1D iterative model for predicting thermal radiation from jet fire

Guillaume Leroy, Stéphane Duplantier

The 1D Iterative Model for Predicting Thermal Radiation from a Jet Fire

Leroy, G.* and Duplantier, S.

INERIS (Institut National de l'Environnement et des Risques)
Parc Technologique Alata, BP 2, 60550 Verneuil-en-halatte, France
**Corresponding author email: guillaume.leroy@ineris.fr*

ABSTRACT

Most of the current jet fire models used in the accidental fire risks department are semi-empirical. They depend on experimental data and are limited to the experimentally studied fire. Moreover, they are not applicable to very large scales (flame length > 100 m) and tend to overestimate large-scale radiation effects. Therefore, predicting accurately the large-scale jet fires radiation effects is today a challenge in a context where the optimisation of industrial site dimensions is at stake. A 1D model based on physical laws has been developed by INERIS for predicting the flame shape and radiation field for large-scale gas or liquid released jet fires. This model is not based on an experimental correlation but takes into account the physical laws like energy balance, momentum balance through an iterative method. Moreover, the model includes the buoyancy forces which gives bent shape to the horizontal or lifted flame and takes into account wind velocity according to the release direction. At a small-scale, good agreement was noticed, first, between the new model predictions and experimental measurements and, second, between the new model predictions and the semi-empirical model results. We expect the agreement to be equally good for a large scale jet fire. Large scale experiments will be carried out in the near future to validate this physical approach.

KEYWORDS: Jet fire, thermal radiation, buoyancy forces.

NOMENCLATURE LISTING

A	flame surface area (m²)	s	curvilinear coordinate (m)
$\vec{F}$	force acting on volume control	vol	volume (m^3)
F_l	flame length (m)	**Greek**	
g	gravitational acceleration (m/s²)	τ	atmospheric transmissivity
h	enthalpy (J/kg)	ρ	density (kg/m^3)
ΔH_c	heat of combustion (J/kg)	χ_r	radiative fraction
$\vec{I}$	momentum (kg.m/s)	**Subscripts**	
$\dot{m}$	mass flow rate (kg/s)	$_a$	air
M_w	molecular weight (kg/mol)	$_b$	buoyant
P	pressure (Pa)	$_g$	gas
q	incident radiative flux (kW/m^2)	$_{liq}$	liquid
R	gas constant (J.K/mol)	$_{st}$	stoichiometric conditions
Ri	Richardson number	$_v$	vaporized gas
T	temperature (K)	$_0$	jet exit
u	velocity (m/s)		

INTRODUCTION

Jet fires occur as a result of ignition and combustion of flammable release (natural gas, LPG and others) usually from a pipe or tank. They emit high radiative flux creating a risk for humans and plants. A safety engineer needs to determine the flame trajectory, flame length and radiative fluxes to the surrounding plant and personnel. Typical critical radiative fluxes for humans are 3, 5, 8 kW/m² which represents respectively threshold for injured, 1% lethality and 5% lethality in French legislation.

In order to predict jet fires effects and especially radiative fluxes generated by flame, several models have been developed. The current software uses semi-empirical models to compute the distances of thermal effects associated with jet fires. This software is based on models which calculate geometry of the frustum based on input data (mass flow rate, orifice diameter, pressure in the pipe or tank, wind speed and others) and flame characteristics are obtained from experimental data [1-3]. The semi-empirical models are less expensive to implement because they are usually based on simple equations, and these models are easier to formulate, modify and implement in computer programs. Furthermore, they require low computational resources.

However, such an approach is highly dependent on experimental data, and therefore it is limited to the types of fires investigated during the experiments. Moreover, this approach is rarely applicable to very large scales (flame length greater than 100 m) because experiments at this scale are scarce. Finally, in the case of horizontal or inclined released jet fires, semi-empirical models do not take into account the buoyancy effect which significantly changes the shape of the flame (bent shape). As an example, the semi-empirical model by Johnson [1] takes into account buoyant forces but, being based on natural gas experiment; it cannot be used for LPG releases for which it was not validated.

Computational Fluid Dynamics, CFD, is also used to predict jet fire effects. However CFD models are highly CPU time consuming and are not always suitable to produce quick results.

As a compromise, a 1D model based on simplified fluid mechanic equations is presented in this paper for predicting the flame shape and radiation field for large-scale gas or liquid released jet fires. In the following section, the mathematical basis used in this computational model is presented. In the next section, predicted values obtained with the jet fire model are compared with semi-empirical model results and with experimental data.

