$$W_1 = D_s(13.5e^{-6R_w} + 0.31)\left[1 - 0.93\sqrt{\frac{\rho_{air}}{\rho_j}}\right]^{e^{-7.5R_w}} \tag{6}$$

$$W_2 = L_b(0.18e^{-1.5R_w} + 0.31)(1 - 0.47e^{-25R_w}) \tag{7}$$

Then the area of the frustum is calculated in $m^2$ using

$$A = \frac{\pi}{4}(W_1^2 + W_2^2) + \frac{\pi}{2}(W_1 + W_2)\sqrt{R_L^2 + \left(\frac{W_2 - W_1}{2}\right)^2} \tag{8}$$

The surface emissive power (SEP) of the let flame is calculated in kW using:

$$SEP = \frac{F_s Q}{4} \tag{9}$$

where
$F_s = 0.21e^{-0.00323u_j}$(Fraction of heat radiated)
$Q$ = Total net power released in kW

The atmospheric transmissivity $\tau$ depends on absorption by carbon dioxide and water vapour in the intervening path between flame surface and receiver point. The transmissivity for hydrocarbon fires is expressed through the following equation.

$$1.006 - 0.01171 log_{10}X(H_2O) - 0.02368\left(log_{10}X(H_2O)\right)^2 - 0.03188 log_{10}X(CO_2) + 0.001164\left(log_{10}X(CO_2)\right)^2 = \tau \quad (10)$$

where
$X(H_2O) = R_H P_L S_{wp}\left(\frac{288.65}{T_{air}}\right)$
$X(CO_2) = P_L\left(\frac{273}{T_{air}}\right)$
$R_H$ = Relative humidity expressed as a fraction
$P_L$ = Path length through the atmosphere
$S_{wp}$ = Saturated water pressure in mmHg at the ambient temperature in K
As can be seen in Figure 2, the View Factor (VF) is obtained by using below formula:

$$VF = \iint_{R_s} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 \quad (11)$$

where
$R_s$ = Visible section of flame surface $A_1$ by receiver at surface $A_2$
$r$ = Distance along a line from surface $A_2$ and differential element $A_1$ of the flame
$\theta_1$= the angle between the local normal to the surface at $A_1$ and the line
$\theta_2$= the angle between the normal to $A_2$ and the line.

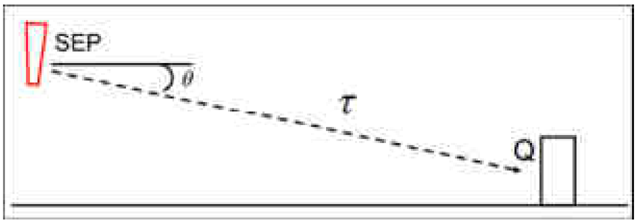


Figure 2: Heat radiated at a particular distance

Finally the heat radiation q, from the flame is calculated in kW/m$^2$ using:

$$q = SEP \times VF \times \tau \quad (12)$$

Once the heat radiated is obtained, a relationship between the heat radiations can be used to determine the minimum safety distance for people assuming that they can withstand 6.3kW/m$^2$, and the minimum safety distance for equipment to avoid impingement assuming steel structures can withstand 35kW/m$^2$.

## 3. Results and discussion

This study considers a case of high pressure natural gas pipeline with an operating pressure of 8.9 MPa (89 bar), pipeline diameter of 720 mm (0.72 m), and estimated puncture sizes of 0.1 m, 0.2 m and 0.3 m and a full bore rupture (FBR). Using the above data the outflow rate and flame length is calculated first following the outlined puncture sizes and full bore rupture. Due to the complexity of the calculation process, the jet fire consequence was calculated by the computer-assisted program (MATLAB). MATLAB being a high-level language and interactive environment for numerical computation, visualization, and programming was applied to compute the calculation and simulation. The calculation and simulation of the jet fire consequence results for the natural gas pipeline is demonstrated in this paper as discussed below.

