PARAMETRIC AND THERMAL ANALYSIS OF HORIZONTAL JET FLAMES

NUR SHAHIDAH BINTI AB AZIZ

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

First and foremost, this thesis is dedicated to my father, who taught me that the best kind of knowledge is that which is learned for its own sake, and to my mother who taught me that even the largest task can be accomplished if it is done one step at a time. More than anything else, this thesis is dedicated to my husband who has inspired me all the way and my children who patiently wait to the end.

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ABSTRACT

Jet fire occurrence in an industrial installation can be severe as it can trigger a series of related events. The main hazard associated with jet fire occurrence is the heat released by radiation, which can be very high at a very short distance. The evaluation of jet flame geometry could assist the safety officer to prevent flame impingement on the nearby equipment and therefore, reduce the inventory losses and structural collapse. Previous observation indicates that the horizontal jet fire poses more significant thermal hazards as compared to that of other types of fire. However, to date, scarce and limited data are available as a reference on a jet flame for horizontal orientation, particularly for parametric characteristics and correlation model development. Thus, this study aims to investigate the thermal radiation and geometrical flame features of buoyant horizontal jet fires. Two scenarios were considered for this work i.e. free jet fires and jet fire impingement. This study used propane as the fuel that was released from a circular nozzle with a diameter of 7.15 mm and 9.8 mm. The jet fire tests were performed with different ranges of flow rates between 30 – 600 g/min at a release distance of 0.8 m and 1.2 m. Differences in flame shapes are evaluated with the use of the MATLAB. Meanwhile, linear correlations of the main geometrical parameters of interest are determined as a function of Reynolds number and Froude number (i.e. lift-off distance, projected flame length, flame height, flame trajectory, flame width). For thermal radiation analysis measurement, semi-empirical model prediction of the line-source (LSM) model was adopted to account the flame geometrical features. From the findings, it was found that the lift-off length, L_f estimation from this work was in a good agreement with Bradley's correlation for both free and impinging jet release with R^2 of 0.95. Due to the flame Froude number value is between 0.8 to 3.5, it signifies that the flame is controlled by buoyancy and momentum, thus flame trajectory, L_t was proposed to be used to estimate the radiant heat release. Using the flame trajectory, L_t for radiant heat estimation, it was observed that L_t could give a better prediction of radiant heat release for free jet fire release with R^2 of 0.99 as compared to projected flame length, L_p (horizontal kite flame shape) (R^2 = 0.94). It also gave consistent results with the measured data for an impinging jet release with R^2=0.99 for all release scenario, using a similar approach. It can be deduced that the modified LSM using the flame trajectory parameter is a reliable method for radiant heat prediction, on both scenario in this work; free jet release and impinging jet. Implicitly, it can be suggested that the applicability of LSM becomes wider to include the effects of buoyancy and impingement scenario. Furthermore, it offers additional provision to determine the minimum spacing distance of the equipment sitting for the plant layout.