PHYSICAL BASIS OF THE MODEL

Jet fire is one highly directional phenomenon due to high source momentum close to the release point, which means that the 3D fluid mechanic equations can be reduced to a 1D axisymmetric model. The present model uses a phenomenological approach based on global balances for the characteristics of a steady-state jet fire. The model uses the following input data: pipe or tank pressure, orifice diameter, ambient wind speed and temperature. Figure 1 presents step-by-step methodology of the model. In each control volume represented by a frustum located by a downwind curvilinear coordinate, s, physical quantities including mass, momentum, temperature, density, volume are calculated sequentially using the physical laws. Finally, the flame shape is represented by lateral surface of the whole control volume (i.e. the sum of each cell).

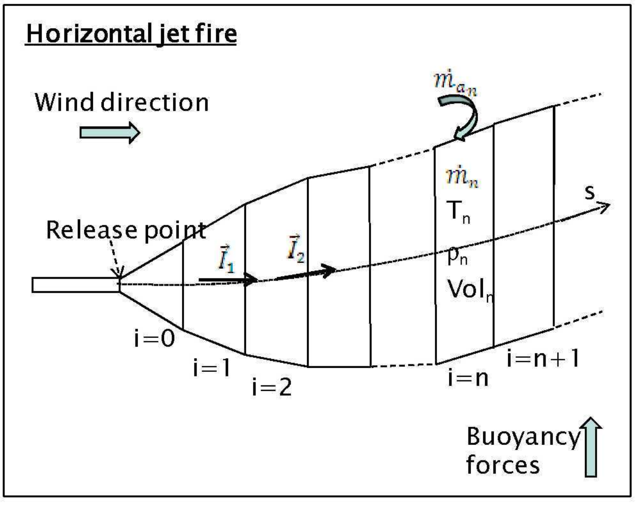

Figure 1. Step-by-step methodology of the model.

The jet fire methodology is presented and demonstrated for natural gas, propane and butane, although its extension to other fuels or fuels mixtures is straightforward. Following paragraphs describe different sub-models incorporated in this jet fire model.

Source Term Calculation

In order to estimate jet fire effects from a line rupture or a leak, it is required to calculate the release characteristics in terms of mass flow rate, velocity, temperature and liquid mass fraction. Depending on the release phase (gaseous, liquid, or two phase flow) and the nature of the breach (line rupture, leak or others), different models are used [4]. Descriptions of these models are out of the topic of the present study.

The Fundamental Conservation Equations

In a steady flow, the fluid mechanics equations set can be reduced to:

1) Conservation of mass

$$\frac{d\dot{m}}{ds} = \dot{m}_a \tag{1}$$

The air mass production rate $\dot{m}_a$ depends on the entrainment rate model, described in the following paragraph. The vaporised mass production rate is calculated with the vaporisation Eq. 4.

2) Conservation of momentum

For the steady state, the momentum balance can be expressed as:

$$\frac{d\vec{I}}{ds} = \vec{F}_b + \vec{F}_a + \dot{m}_a \vec{u}_a, \qquad (2)$$

where $\vec{F}_b$ is the buoyant vertical force acting on the control volume, $\vec{F}_a$ is the drag force due to wind which is supposed to act in the direction perpendicular to the jet axis for the computed control volume, shifting the reaction zone of the jet.

The third term in Eq. 2 is related to the air entrainment. Its contribution rises with curvilinear coordinate in relation to air entrainment model as described below.

3) Conservation of energy

The first principle of thermodynamics leads to the energy conservation equation that can be expressed using several quantities. The present model uses the total enthalpy equation that can be expressed for the steady state as follows:

$$\frac{dh}{ds} = Q_C - Q_V - \dot{m}_f h_f - \dot{m}_g h_g - \dot{m}_{liq} h_{liq} \qquad (3)$$

The first term on the right is the source term related to fuel nominal heat release and mass of reacting gas:

$$Q_C = \chi_C (1 - \chi_r) \Delta H_C m_R, \qquad (4)$$

where χ_C is the combustion efficiency and χ_r is the radiative fraction, Q_V is the energy consumption due to liquid fuel vaporisation.

Combustion efficiency varies along the jet axis [5], see Fig. 2. In region I, only a small amount of air is mixed with fuel because of the high velocity of the jet leading to limited development of turbulence; this implies bad conditions for combustion. Moreover, in that zone of the jet, most of the energy released is spent to evaporate liquid phase in case of two-phase or liquid leak. Therefore, burning rate is low in region I. In region II, the gas entering is hot and the gas mixing is facilitated by developed turbulence and lower velocity; the mixture is better prepared for combustion. Consequently, higher temperatures are reached, and the combustion efficiency is close to unity (χ_C~1). Finally, in region III, although the temperature decreases due to the fresh air entrainment into the jet, buoyancy leads to efficient mixing and high combustion efficiency. Thus, in this model, three regions are identified based on dimensionless variable s/F_l, where s is the curvilinear axial co-ordinate and F_l is the flame length:

- region I is positioned as $s/F_l < 0.4$,
- region II corresponds to $0.4 < s/F_l < 0.7$,
- region III represents the flame tip ($s/F_l > 0.7$).