Table 1: Calculated key parameters for the studied puncture sizes

| Puncture sizes (m) | Flame length (m) | Outflow rate (kg/s) |
|---|---|---|
| 0.1 | 12.19 | 13.07 |
| 0.2 | 29.68 | 52.28 |
| 0.3 | 47.88 | 105.35 |
| FBR | 73.04 | 215.86 |

Table 1 shows the flame length and outflow rate based on for the selected puncture sizes. The results obtained show that with increasing puncture size there is a corresponding increase in both flame length and outflow rate. Significantly, the case of full bore rupture the flame was about 73.04 m high and the outflow rate was massive 215 kg/s signalling a huge loss of inventory per second and a giant flame of jet fire.

Table 2: Calculated minimum safe distances for humans and steel structures

| Puncture sizes (m) | Minimum safe distance for humans (m) | Minimum safe distance for steel structures (m) |
|---|---|---|
| 0.1 | 38.5 | 17.5 |
| 0.2 | 60 | 24 |
| 0.3 | 79.5 | 33.5 |
| FBR | 95.5 | 39 |

Table 2 shows the calculated results for minimum safe distances for humans and steel structures. As established earlier, the minimum safe distances for humans and steel structures are 6.3 $kW/m^2$ and 35 $kW/m^2$ respectively. From the results presented in Table 2 showed that for puncture sizes of 0.1 m, 0.2 m, 0.3 m and FBR, the minimum safe distances for humans were 38.5 m, 60 m, 79.5 m and 95.5 m respectively. Whereas that for steel structures are 17.5 m, 24 m, 33.5 m and 39 m respectively. This means that any humans and structures with 15 m to the rupture point is in imminent danger of receiving very high heat flux beyond their recommended safe quantity. Thus, the considered case study natural gas pipeline is a hazard and catastrophic waiting to happen。

