Modelling Safety Distance from Industrial Turbulent Non-Premixed Gaseous Jet Flames

Nattan Roberto Caetano[1], Giulio Lorenzini[2], Andressa Rocha Lhamby[1], Zeban Shah[1], Marcos Antônio Klunk[3], Luiz Alberto Oliveira Rocha[3]

[1]*Mechanical Engineering Department, Federal University of Santa Maria, Santa Maria-RS, Brazil*
[2]*Department of Engineering and Architecture, University of Parma, Parma, Italy*
[3]*University of Vale do Rio dos Sinos, São Leopoldo-RS, Brazil*

ABSTRACT: The understanding of the heat transfer and thermodynamics of flame radiation, commonly found in many industrial processes, is important for safety code and energy efficiency. In this paper, several models of thermal radiation were reviewed and summarized to achieve a reliable formulation of heat radiation from industrial flame. The formulation may be used to predict the thermal radiation of various applications such as high temperature combustion. The model used in the standard, by American Petroleum Institute, recommended the limits of dosage considering that thermal radiation emitted by a flame is a portion of the energy amount provided by the fuel. The proportional factor is the radiation fraction, which is obtained by an inaccurate fitting. On the other hand, the recent effort made by several investigators have produced detailed models that considering flame temperature, geometry and fuel. These models can predict thermal radiation emitted to the near field, which allows predicting the safety distances between radiation sources, operators and equipment. Thus, the present study consists of applying the gaseous jet diffusion flames thermal radiation data obtained from experiments in the safety distance formulation employing the standard. Furthermore, the results are compare with that achieved by using other recent detailed model. A wide range of combustion flame regimes was evaluated as laminar and turbulent, buoyancy and momentum-driven, low-carbon and high-carbon chain fuels. Here, a safety diagram was proposed to provide a simple engineering tool that can be used by a safety distance operator to obtain prompt estimation. Such tool is important to assist industrial system designers and managers on project that involve arrangement of staff and facilities positions around a combustion system.
Keywords: Safety distance; Radiation heat transfer; Gaseous jet flames; Industrial fires.

1. INTRODUCTION

Several formulas for estimating flame length and flame tilt are shown in the literature [1]. Each one with a special range of applicability, which considers the combined impact of many factors as radiation emission and flame geometry [2].

Several models considered thermal radiation emission were developed in the last decades in order to predict the effects of the flames in the surrounds [3-5]. Various conditions and fuels were investigated, mainly for fire spread [6-9]. The heat flux and temperature determine the safety positions around a radiation fire source, based on the limits suggested by the standard [10].

The knowledge about flames heat radiation emitted to surrounds allows to design and management of safety, regarding facilities and mainly operators in the industry, which are based on the radiation dose load and temperature limits [10,11].

In industry, the safety distance from a flame is determined regarding the American Petroleum Institute standard [10], which depends on the safety level for an operator or equipment. The limits is 0.1 W/cm^2 to pain, or 0.21 W/cm^2 during one minute of exposition [12]. The thermal balance is considered to achieve the manufacturer recommendation limit temperature to achieve the safety distance for equipment.

The permissible design level considered in the API standard, named K and given in (kW/m^2), has different value limits depending on the condition in which it is employed in the industry. The detailed recommended design thermal radiation for personnel is found in the standard [10]. The value of K considered in this work was 1.58 kW/m^2, defined by the maximum radiant heat intensity for a continuum exposure when wearing services clothing. Therefore, the determination of the minimum safety distance is important considering that some clothing provides only shielding in parts of the body. Appropriate clothing consists of hard-hat, long-sleeved shirts with cuffs buttoned, work gloves, long-legged pants, and work shoes, which minimizes direct skin exposure to thermal radiation [10].

A methodology for estimating safety distances in the vicinity of pipelines was proposed by [11], regarding the application in emergency response planning. The presented methodology considers that the flammable gas pipelines have risks of fire and explosion [11]. Moreover, authors suggest that diagrams of safety distances may be created in the function of independent variables. These diagrams should be employed in loss prevention applications, i.e., assess of ignition sources within the risk zone in industrial sites, as well as in safer planning of the use of the plant [11].

A theoretical investigation of the heat transferring in fire was performed by Zhang and Usmani [13], in which many discusses the heat transfer principles in the thermal calculation of fire structures were done. Authors recommended the use of a localized fire modeling instead of the two-zone model for structural fire safety design in large enclosures. A theoretical model was created to predict the radiation emitted by a fire plume to the area placed above the fire, whereas the approach yields inaccurate results [13].

An investigation on safety in fuel storage tanks was performed in high temperatures caused by ûre excitation. The inûuence of several parameters was considered, as the type of stored fuel, material of the tank, wind incidence and distance between the tanks. Authors recommend that the design regarding the minimum safety distances between storage tanks shall be verified, in order to yield a more accurate prediction of failure considering different storage fuels, structural material and wind incidence [14].