ABSTRAK

Kejadian kebakaran jet yang berlaku di industri boleh menjadi parah di mana ia boleh mencetuskan satu siri peristiwa yang berkaitan. Kesan bahaya utama yang berkaitan dengan kejadian kebakaran jet adalah haba yang dilepaskan secara radiasi, boleh terjadi sangat tinggi pada jarak yang sangat dekat. Penilaian terhadap geometri api jet dapat membantu pegawai keselamatan untuk mencegah api hentaman pada peralatan yang berdekatan dan seterusnya dapat mengurangkan kerugian inventori dan keruntuhan struktur. Menurut pemerhatian masa lepas, didapati kebakaran jet secara melintang adalah lebih bahaya secara termal berbanding dengan kebakaran jenis lain. Walau bagaimanapun, sehingga kini, terdapat keterbatasan data bagi kebakaran jet secara melintang terutamanya yang berkaitan ciri-ciri parametrik dan pembangunan model perhubungan (korilasi). Justeru, kajian ini dijalankan untuk mengkaji termal radiasi dan geometri ciri nyalaan bagi kebakaran jet secara melintang. Dua senario telah dipertimbangkan dalam kajian ini iaitu kebakaran bebas dan kebakaran jet secara hentaman. Kajian ini menggunakan propana sebagai bahan bakar yang dilepaskan dari muncung bulat dengan diameter 7.15 mm dan 9.8 mm. Ujikaji kebakaran jet dilakukan dengan halaju yang berbeza antara 30 - 600 g/min pada jarak pelepasan 0.8 m dan 1.2 m. Perbezaan bentuk nyalaan api yang terhasil telah dinilai dengan penggunaan perisian MATLAB. Sementara itu, korelasi linear bagi parameter utama geometri telah ditentukan sebagai fungsi nombor Reynolds dan nombor Froude (iaitu jarak angkat, unjuran panjang nyalaan, ketinggian api, panjang lintasan api, lebar nyalaan api). Bagi pengukuran analisis haba radiasi, ramalan model separa empirikal bagi model sumber garis (LSM) telah diterima pakai untuk mengambil kira ciri geometri nyalaan. Daripada hasil penemuan itu, didapati jarak panjang pengangkatan, L_f dari kajian ini sangat sesuai menggunakan korelasi Bradley untuk kedua-dua pelepasan jet bebas dan hentaman jet dengan nilai R^2 bersamaan 0.95. Oleh kerana nilai nombor Froude antara 0.8 ke 3.5, ia menandakan nyalaan api dikawal oleh daya apungan dan momentum, dengan itu lintasan api, L_t dicadangkan untuk digunakan untuk menganggarkan haba radiasi. Daripada menggunakan unjuran panjang nyalaan, L_p untuk perkiraan haba radiasi, panjang lintasan api, L_t telah digunakan. Diperhatikan L_t dapat memberikan ramalan yang lebih baik mengenai pelepasan haba radiasi bagi pelepasan kebakaran jet bebas dengan R^2 bersamaan 0.99 dibandingkan jika menggunakan unjuran panjang nyalaan (bentuk layang-layang mendatar) (R^2 = 0.94). Ia juga memberi kesepakatan yang baik untuk pelepasan jet secara hentaman, dengan R^2 bersamaan 0.99 bagi kesemua senario, menggunakan kaedah yang sama. Secara ringkasnya, LSM yang diubah berdasarkan panjang lintasan api adalah kaedah yang lebih jitu untuk ramalan haba radiasi bagi kedua-dua senario di dalam kajian ini, pelepasan jet bebas dan pelepasan kebakaran jet secara hentaman. Hasil kajian ini telah memberi lebih keyakinan bagi penerapan LSM menjadi lebih luas dengan mempertimbangkan kesan keapungan. Selain itu, ia dapat menjadi ketentuan tambahan untuk menentukan jarak minimum peralatan di dalam susun atur loji.

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LIST OF SYMBOLS

A	-	Area (m^2)
$b(b_0)$	-	(Maximum) flame radius
$b*$	-	Actual flame radius corrected for the temperature effect [m]
c	-	Constant with a dimension of time
C	-	Constant
c_p	-	Heat capacity
D	-	Nozzle to object separation distance(m)
d	-	Diameter (mm)
D_f	-	Visible flame height (free burning, without the ceiling)
E	-	Total emissive power
E'	-	Emissivity power per line length
f	-	Ratio of fuel to air moles in the fuel-air mixture
Fr	-	Froude number
Frf	-	Flame Froude number
g'	-	Driving force owing to gravity [$m.s^{-2}$]
g	-	Gravity force, 9.81 m/s^2
H	-	Net calorific value of the fuel (kj/kg)
Hp	-	Projected flame height
H_c	-	Heat of combustion
k_g	-	Thermal conductivity,
K	-	Karlovitz stretch factor
L	-	Length
L_0^*	-	Non-dimensional flame height of upward jet fire
L_s^*	-	Non-dimensional flame trajectory length
L_b	-	Buoyancy characteristic length
L_f	-	Lift-off length
L_m	-	Momentum characteristic length
L_p	-	Projected flame length
Lt	-	Trajectory length
M_0	-	Source momentum