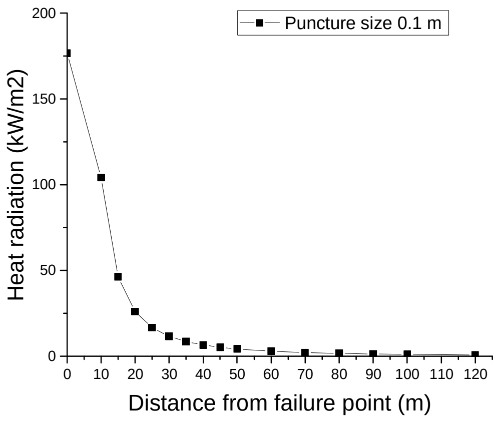


Figure 3: Jet fire heat radiation with distance for 0.1 m puncture diameter

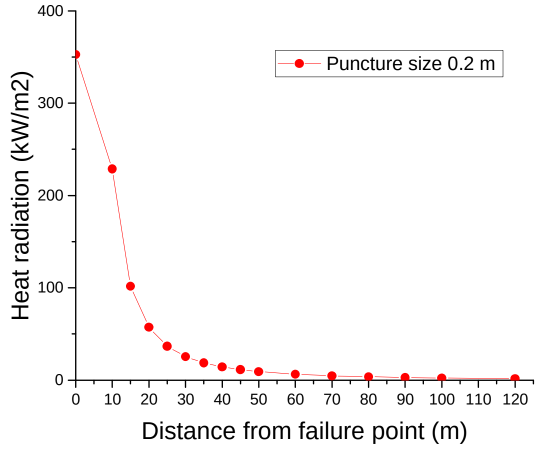


Figure 4: Jet fire heat radiation with distance for 0.2 m puncture diameter

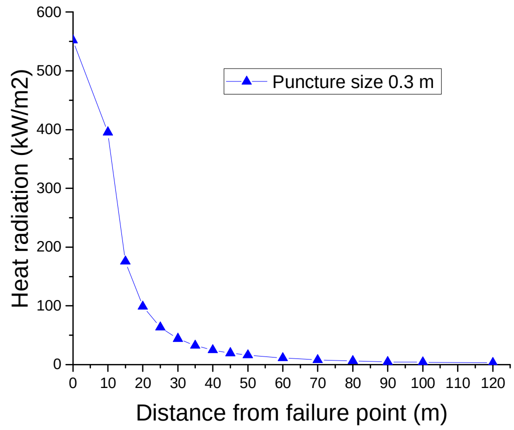


Figure 5: Jet fire heat radiation with distance for 0.3 m puncture diameter

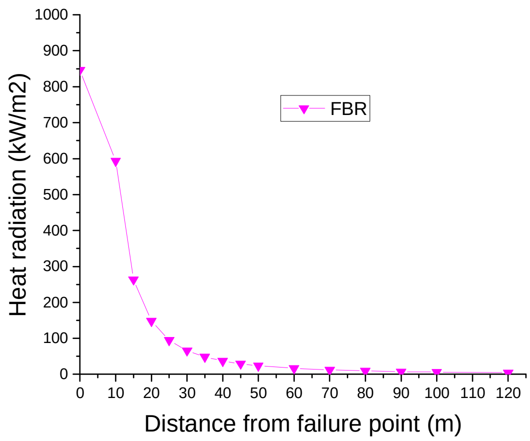


Figure 6: Jet fire heat radiation with distance for FBR

Figures 3 to 6 show the heat radiation or heat flux variation with distance from failure point for the considered punctures sizes 0.1 m, 0.2 m, 0.3 m and FBR respectively. The result is highly significant because considering that there is a major road is just 10 m away from the proposed point of puncture or rupture. Following a 10 m distance from the puncture point the heat fluxes received were 104.05 kW/m$^2$, 288.91 kW/m$^2$, 395.39 kW/m$^2$ and 593.09 kW/m$^2$ respectively for 0.1 m, 0.2 m, 0.3 m and FBR. This shows a possible devastating impact on nearby human settlements and other equipment within reach. As such it is strongly recommended that proper safety procedures are followed and the above safe distances be adhere to strictly.

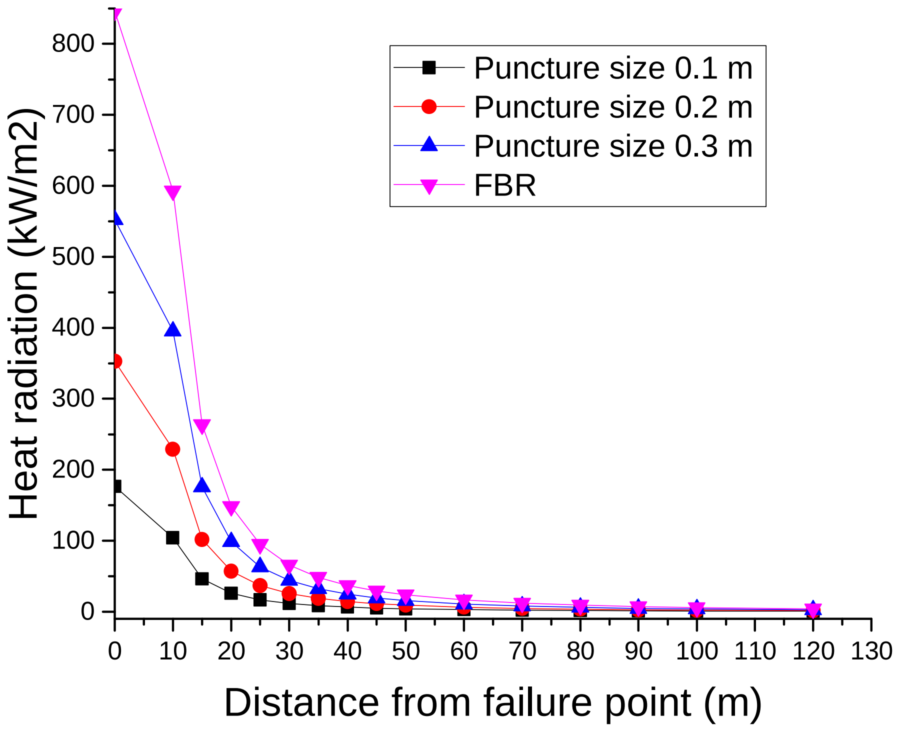


Figure 7: Jet fire heat radiations with distance for all puncture diameters and FBR

Figure 7 demonstrates a combination of all four cases and significant changes in the safe distances as the heat flux increases with puncture diameter. In other words, the FBR cases poses a greater threat of higher heat flux released to the surrounding environment. Consequently, higher rate of fatalities and property damage will be inevitable should a 593.09 kW/m$^2$ heat flux released from a FBR situation finally impinges on highly populated area. The predicted heat releases shows the need careful and safe operational procedures such that the minimum safe distance rule is enforced.