Many authors have studied the flame thermal radiation. However, very few used the data to determine zones in which people are safe in the event. The flame heights were estimated at different severe meteorological conditions for 13 types of fuel by [15]. Thermal radiation was calculated as a function of the distance [10]. This compiled data allow to determine the safety distances based on the person's vulnerability to thermal radiation, who are wearing protected clothes or not. These results were used to estimate the safety distances, which yielding values 25% higher for staff than required by protected people. This information allow for the establishment of safety regions, in terms of prevention and emergency planning. Therefore, a suitable evacuation plan and delimitation between radiation sources and risk areas can be created [15].

Two methods for radiation heat flux measurement were performed for fire safety applications by [16]; thermography source-target and radiation contact target. The dependence of heat flux intensity on a distance and direction from a heat source was evaluated in this study. Also, the safety risks were assessed from high temperatures and high heat fluxes. The heat flux was found as the most important parameter for fire safety precautions, such as suitable distances. The maximum heat flux from the fire was 40 kW/m2. However, the safety distance was found as more than 10 m, considering personal dosage of 1.4 kW/m^2. Moreover, the safety distance should be greater than that recommended by standard, regarding the possibility of collapse, explosions and fire which can cause serious financial, ecological, and process problems [16].

Fires spread factors are considered in industrial applications, as approached in studies in which radiation emission by wood, pool and jet combustion were assessed. Indeed, several characteristics of the flames, as geometry, mainly the flame length, jet diameter and Reynolds number. Also, the chemical composition of the fuel is relevant to fit correlations between empirical and theoretical models [4,7,11].

Moreover, other parameters as flame temperature and soot production based on the fuel or flame condition are important factors for the suitable prediction on thermal radiation models [2,17-23]. Thus, this work relates algebraic modeling predictions using experimental data of flames radiation emitted in different conditions, mainly turbulent non-premixed jet flames, in order to investigate the safety distance applied to a wide range of industrial conditions.

After this assessment, a simple model was proposed, based on only in the flame length and considering the fuel and jet diameter for adjusting. Moreover, a safety diagram was proposed for a rapid and direct assessment for flames size common in the industry.

A more detailed relation between the distance and radiation emitted by well-known flames was described in the model development in this work and a fitting considering experimental database was performed in order to perform the model validation.

In this work, a linear formulation for Safe Distance that considers the height of the flame was proposed. The proposed formulation was claimed to be simpler and more accurate than the established API standard. The results of Safe Distance is also 10% shorter than that suggested by API standard. Several experiments using typical fluids applied in the industry have enough data to support the determination of the constants for the formulation. In this way, the model was based on the classical thermodynamic theory, and it was adjusted by the past-published experimental data.

2. BACKGROUND

The emission of flame thermal radiation is mainly controlled by two mechanisms. One due the molecular radiation, which is emitted in the near-infrared, and other emitted by particles, mainly by soot, which emits continuously, from the near until far-infrared in a broadband [24-26]. A large amount of energy loss to the surroundings occurs. It can reach 30% in the case of jet flames. In sooty flames, the radiation emission inhibition is increased by the fuel soot production and Reynolds number [24,26].

Large flames are considered in the standard [10], generally stabilized on nozzles larger than 0.4 m of diameter, in which radiant fraction is set as approximated 0.3, based on a rough empirical correlation between the fuel calorific value and the flame length considering several gases. However, those gases are not frequently employed in the industry. Thus, calculations of safety distance using this information exhibit high discrepancies when flames in industrial conditions were considered. Therefore, this correlation shall not be extended to predict safety distance from medium and small flames.

The radiation fraction, Fr, was considered as a function of the flame length, Lf, with different constants of proportionality for the development of the model in this work, in which empirical correlations were obtained from the measurements found in the literature [27]. Where, Lf is a function of the mass flow rate, which is proofed by several works before [6,20]. Moreover, the total heat released by the combustion, Q, is also a function of the mass flow rate, and, Q_R is controlled by the limits of radiation dose recommended by the standard [10].

The results of fitting made in this work to produce the simple model and a safety diagram, shown in the results section, was based on the measurements available in the literature [27]. These results were employed in order to calculate the safety distance from the flame applying the procedure recommended in the standard [10] and, also, using a more detailed method [22].

These values were compared and the assessment of these results allowed to simplify the detailed model in order to create a new simple model and a safety diagram, which provides more accurate results in cases often found in the industry, i.e., flames smaller than 5 m.

A common consideration of the radiation is the far-field method, in which the single point source flame is considered [17-19]. A methodology of multi-point sources is suitable for near field [17-19]. This method relates the heat rate, Q_R, radiated to the flame surrounds as shown in Eq. 1, whereas the term qr is the radiant heat flux,

$$Q_R = \int q_r .dA = 2\pi R \int_{y_i}^{y_f} q_r .dy \qquad (1)$$

However, to obtain the value of Q_R, total heat radiated, in kW, the radiant heat flux, qr, is integrated in area A around the flame, in m^2, regarding the flame geometry, whereas the radius R and length (y_f - y_i) are considered, in m.