$\dot{m}$	-	Mass flowrate (kg/s)
(n_x, n_y, n_z)	-	Target surface normal orientation
P_0	-	Internal pressure
P_{out}	-	Pressure downstream of jet exit
Pr	-	Prandtl number
$\dot{Q}$	-	Heat release rate (HRR)
Q^*	-	Dimensionless heat release rate, $\dot{Q}^* = \frac{Q}{c_p \rho_\infty T_\infty \sqrt{gd^5}}$
Q_H^{**}	-	Dimensionless heat release rate of impinging jet
Q_R	-	Radiant heat release
Q_T	-	The total heat release rate
r_f	-	Radial flame extension length beneath the ceiling
Re	-	Reynolds number
Re_L	-	Reynolds number based on S_L and d
s	-	Coordinate of the trajectory (m)
S	-	Distance of the target to any point of the flame centreline
S_e	-	Sensitivity
S_L	-	Maximum laminar burning velocity of fuel-air mixture
S_t	-	Local burning velocity
T	-	Temperature
T_s	-	Surface temperature
$\Delta\bar{T}_{f,a}$	-	Adiabatic flame temperature of the fuel (K)
ΔT	-	Temperature difference between the flame and ambient air
T_∞	-	Ambient temperature
u	-	Velocity (m/s)
u_e	-	Exit velocity (m/s)
$\bar{u}$	-	Local flow velocity
U^*	-	Dimensionless flow number, $U^* = (u_e/S_L)Re^{-n}(\rho_e/\rho_\infty)$
U^{**}	-	Dimensionless flow number, $U^{**} = \frac{u_e}{S_L} Re_L^{-0.4} \frac{d}{D}$
U_s	-	Small voltage
υ	-	Kinematic viscosity
V	-	View factor

V_{fu}	-	Flame volume portion intercepted by the impinging surface in (m^3)
V_f	-	Volume of the free flame (m^3)
W	-	Width
w	-	Flame width
w_0	-	Maximum flame width
x_R	-	Radiative fraction
(x,y,z)	-	Coordinate
(x_0, y_0, z_0)	-	Target coordinate position
Z_0	-	Virtual origin
α	-	Flame ratio
α_1, α_2	-	Coefficients
ε	-	Emissivity
σ	-	Stefan-Boltzmann constant
κ	-	Parameter constant
η	-	Parameter constant
γ	-	Ratio of specific heats
τ	-	Transmissivity
β	-	Proportionality constant
θ	-	Angle (°)
ϕ	-	Angle of target and any point on the flame centreline
ϕ	-	Heat flux measurement
μ	-	Dynamic viscosity (kg/m.s)
$\overline{\rho}$	-	Density ratio (ρ_0/ρ_∞)
ρ_∞	-	Ambient density
ρ	-	Density (kg/m^3)
Λ	-	Dimensionless number (L_m/L_b)
Π_1	-	Dimensionless integer, $\frac{u_e}{S_L}$
Π_2	-	Dimensionless integer, Re_L
Π_3	-	Dimensionless integer,$\frac{d}{D}$

LIST OF ABBREVIATIONS

ARIA	-	Accident Analysis, Research and Information
BLEVE	-	Boiling Liquid Expanding Vapor Explosion
CMOS	-	Complementary Metal Oxide Semiconductor
ED	-	Extra-low Dispersion
fps	-	Frames Per Second
FACTS	-	Failure and Accidents Technical Information System
HRR	-	Heat Release Rate
JFF	-	Jet Fire Free
JFI	-	Jet Fire Impingement
LSM	-	Line Source Model
MAPE	-	Mean Absolute Percentage Error
MARS	-	Major Accident Reporting System
MPSM	-	Multipoint Source Model
MHIDAS	-	Major Hazard Incidents Data Service
RGB	-	Red, Green Blue
RH	-	Relative Humidity
PSM	-	Point Source Model
SFM	-	Solid Flame Model
SLPM	-	Standard Litre Per Minute

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Any industrial facilities that dealt with pressurized pipelines and vessels are exposed to an unwanted incident called a jet fire. Jet fire is a form of diffusion flame resulting from a release of combustible materials from an opening at very high pressure, usually greater than 1.9 bar absolute (Palacios, 2011). In process industries, jet fires are frequently reported as a primary vector leading to domino effects that would lead to mass casualties and asset integrity (Wang et al., 2021; Casal, 2018). The main hazards that come from the jet fire are thermal radiation and jet flame impingement (Swuste et al., 2019). The high momentum release of jet fire entrains a large amount of air and produces much better combustion than in other accidental fires. This will significantly increase the heat release rate in terms of radiation. According to Pula *et al.* (2006), horizontal jet fire is more destructive than vertical due to higher impingement probability and since there is limited data available on horizontal jet flames, thus it has been a focus in this study.

Several methods can be used to predict the main hazards associated with jet fire i.e. simulation, experimental data and semi-empirical model. To date, the development of the semi-empirical models is widely used by the industry in risk assessment associated with fire occurrence as it is easily programmed in the computer which the repetitive calculation can be done in a short time and economical with a reliable prediction. Furthermore, it provides an additional advantage in conducting massive measurement and risk prediction based on theoretical principles and experimental observation.