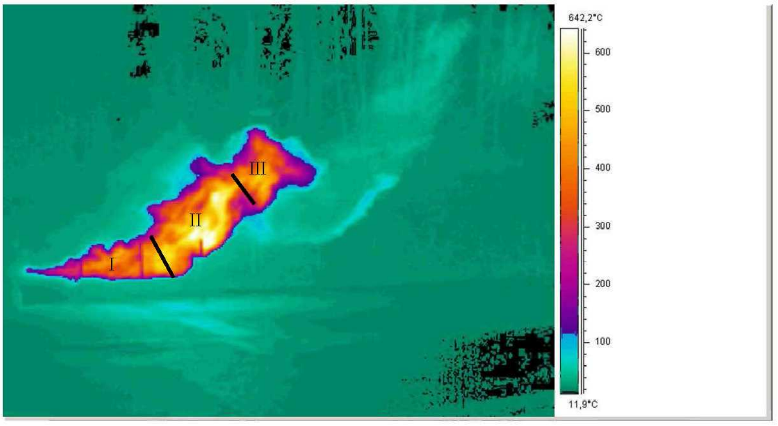

Figure 2. IR picture of the jet fire (INERIS experiments).

The right of Eq. 3 also represents energy consumption for heating non-reacting products, burned gas from the previous control volume, unburnt gas and liquid fuel, respectively. Lateral boundaries of the control volume are considered adiabatic.

4) Perfect gas law

To close the equations sets, an equation of state is required. The perfect gas law was considered:

$$\rho = \frac{PM_W}{RT} \tag{5}$$

Combustion Model

The mixture composition is defined by the equivalent ratio:

$$\phi = \frac{\dfrac{\dot{m}}{\dot{m}_a}}{\left(\dfrac{\dot{m}}{\dot{m}_a}\right)_{st}} \tag{6}$$

where the nominator is the fuel to air mass ratio in the mixture and the denominator is the stoichiometric fuel to air mass ratio corresponding to complete combustion. It can be assumed that no combustion occurs in the lift-off zone, and that the reaction is infinitely fast beyond the lift-off height; the combustion process is then "mixing-controlled".

Irreversible one-step reaction of hydrocarbon fuel and oxygen is considered, in which if $\phi \leq 1$ (lean mixture) then:

$$C_xH_y + \frac{1}{\phi}\left(x + \frac{y}{4}\right)O_2 \Rightarrow xCO_2 + \frac{y}{2}H_2O + \left(\frac{1}{\phi} - 1\right)\left(x + \frac{y}{4}\right)O_2 \, , \tag{7}$$

else (rich mixture):

$$C_xH_y + \frac{1}{\phi}\left(x + \frac{y}{4}\right)O_2 \Rightarrow \frac{1}{\phi}xCO_2 + \frac{1}{\phi}\frac{y}{2}H_2O + \left(1 - \frac{1}{\phi}\right)C_xH_y \tag{8}$$

Air entrainment Model

The air entrainment in reacting turbulent jet is a fundamental parameter that determines the jet fire development since it controls the mixing rate and, consequently, the fuel burning rate. The air entrainment rate can be written as:

$$d\dot{m}_a = \dot{m}_0 C_{el}\frac{ds}{d^*}, \tag{9}$$

where d^* is the jet momentum diameter ($d^* = d_0(\rho_0 / \rho_a)^{1/2}$).

According to [6], the local entrainment rate coefficient, C_{el}, depends on buoyancy, axial position and temperature. To describe the effect of buoyancy, Becker and Yamazaki [7] introduced a parameter that can be expressed as:

$$\xi = Ri^{\frac{1}{3}}\frac{s}{d^*} \tag{10}$$

where $R_i = gd^*/u_0^2$ is the Richarson number. Parameter ξ contains the integrated effect of buoyancy along the jet. Han and Mungal [6] related the buoyancy parameter ξ with the air entrainment coefficient:

$$C_{el} = 0.090\xi^{\frac{3}{2}} \tag{11}$$

As shown in Fig. 3, according to the Ricou and Spalding approach [8], the air entrainment coefficient is constant. Alternatively, according to Han and Mungal [6], buoyancy increases the air entrainment coefficient along the jet axis.

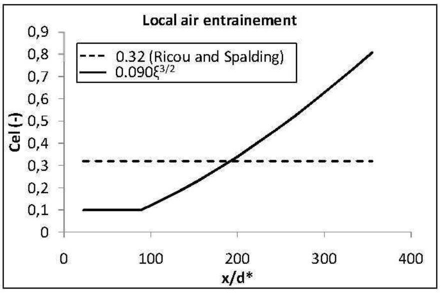

Figure 3. Local air entrainment.