The standard recommends the limit doses, then Q_R can be used for calculations of distance regarding the respective operation safety conditions [10]. Indeed, the flame geometry depends on the flowfield conditions and the fuel composition [28-31]. Basically, laminar flames show a conical shape 10% higher of the jet diameter.

The shape of the turbulent flames is approximately a cylinder the mean flame width is circa 17% of the flame length, 0.17Lf [27]. Thus, the geometry of the flames as length, width and liftoff height is considered to estimate residence time for modeling to predict the radiation [31]. Also, the color and even the sound emitted by flames can assist the predictions [6,24].

The association of radiation and convective heat load in the hot gases of the flames gives the total thermal load for an operator working close to the source [31]. Thus, for suitable modeling the safety distance from a flame is imperative to consider the total heat flux, which varies over the flame surface [17].

A radiant source based on the single point method was considered to assess the safety distance between staff and equipment following the standard recommendations [10, 32-36],

$$Q_R = (4\pi R^2 q_r)/\tau \qquad (2)$$

where R, in the direction of the operator, is the safety distance D, in m, and qr is the radiant heat flux, in kW/m^2, depending on the industrial condition, then, following empirical equation [10,37],

$$D = \sqrt{\frac{\tau\, Q\, Fr}{K}} \qquad (3)$$

where Fr is the fraction of heat radiated, dimensionless, and the radiant heat flux, here expressed as, K, is that the operator or equipment receives the dose considering the limits [10].

Detailed models consider the Stefan-Boltzmann law, with the temperature in the fourth order, the flame geometric characteristics, the products of combustion and, the area on the source and receptor interaction, the atmosphere transmissivity, *t*, and species absorption, etc [22,23].

A model which exhibit excellent results regarding the flame conditions approached in this work consider the relative dependence of the view factor F, into the flowfield and flame shape [2,22],

$$Q_R = Q_T\ \varepsilon\ \sigma\ \tau\ T^4\ F \qquad (4)$$

where s is the Stefan-Boltzmann constant, in kW/m^{2}K^4, T is the mean flame temperature, in K, and Q_T is the total energy released by combustion, in kW.

Thermal radiation from a fire to the surrounding area is attenuated by mainly two mechanisms, absorption and scattering, due to hot gases, water vapor and carbon dioxide, and also by dust in the path. Thus, the heat radiation fraction was determined considering the concentration of attenuate compounds and path length. The atmospheric transmissivity is roughly 0.98 depending on the air conditions. Also, the flame emissivity, e, is related to its thickness, consequently proportional with the flame length, by,

$$\varepsilon = 1 - \exp(-kL_f) \quad (5)$$

in which the coefficient, k, relative to the surface-emission is proportional to the flame temperature and soot production [2,22,23]. The soot in flames was found in 10^{-6} ppm order [24].

The heat radiated from flames depends on the emissive power, net heat emitted and superficial flame area [22]. The jet flame length for a range of propensity to soot production fuels was fitted using experimental data [26,27], which is expressed by,

$$L_f = 2.8893 Q_T^{\,0.3728} \quad (6)$$

The flame geometry is not critical for the single point model. The benefit of the use of the standard is due to the difficult to determine the flame shape, however, the results can be seriously compromised [2]. Thus, Lf and Fr relations were provided by measurements considering different fuels and used in this work for developing a new model.

3. METHOD

This information described above is useful for modeling the safety distance from a radiation source, also considering the square order reduction relation to distance [21]. In this way, is possible to substitute the parameters shown before in order to yield a direct linear dependence, in which a graphical correlation has shown that D is controlled by Lf, then,

$$D = C_1 + C_2.L_f \quad (7)$$

where the constants C1 and C2 are determined by empirical data. After a systematical assessment, was found the dependence of these constants with the fuel characteristics, as the propensity to soot production, i.e., methane, propane and ethylene, in this order.

Several cases were investigated by applying the methodology proposed in this work. First, safety distance prediction for the industry was calculated considering a constant radiant fraction, based on the standard method. Second, safety distance was calculated using the measured radiation fraction [27]. Third, safety distance was calculated using a detailed radiation model. Also, to compare these results and propose a new correlation between both safety distance and flame length. In this way, it allowed to suggest a new simple model.

Basically, the data provided in the literature [27] was used to performed calculations employing detailed models [22] in order to obtain the specific results in this work. These new values were compared with the results obtained using the same data bench for input in the standard method [10], in order to show that the approximation of the radiation fraction for a constant leads to a high errors values in the determination of the safety distance, in which the discrepancies reaches 20%.

The model considered in this work to provide the main results was selected in previous work [2,22], which allows to predict the heat rate radiated with higher accuracy, with lower discrepancies in comparison with experimental data provided by [27]. The results were used in order to create a new simple model. This engineering tool also allows to perform risk analysis in industrial combustion applications. Thus, in these cases, a higher accuracy on prediction is required as a safety factor.