At present, four semi-empirical models could be adopted to predict the radiant heat flux based on the geometrical flame features which are solid flame model (SFM), point source model (PSM), weighted multipoint source model (MPSM) (Hankinson and Lowesmith, 2012), and line source model (LSM) (Zhou and Jiang, 2016; Zhou et al., 2016). To have a better prediction of radiant heat release by using a semi-empirical model, a true definition of geometrical flame features is very important (Palacios et al., 2012; Mashhadimoslem et al., 2020; Palacios et al., 2020). For a horizontal jet flame, the involved parameters include the lift-off length, the flame length, the flame height, the flame width and the flame trajectory (Palacios *et al.*, 2020; Smith *et al.*, 2005; Changchun *et al.*, 2019) in which several correlations were developed for each of these parameters. These correlations are varied according to scenario i.e flame orientation, scale and receiver location which then further used as an input to semi-empirical model for radiant heat prediction.

In a study of horizontal jet flames governed by momentum and buoyancy, the flame length was defined as the length located along the flame axis centreline which is called flame trajectory (Liu *et al.*, 2019a; Changchun *et al.*, 2019; Kim *et al.*, 2009). The description of flame trajectory is very important for these types of flame as it may lead to the underestimation of radiant heat by 40% or more if an incorrect definition of flame length is used (Ekoto et al., 2014). Other than the effects of buoyancy, the presence of an obstacle downstream that leads to flame impingement, may give a direct effect on the resulted flame length and consequently the measured radiant heat. In this study, the effects of the buoyancy on the horizontal jet flames and the effects of the impingement scenario were investigated to affirm the validity of the suggested correlation for the involved input parameters which can further extend its applicability to the said scenarios.

1.2 Problem Statement

Most available radiant heat models for jet fire occurrence were developed based on ideal flame shape assumption namely as Solid Flame Model (SFM), Point Source Model (PSM), Multipoint Source Model (MPSM), and Line Source Model (LSM). SFM, PSM and MPSM are well established for radiant heat prediction of jet fire and there is a vast amount of data available. Nonetheless, each of these models has its limitation as such SFM is more suitable to be used for near field observation, PSM for far-field observation, and MPSM which can be used for both near and far-field observation but data available are limited to a large scale of the jet fire. The most recently developed, LSM offers a better option among the rest which are applicable for radiant heat prediction of vertical and horizontal jet release in both near and far-field observation and has been tested against a large and small scale of the jet fire. Yet, the validity has to be explored more for low initial momentum release of jet fire as LSM does not consider the buoyancy effects. In general, the input parameter that has to be determined for LSM is the flame length, the heat release rate, the radiative fraction, the flame length ratio, and the lift-off distance.

For a horizontal jet flame, it was dictated the flame length and the lift-off length hold a considerable effect on the radiant heat prediction. An earlier study using LSM, defines the flame length as the length of the flame either in a horizontal or vertical direction based on ideal flame shape. However, for a horizontal jet flame, as the initial momentum is consumed, the buoyancy will take over causing the flame to bend upwards or flame shape deformation. Thus, the consideration of these buoyancy effects has to be taken into accounted by introducing the trajectory length instead of a conventional flame length based on ideal flame projection. Based on this challenge, this study attempts to extend the validity of expression developed for radiant heat flux using the flame trajectory as a basis for horizontal jet flames governed by considering both momentum and buoyancy effect.

Besides, the jet release is not necessarily happened in a free release since there is a possibility of impingement jet fire in the process plant vicinity. The presence of an obstacle as an impingement object may have a significant effect on the air entrainment volume that may further result in the distortion of the flame shape and flame size. This work will investigate the possibility of accurately determining the properties of a horizontal jet flame without large-scale experiment or computational simulations by analyzing the jet flame with various release conditions at subsonic regimes in the near field, as well as considering the effect of impingement effect. Due to the unique feature of the flame trajectory concept, this work aims to propose a modified correlation of the Line Source Model (LSM) for radiant heat estimation for a general horizontal jet flame that covers both free and impinging jet release.

1.3 Objectives of Study

Based on the preceding research background and problem statements, the main objective of this study is to develop a semi-empirical model that can incorporate an impingement scenario for a horizontal jet fire in a near field. To achieve the main objective, several objectives were carried out.