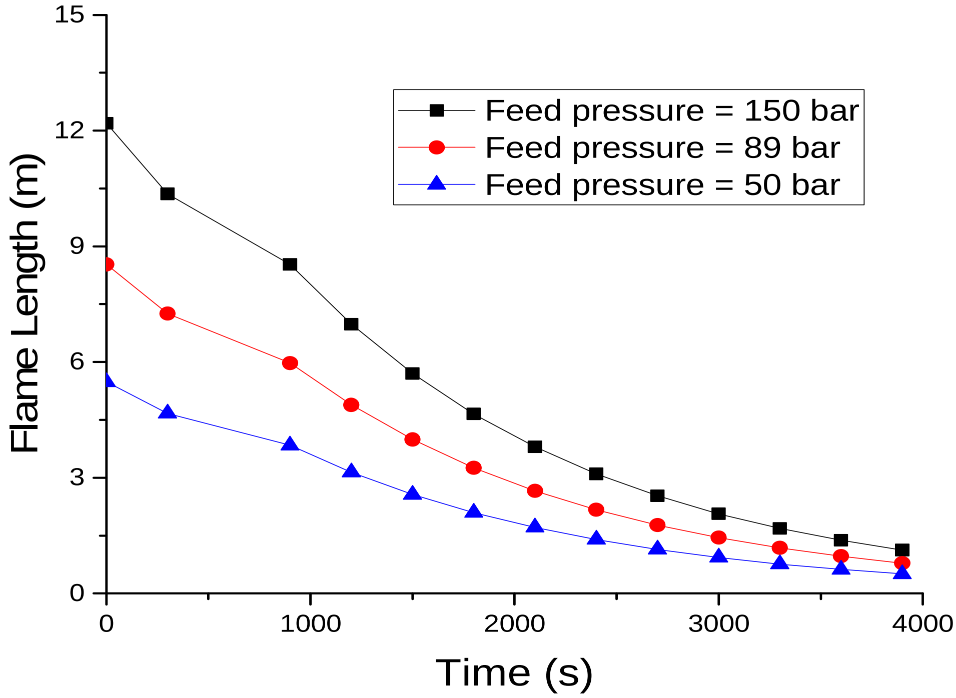


Figure 8: Jet fire flame length with time at varying feed pressure

Figure 8 shows the flame length in still air with time at varying pipeline pressure conditions. High feed pressure of 150 bar predicted a higher flame whereas low feed pressure of 50 bar predicted a lower flame compared with the base case of 89 bar. In all cases the flame length decreases with time and stabilises slowly. Notably, the flame length in still air as can be seen in Figure 8 is directly proportional to the heat radiation received by an object from a particular distance. The higher the flame from the jet the higher the heat radiation the receiving object receives.

Table 3: Calculated flame length for the studied puncture sizes with varying wind speed

| **Puncture sizes (m)** | **Flame length at varying wind speed (m)** | | | |
|---|---|---|---|---|
| | **Wind speed (1 m/s)** | **Wind speed (3 m/s)** | **Wind speed (5 m/s)** | **Wind speed (7 m/s)** |
| 0.1 | 12.19 | 10.07 | 8.57 | 7.02 |
| 0.2 | 29.68 | 25.28 | 22.64 | 20.22 |
| 0.3 | 47.88 | 38.35 | 35.03 | 32.12 |
| FBR | 73.04 | 60.86 | 58.62 | 55.27 |

Table 3 shows the effect of varying wind speed on the length of the jet flame. A significant wind effect on the flame length was predicted, as can be seen in Table 3 the flame length decreases with increasing wind speed. For instance, considering the case of 0.1 m puncture diameter the flame length was 12.19 m for the base 1 m/s wind speed but as the wind speed increases from 1 to 7 m/s the flame decreases significantly to 7.02 m.