Methane, propane and ethylene were used to produce turbulent non-premixed jet flames, stabilized in nozzles of different diameters, such as 5, 6 and 8 mm. Several measured parameters presented in the literature were considered as a database for the calculations performed in this work. In this way, a broad range of flames conditions was approached, since from laminar to turbulent, and also, from buoyancy to momentum-driven, and different fuels in order to assess the safety distance. Thus, this work considers a wide applicability range on industrial flame employments.

Detailed models are more precise since they effectively modeled the safety distance from turbulent flames. Also, the suitable model takes into account the flame characteristics and the environment, that are not considered in simple models, as flame shape, the power emission. The results of these calculations provide constants factors used in this work such to create a new simple model [2].

The values presented in this work were calculated in the following form: equation 4 adapted from a detailed model [22] was filled with measured values of each parameter taken from the literature [27]. Then, equation 3 was completed with these partial results in order to generate the safety distances.

In this work, the flames emissivity values was an important parameter for the model [23]. Data relative to soot, k, were chosen regarding the range provided by the literature [2] to feed the model [22]. Previously results from the literature were used to calculate the safe distance by the classical method [10]. Finally, a linear regression considering flame types and fuels very often used in industry was made in order to achieve a simple new model and more specific results for a safe distance.

In the next section, the figures show the safety distance behavior obtained from the calculations performed before, using the models described above [2,27].

4. RESULTS

Several cases were investigated by applying the methodology proposed in this work. The following sequence was applied in the assessment: (i) Safety distance prediction for industry were calculated considering a constant radiant fraction, based on the standard method [10], which results are presented in figure 1. (ii) Safety distance was calculated using measured radiation fraction [27] applying the standard method [10], which presented a linear decrease behavior as the flame length increases. These results are shown in figure 2. (iii) Safety distance was calculated using measured radiation fraction [27] applying the detailed radiation model [22], in order to provide more accurate results for scale smaller than that considered in the standard. These results are exhibited in figure 3.

The heat transfer radiated from flames of fuels with high residence time (as ethylene) is higher than that of low residence time flames (as methane). It is due to the radiation emitted by soot. This emission showed a radiation peak in the middle of the visible length of the flame. However, the hot exhaust gases contribution is smaller if compared with soot emission, even with the presence of CO_2 and H_2O in the whole flame and hot gases plume [2,17,27].

Figures presented in this section show the behavior of the safety distance calculated by the experiments performed before [27], and from the models presented in this and previous studies [22]. Thus, the safety distance in the function of the flame length is presented for three fuels type (methane, propane and ethylene) and a short variation of the jet diameter (5, 6 and 8 mm).

The safety distance results as a function of the general parameters presented by the standard [10] are shown in figure 1.

Values of safety distance in the function of flame length shown in Figure 1 were obtained from the model considered by the standard, by implementing the values of the parameters also considered by the standard, to provide a base of values as a reference. These values are currently displayed if the safety distance was calculated without the use of detailed models and experimental data available in the literature and treated in this work.

The thermal heat loss is the dominant factor for define the safety distance between equipment or workers and sources [35,36].

Results show an increase in the safety distance in the relation to the flame length as the fuel propensity to soot production is higher. The same behavior, but with low amplitude, was observed when the jet diameter is higher. Basically, hydrocarbon flames are luminous due to the incandescent of soot particles, so this characteristic can help to adjust the settings in practical applications. Indeed, the jet exit velocity is a function of the jet nozzle design, pressure and fuel composition [38] and all these parameters are interconnected [39]. The mechanisms by which soot is produced are still being studied. However, the soot is produced in a fuel-rich combustion and is higher for heavier carbon chains. In other hand, soot production is reduced in conditions of low hydrogen atoms [40].

The results presented in the graphs of figures 1, 2 and 3 were calculated considering the K=1.58 kW/m^2, which represents the radiation limit allowed for operators wearing appropriate clothing during the entire working period [41].

Figure 2 shows safety distance as a function of the values achieved by measurements, presented by [27], and calculated applying the same model suggested by the standard [10].

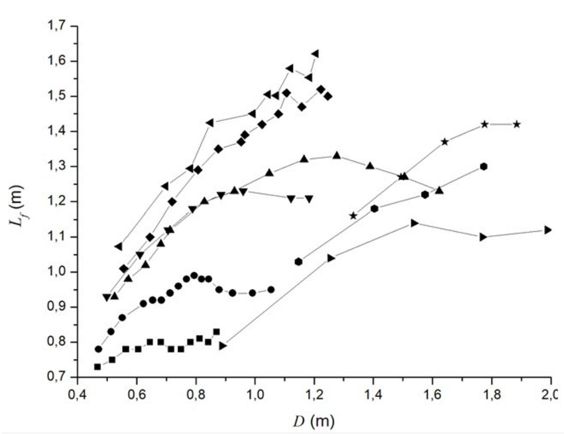

Figure 1. Safety distance in the function of the general parameters presented by the standard [10]. Methane :■ 5, ● 6, ▲ 8 mm; Propane : ▼ 5, ◆ 6, ◀ 8 mm, Ethylene: ▶ 5, ● 6, ★ 8mm.