(a) To determine the parametric and geometrical flame features of horizontal jet fire with and without impingement in respect to a change of gas flowrate, u (m/s), nozzle release diameter, d (mm), and nozzle-object separation distance, D (m).

(b) To formulate the modified model using the input parameters in (a) for the radiant heat release prediction of horizontal turbulent jet fire with and without impingement in the near field.

(c) To verify the modified model applicability and performance using this work experimental data and previous literature data, using line source model as a prescribed model.

1.4 Scope of Study

To fulfill the objectives of the study, the scopes of study have been drawn:

(a) Only the line source model (LSM) was considered as a semi-empirical model prescribed to be used for radiant heat estimation for both free and impinging jet release scenarios in this study. Thus, the input parameters considered were flame length, the heat release rate, the radiative fraction, the flame length ratio, the flame width and the lift-off distance.

(b) To create the impingement scenario, a cylindrical vessel with an internal diameter of 2-m, a thickness of 10-mm, and a material of carbon steel is used as an object to be impinged with a nozzle-object separation distance of 0.8 m and 1.2 m.

(c) The gas flowrates used were between 30-600 g/min released from a circular nozzle with a diameter of 9.8 mm and 7.15 mm, in which it produces jet flames governed by momentum and buoyancy. Besides, with the flow rate, the Reynolds numbers are ensured above 4000 which indicates turbulence behavior.

(d) CMOS sensor camera with video function was located orthogonally to the flame axis was used to capture a simultaneous image of the jet flame. The captured images were analyzed using MATLAB Image Processing Toolbox. The flame geometrical features i.e the flame length, flame height, flame width and lift-off length were obtained from the results of the analysis.

(e) Propane of 99% purity was used as fuel as it represents the worst-case scenario of jet flame occurrence based on historical event data.

(f) An environmental condition that includes the ambient temperature, relative humidity, and wind speed are obtained from an anemometer reading near the test area station.

(g) The flux sensor was located near-field which within half of the predicted projected flame length in a radial direction to eliminate the effects of atmospheric transmissivity on the readings.

1.5 Significance of Study

A lack of data to validate the use of a semi-empirical model based on the flame trajectory has been a motivation for this study. The prediction of radiant heat flux in the near field is of utmost importance as the radiant heat is among the elements of heat transfer to the nearby target that could induce accident escalation and will be the additional provision to determine the minimum spacing distance of the equipment sitting for the plant layout. The modified semi-empirical model developed based on the flame trajectory is believed could give a more accurate and reliable prediction on radiant heat of the horizontal jet flame either in a free jet or during impingement. In addition, it can be used by safety practitioners to assess asset integrity by considering the possibility of a jet fire impingement scenario for a release in a horizontal orientation.

1.6 Limitation of Study

From the discussion stated above, it is crucial to investigate the thermal behavior of jet flame projection and the presence of obstacles near the flame source. However, the model that is developed is strictly valid for a horizontal jet fire impingement scenario on a curved surface (cylinder) in close vicinity. The model for impingement assumes the flame hits perpendicularly to the center of the surface of the target object. The flame spread will be assumed to be similar on the left and right-hand sides of the impingement point. Thus, the measurement on the impingement side is taken only on the vertical side considering it to be in one dimension. Lastly, the outcome of this study may only apply for jet fire occurrence of propane with a range of parameters as stated in the scope of the study.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Ab Aziz, N. S.**, Kasmani, R. M., Samsudin, M. D. M. & Ahmad, A. (2019a). Main Geometrical Features of Horizontal Buoyant Jet Fire and Associated Radiative Fraction. *Process Safety Progress, 39(S1).* https://doi.org/10.1002/prs.12124. **(Q3, IF: 1.34)**

2. **Ab Aziz, N. S**., Md. Kasmani, R., Samsudin, M. D. M. and Ahmad, A. (2019b). Comparative Analysis on Semi-Empirical Models of Jet Fire for Radiant Heat Estimation. *Process Integration and Optimization for Sustainability, 3, 285-305.* https://doi.org/10.1007/s41660-019-00081-y. **(Q3, IF: 1.19)**

3. **Ab Aziz, N. S.** and Kasmani, R. M., (2022). The Effects of Geometrical Flame Feature on Radiant Heat Flux Prediction of Horizontal Jet Flames Using Line Source Model. *Process Safety Progress.* https://doi.org/10.1002/prs.12350. **(Q3, IF:1.34)**