 

## 4. Conclusions

In conclusion, this study is very critical to the assessment of safety and risks associated with operation of high pressure natural gas pipelines and their proximity to human settlements and other facilities such as roads and rail networks. Considering cases of such pipeline failures is imperative to predicting the possible outcomes and precise safe distances from the rupture point. The study was conducted based on the recommended maximum heat radiation of 6.3 kW/m$^2$ and 35 kW/m$^2$ that humans and steel structures can withstand respectively. This study is of great importance as it provides the reader with required safety knowledge and accurate risks assessment in the case of high pressure natural gas pipeline failure and its associated jet fire when ignited.

This study was based on the analysis of jet fires that occur during puncture or rupture of pipelines transporting natural gas at high pressures. A case study of high pressure natural gas pipeline along the Tombia – Amassoma road with an operating pressure of 8.9 MPa (89 bar), pipeline diameter of 720 mm (0.72 m), and puncture sizes of 0.1 m, 0.2 m and 0.3 m and a full bore rupture (FBR) was considered. The severity of jet fires from natural gas pipeline as shown in the predicted results is dependent on the orifice exit diameter (puncture size), and the presence of an ignition source. This severity is also dependent on the flame length and its impingement on nearby equipment, accompanied heat fluxes and the distance between flame zone and target (humans/equipment). Notably, 6.3 kW/m$^2$ is the maximum bearable heat flux recommended for humans, buildings and other facilities. Hence, it is recommended that such a minimum safe distance is maintained between the pipeline facility and humans/equipment based on the bearable heat radiation. The results obtained from the study showed that for puncture sizes of 0.1 m, 0.2 m, 0.3 m and FBR, the minimum safe distances from receiving 6.3 kW/m$^2$ heat radiations are 38.5 m, 60 m, 79.5 m and 95.5 m respectively. However, a highly busy major road with residential houses is 10 m away from our case study pipeline. Therefore, calculating the heat fluxes received by a person 10 m away from the release point for puncture sizes of 0.1 m, 0.2 m, 0.3 m and FBR, the results was 104.05 kW/m$^2$, 288.91 kW/m$^2$, 395.39 kW/m$^2$ and 593.09 kW/m$^2$ respectively.

Finally, it is critically important to bear in mind that the above conclusions are not universal. On the contrary, they are only based on the case study investigated. Each pipeline scenario must be individually examined in order to determine the likely risks. In this project, the necessary computational tool is developed to make such risks assessment.

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**Engr. (Dr) Zekieni Robert Yelebe** was born in Yenagoa, Bayelsa State, Nigeria. Prof Yelebe obtained his Chemical Engineering B.Tech in 2000, M.Tech in 2004, and PhD in 2010 from the Rivers State University of Science and Technology, Port Harcourt.

Dr Yelebe is an Associate Professor and has held various positions including Deputy Rector, Federal Polytechnic Ekowe, Bayelsa State, HOD Chemical and Petroleum Engineering and currently Sub-Dean (Postgraduate studies), Faculty of Engineering, Niger Delta University, Bayelsa State.

Dr Yelebe is an expert in Enzyme and Bio-reaction Engineering and has conducted outstanding researches in fermentation, bioremediation and biodegradation. He also teaches Advanced Modelling and Simulation and Advanced Heat Transfer. Engr. Yelebe is a registered Engineer of the Council for the regulationn of Engineers in Nigeria (COREN). He has over twenty-five publications in various reputable journals.

**Revelation Jacob Samuel** was born in Nembe, Bayelsa State, Nigeria. Mr Samuel obtained an outstanding first degree (B.Eng) in Chemical Engineering from Niger Delta University, Nigeria in 2009 and M.Sc. in Chemical Process Engineering from UCL in 2013 after securing a fully funded scholarship award in 2012 from Shell Nigeria. He joined UCL Chemical Engineering department in 2015 as a Postgraduate Researcher after securing a fully funded scholarship award in 2014 from the Nigerian Government.
His main research areas include multiphase flow modelling, pipeline safety and risk management and Carbon Capture and Sequestration (CCS) supervised by Prof. Haroun Mahgerefteh.

Mr Samuel is a member of the Institute of Chemical Engineers (IChemE) and has over ten publications in various journals.