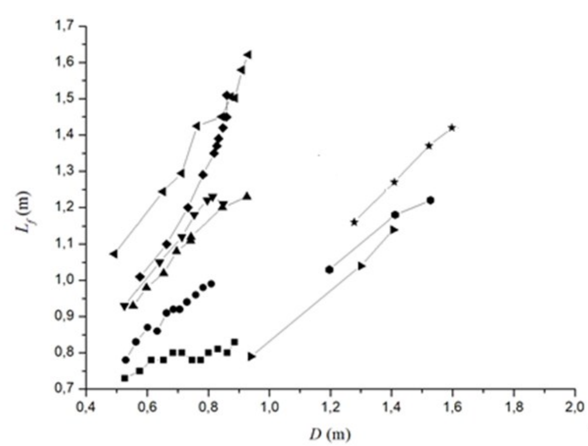

Figure 2. Safety distance in the function of the measured parameters [27], and calculated applying the standard method [10]. Methane: ■ 5, ● 6, ▲ 8 mm; Propane: ▼ 5, ◆ 6, ◀ 8 mm, Ethylene: ▶ 5, ● 6, ★ 8 mm.

Results showed the same behavior that seems in figure 1, but the safety distance values are lower. This indicates that the data used for design industrial facilities are providing higher values of safety distance and, consequently, exposing operators and equipment to a higher radiation dose than the limits.

A specific evaluation of the main factors is expected, in each case, to determine a safe level of radiation exposure for the workers. Equipment tolerates higher levels of heat than human. However, overheating risks are involved, such as structural systems, which present low melting points, mainly electronic or electrical equipment. Thus, the effect of radiant heat on these systems is significant, then it is required a precise determination regarding the safety distance. The heat balance is performed to determine the resulting surface temperature for comparison with the operational maximum limit temperatures for the equipment.

Figure 3 shows the safety distance results as a function of the values achieved by measurements, presented by [27], and calculated applying the detailed model [22] approached by the complete analysis described in this work.

The radiation is proportional to the residence time [2], that in turn, is proportional to the flame visible volume. Indeed, the residence time showed a dependence on the propensity to soot production [26,27].

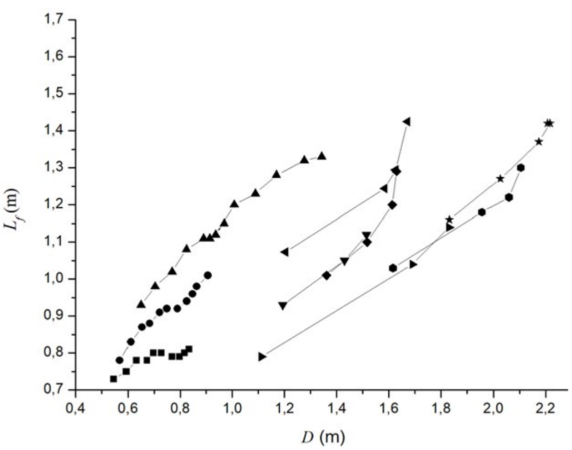

Figure 3. Safety distance in the function of the parameters achieved by measurements [27], and calculated by detailed model by the complete analysis [2]. Methane: ■ 5, ● 6, ▲ 8 mm; Propane: ▼ 5, ◆ 6, ◄ 8 mm, Ethylene: ► 5, ● 6, ★ 8 mm.

Results showed the same behavior that seems in figures 1 and 2. Although, the safety distance values are higher for this detailed method. In this case, the results showed average values of 10% higher when compared with the standard recommendations [10]. This also indicates that the data used for design industrial facilities is exposing operators to a higher radiation dose than the allowed limits.

The fitting of detailed results generates a simple model, in which dependence between safety distance and the flame length was found as linear behavior. The constants of the line equation are physically based on the fuel characteristics and jet size, in which the fit of the values vary strongly with the propensity to soot production of the fuel and weakly with the jet diameter. The constants of the equation the fuel propensity to soot production and the jet diameter. Thus, new safety limits were delimited and a new model was achieved by adjustments regarding empirical data and detailed models applied to assist in industrial facility designs.

Table 1 relates the fuel type. Data shown in table 1 were obtained from the linear fit performed on the results of figure 3 values.

Table 1. Relation of data considered for the model adjustment.

Parameter /Fuel	M(g)	D (mm)	C_1	C_2	R_2
Methane(CH_4)	16	5	0.49	0.47	0.97
		6	0.50	0.49	0.98
		8	0.57	0.52	0.99
Propane(C_3H_8)	44	5	0.24	0.56	0.99
		6	0.28	0.61	0.95
		8	0.31	0.63	0.93
Ethylene(C_2H_4)	28	5	0.22	0.53	0.99
		6	0.26	0.57	0.98
		8	0.28	0.59	0.99

The sequence of fuels is ranked considering the flame residence time. This information allow to verify a direct dependence between those data. Based on the fit results, it was noticed that C1 decreases with the molecular mass, M, and consequently, the propensity to soot production, while increases slightly with the jet diameter. C2 also increases with both jet diameter and molecular mass.

However, these combined effects lead to a discrepancy of up to 10% within the considered range. It can lead to a cumulative in the operator exposure dose, which can lead to serious health damage along the time in their entire career. In the event of exposure to equipment, damage may compromise operation or lead to serious damage and even loss of materials.

The range considered in this work is for medium size flames, mainly from 0.5 to 3 m, which are common in the industry. This new model depends only on flame length, which was adjusted by the flame residence time, that in turn, is controlled by the fuel propensity to soot production.

Linear regressions from the results shown in figure 3 for the flame types considered in this work and fuels used in industry were performed. In this way, the assessment of these data provides a result that is more accurate and allowed to create the safety diagram. This fine adjust can be made considering a correlation between the propensity to soot production of the fuel, after that, the flame residence time.

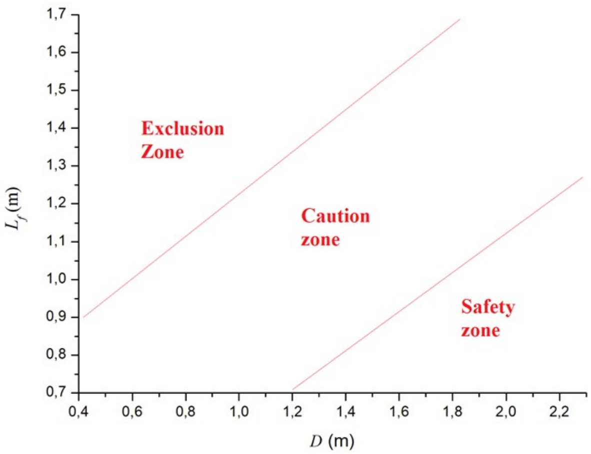

Figure 4. Safety diagram of safety distance in the function of the flame length.

The methods presented in this work assume that a flame can be modeled by a single point source of radiation emission regarding the far-field [39]. However, for short distances, i.e. less than 2.5Lf, the flame shape must be considered to achieve a more accurate prediction. The safety distance modeled complies with this assumption based on both radiation flux and exposure. Although, the standard is still the more used way to calculate the safety distance in industrial applications there are other models to estimate the safety distance.

Flame height varies with emission rate and heat release. Thus, the position of the flame center is important considering radiation levels, mainly for dose limits in operators [42]. The amount of information on these subjects is still limited and it is often carried on by empirical observations in industry.

There are other existing methods, regarding more sophisticated model, which are able to calculate radiation. Some of them considers wind velocity, jet exit velocity and flame geometry analysis, which are appropriate for special cases, especially for large systems in open surroundings [43]. However, this work focused on the more common industrial flames.

5. CONCLUSIONS

In this work, a model with the same simplicity as the standard, but more accurately and suitable for smaller flames, was proposed. The standard method for safety distance calculation [10] does not consider medium height flames for the determination of safety distance. Thus, many industry sectors are uncovered and consequently unprotected in terms of design and operation of radiation exposure.

Results shown in this work enable to conclude that if standard recommendations [10] are used for safety distance prediction the result will be a shorter distance, i.e., in practice, the operator is exposed to a radiation intensity or heat flux greater than the limits.

This work applied detailed measurements of several parameters for three fuels considering the characteristics needed to determine the safety distance from medium-size flames, using the model recommended by the standard [10] and, developing a more detailed model to determine with higher accuracy the safety distance for workers and equipment from a radiation source.

New safety limits were proposed, and, in addition, a new model with adjustments to assist in industrial facility designs considering the safety of workers and safeguarding equipment. The results reach 10% over the limits recommended before, which shows a lack of protection.

In this work, was proposed a simple but accurate model for small flames, from 0.5 to 3 m, dependent only on the flame height and which is adjusted regarding the fuel type. Whereas, this adjust is made by a correlation between the propensities to soot production of the fuel, thereafter, the residence time.

For future works new algebraic and numerical models to determine safety distance between operator and flame might be achieved by a deduction of the equations in which the safety distance is a function of the flame height, which can be obtained from the empirical coefficients and models available in the literature.

Nomenclature

A	=	area, m^2
d	=	jet injector diameter, m
D	=	safety distance from a radiation source, m
e	=	flame emissivity
F	=	view factor
Fr	=	fraction of heat radiated
f_v	=	soot volume fraction, ppm
K	=	radiant heat intensity, kW/m^2
k	=	effective coefficient of surface emission
L_f	=	length of the flame, m
Q_R	=	total heat radiated, kW
q_r	=	radiant heat flux, kW/m^2
Q_T	=	total energy released by combustion, kW
M	=	molecular mass, g
R	=	distance between source and receptor, m
s	=	surface

s = Stefan-Boltzmann constant, kW/m^2K^4

T = mean flame temperature, *K*

t = time interval, s

t = atmosphere transmissivity

y = height, m

Acknowledged

Author thanks the Federal University of Santa Maria by the support for this work.

References

1. Brzustowski T.A. and Sommer Jr. E.C., "Predicting Radiant Heating from Flares, Proceedings–Division of Refining", Volume 53, American Petroleum Institute, Washington, D.C., pp. 865–893, 1973.
2. Caetano, N. R., Venturini, M. S., Centeno, F. R., Lemmertz, C. K., Kyprianidis, K. G. Assessment of mathematical models for prediction of thermal radiation heat loss from laminar and turbulent jet nonpremixed flames. Thermal Science and Engineering Progress. v. 7, pp. 241–247, 2018.
3. Sparrow, E.M., and Cess, R.C., "Radiation Heat Transfer – Augmented", Ed. Hemisphere, Washington, D.C., 1978.
4. Malhar Malushte, Sudarshan Kumar "Flame dynamics in a stepped micro-combustor for non-adiabatic wall conditions". Thermal Science and Engineering Progress, v. 13, 100394, 2019.
5. Chui, E. H., Raithby, G.D., Hughes, P. M. J., "Prediction of radiative transfer in cylindrical enclosures with the finite volume method", Journal of Thermophysics and Heat Transfer, 1992, v. 6, No. 4, pp. 605-611.
6. Caetano, N. R., Stapasolla, T. Z., Peng, F. B., Schneider, P. S., Pereira, F. M., Vielmo, H. A. Diffusion Flame Stability of Low Calorific Fuels. Defect and Diffusion Forum, 2015, v. 362, pp. 29-37.
7. Leite, R.M. ; Centeno, F.R. "Effect of tank diameter on thermal behavior of gasoline and diesel storage tanks fires". Journal of Hazardous Materials, 2018, v. 342, pp. 544-552.
8. Yanán Camaraza Medina, Oscar Miguel Cruz Fonticiella, Osvaldo F.García Morales "New model for heat transfer calculation during fluid flow in single phase inside pipes", Thermal Science and Engineering Progress, 2019, v. 11, pp. 162-166.
9. Cassetti, G., Colombo, E., Zio, E. "A Thermorisk framework for the analysis of energy systems by combining risk and exergy analysis". Energy Conversion and Management, 2016, v. 117, No 1, pp. 281-288.
10. API, "Pressure-Relieving and Depressuring Systems - American Petroleum Institute Recommended Practice 521". American Petroleum Institute, Sixth Edition, 2014.
11. Sklavounos, S. and Rigas, F. "Estimation of safety distances in the vicinity of fuel gas pipelines". J. Loss Prevention in the Process Industries, 2006, v. 19, Issue 1, pp. 24-31.
12. Beuttner, H., "Effects of Extreme Heat and Cold on Human Skin, II, Surface Temperature, Pain and Heat Conductivity in Experiments with Radiant Heat". Journal of Applied Physiology, 1951, v. 3, No. 12, pp. 703-713.
13. Zhang, C. and Usmani, A. "Heat transfer principles in thermal calculation of structures in fire". Fire Safety Journal, 2015, v. 78, pp.85–95.
14. Santos, F.S, Landesmann, A. "Thermal performance-based analysis of minimum safe distances between fuel storage tanks exposed to ûre". Fire safety journal, 2014, v. 69, pp. 57-68.
15. Zárate, L., Arnaldos, J., Casal, J. Establishing safety distances for wildland fires. Fire Safety Journal, 2008, v. 43, pp. 565–575.
16. Švantner, M., Vacíková, P., Honner, M. "IR thermography heat flux measurement in fire safety applications". Infrared Physics & Technology, 2012, v. 55, pp. 292–298.
17. Sivathanu, Y.R., Gore, J.P., "Total Radiative Heat Loss in Jet Flames from Single Point Radiative Flux Measurements", Combustion and Flame, 1993, v. 94, pp. 265-270.
18. Song, T.H., and Viskanta, R., "Interaction of radiation with turbulence - Application to a combustion system", Journal of Thermop. and Heat Transfer, 1987, v. 1, No. 1, pp. 56-62.
19. Hankinson, G., Lowesmith. B. J., "A Consideration of Methods of Determining the Radiative Characteristics of Jet Fires", Comb and Flame, 2012, v. 159, pp. 1165-1177.
20. Delichatsios, M.A., "Transition from momentum to buoyancy-controlled turbulent jet diffusion flames and flame height relationships", Comb. Flame, 1993, v. 92, pp. 349-364.
21. Holman, J. P., Heat Transfer, McGraw-Hill Book Company, 1976.
22. De Ris, J. L., Wu, P. K., and Heskestad, G., "Radiation Fire Modeling", Proceedings of the Combustion Institute, 2000, v. 28 pp. 2751–2759.
23. Rossi, J. L., Chetehouna, K., Collin, A., Moretti, B., Balbi, J. H., "Simplifed flame models and prediction of the thermal radiation emitted by a flame front in an outdoor fire". Combustion Science and Technology, 2010, v. 182, pp.1457-1477.
24. Caetano, N. R., Soares, D., Nunes, R. P., Pereira, F. M., Schneider, P. S., Vielmo, H. A., van der Laan, F. T., "A comparison of experimental results of soot production in laminar premixed flames". Open Engineering, 2015, v. 5, pp. 213-21.
25. Faeth, G. M., Gore, J. P., Chuech, S. G., Jeng, S. M., "Radiation from turbulent diffusion flames", Annual Review Heat Transfer,1989, v. 2, pp. 1-38.
26. Becker, H. A., Liang, D., "Total emission of soot and thermal radiation by free turbulent diffusion flames", Combustion and Flame, 1982, v. 44, pp. 305-318.
27. Santos, A., Costa, M., "Reexamination of the scaling laws for NOx emissions from hydrocarbon turbulent jet diffusion flames", Comb. and Flame, 2005, v. 142, pp. 160–169.
28. Caetano, N. R., Figueira da Silva, L. F., "A comparative experimental study of turbulent non premixed flames stabilized by a bluff-body burner", Experimental Thermal and Fluid Science, 2015, v. 63, pp. 20-33.
29. Caetano, N. R., Cataluña, R., Vielmo, H. A. Analysis of the Effect on the Mechanical Injection Engine Using Doped Diesel Fuel by Ethanol and Bio-Oil. International Review of Mechanical Engineering, 2015, v. 9, issue 2, pp. 124-128.
30. Caetano, N.R.; Silva, B. P. Technical and Economic Viability for the Briquettes Manufacture. Defect and Diffusion Forum, 2017, v. 380, pp. 218-226.
31. Lowesmith, B. J., Hankinson, G., Acton, M. R., Chamberlain, G., "An Overview of the Nature of Hydrocarbon Jet Fire Hazards in the Oil and Gas Industry and a Simplified Approach to Assessing the Hazards", Process Safety and

Environmental Protection, 2007, v. 85, pp. 207-220.

32. Hajek, J.D and Ludwig, E.E., "How to Design Safe Flare Stacks, Part 1," Petro/Chem Eng, Number 6, pp. C31–C38; "Part 2," Petro/Chem Engineer, 1960, v. 32, N. 7, pp.44–51.

33. Cataluña, R., Shah, Z., Venturi, V., Caetano, N.R., Da Silva, B.P., Azevedo, C.M.N., Da Silva, R., Suarez, P.A.Z., Oliveira, L.P., "Production process of di-amyl ether and its use as an additive in the formulation of aviation fuels", Fuel, 2018, v. 228, p. 226-233.

34. Cataluña, R., Shah, Z., Pelisson, L., Caetano, N. R., Da Silva, R., Azevedo, C., Biodiesel Glycerides from the Soybean Ethylic Route Incomplete Conversion on the Diesel Engines Combustion Process. Journal of the Brazilian Chemical Society, 2017, v. 00, pp. 1-8.

35. Stoll, A.M. and Green, L.C., The Production of Burns by Thermal Radiation of Medium Intensity, 1958, Paper Number 58-A-219, American Society of Mechanical Eng, New York.

36. Hoehne, V.O., Luce, R.G., Miga, L.W., The Effect of Velocity, Temperature, and Gas Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon Gases, Report to the American Petroleum Institute, Battelle Memorial Institute, Columbus Ohio, and Proc. API Division of Refining, 1970, v. 50, pp. 1057-1081.

37. Hajek J.D. and Ludwig, E.E., "How to Design Safe Flare Stacks", Part 1, Petro/Chem Engineer, v. 32, N. 6, pp. C31–C38; Part 2, Petro/Chem Engineer, 1960, v. 32, N. 7, pp. 44–51.

38. Schwartz R.E. and White J.W., Predict Radiation From Flares, Chemical Engineering Progress, 1997, pp. 42-49.

39. Schwartz R.E. and Kang S.G., Effective Design of Emergency Flaring Systems, Hydrocarbon Engineering, 1998, pp. 57-62.

40. Arthur R., Some Reactions of Atomic Hydrogen in Flames, Nature, 1950, v. 165, pp. 557-558.

41. Buettner K., Heat Transfer and Safe Exposure Time for Man in Extreme Thermal Environment, 1957, Paper Number 57-SA-20, American Society of Mechanical Engineers, New York.

42. Zabetakis M.G. and Burgess D.S., Research on the Hazards Associated with the Production and Handling of Liquid Hydrogen, U.S. Bureau of Mines Rept. Invest. 5707, U.S. Department of the Interior, Washington, D.C., 1961.

43. Wan, H., Gao Z., Zhang Y., Experimental study on flame radiant heat flux from two heptane storage pools and its application to estimating safety distance, Energy, 2019, v. 182, pp. 11-20.