Thermal Radiation Intensity

According to the solid flame model, the Surface Emissive Power (*SEP*, kW/m²) can be related to the fraction of heat radiated from the surface of the flame χ_r, fuel mass flow rate $\dot{m}$, total heat released ΔH_C by the following equation:

$$SEP = \frac{\chi_r \dot{m} \Delta H_C}{A}, \tag{12}$$

where the flame surface area A is given by the sum of lateral area of all the control volumes. The fraction of heat radiated from the surface of the flame χ_r is given by [3]:

$$\chi_r = \begin{cases} 0.21e^{-0.00323u_0} + 0.11 \cdots\cdots\cdots\cdots\cdots\cdots\cdots M_w < 21 \\ \left(0.21e^{-0.00323u_0} + 0.11\right)\left(\dfrac{M_w}{21}\right)^{\frac{1}{2}} \cdots\cdots\cdots 21 \le M_w \le 60 \\ 1.69.\left(0.21e^{-0.00323u_0} + 0.11\right) \cdots\cdots\cdots\cdots M_w > 60 \end{cases} \tag{13}$$

In Eq. 13, u_0 is the jet inlet velocity and M_w is the molecular weight of the fuel. This model assumes that the flame emits homogeneous surface radiative flux and does not take into account the fact that the radiative emissions depend on temperature and chemical composition of the flame zone which vary along the flame axis. Moreover, the thermal radiation is also dependent on soot concentration.

Finally, the radiative flux received by a target outside the jet fire is expressed as:

$$q = VF \times SEP \times \tau, \tag{14}$$

where VF is the view factor. It depends on location of the flame in space relative to the target position. The view factor between an elementary receiver surface C and an elementary emitter area dA from the control volume surface is given by:

$$VF = \int \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA, \tag{15}$$

where θ_1 is the angle between local normal to surface element dA and the line joining elements dA and target, and θ_2 is the angle between normal of the target and the same line. The atmospheric transmisivity τ is obtained by the Brzustowski and Sommer's empirical law [9].

RESULTS AND DISCUSSION

Comparison Between Predicted and Measured Values

A safety engineer is mainly interested in predicting the worst case scenarios for the accidental phenomena. That is the reason why, in case of released jet fire, the downwind effects of horizontal jet fire are most thoroughly investigated and the critical thresholds of 3, 5, and 8 kW/m² are examined.

Large-scale experiments data are scarce in the literature. Moreover, in the jet fire experiments, the radiometers are not normally located downwind, in the flame axis; instead, they are usually located on the flame side, which is out of the topic of the present paper.

Experimental data used in this work are listed in Table 1. It includes data for natural gas, propane and butane jet fires releases.

Table 1. Experimental overview.

Reference	Johnson [1]	Cook and al. [3]	INERIS [10]			
Test	Test 1083, Type C	3,2 GW	Test 1	Test 2	Test 3	Test 4
Fuel	Natural Gas	Natural Gas	Propane		Butane	
Release Phase	Gaseous	Gaseous	Liquid		Liquid	
Mass flow Rate (kg/s)	8,4	65.1	1,5	4,1	1,5	3
Release direction	Horizontal	Vertical	Vertical	Vertical	Vertical	Vertical

Figure 4 and Table 2 show a comparison of computed incident radiative flux and flame length with experimental results.

At small and medium scale, the level of agreement between the model predictions and experimental measurements is good for far field. All predicted jet fire radiative flux and flame length are within 10% of the measured value, 15% for flame length. However, it can be observed that the model tends to underestimate the results which can be problematic in safety department. It is essential to ensure that the discrepancy between prediction and measured values does not increase at large scale and in case of horizontal LPG released jet fires.

Two parameters could be reviewed in order to make results more conservative: the radiative fraction of the flame and the air entrainment parameter of the jet. A radiative fraction prediction model based on Stefan–Boltzmann law which gives the radiation of a black body in relation to its temperature, coupled with a simplified soot formation model, for example, the model in [11] would distribute radiative heat on the flame surface. This model will be integrated in the near future, with the contribution of medium-scale experiments, in order to compute more accurately the surface emissive power.

Soot concentration peaks at the fuel-rich side of the flame. in region I, see Fig. 1. At the same time, the peak temperature is located in the region II, as mentioned in the combustion model section. As a result, in any jet fire regions I and II emit the largest radiative flux. However, in the present model, the radiative flux is assumed to be uniformly distributed over the flame surface. More experiments will also be necessary to improve the air entrainment model.

Comparison of INERIS and Semi-empirical Models

Two representative medium scale scenarios of accidental liquid jet fire were computed in this work using two models. The first one is the new model presented in this paper

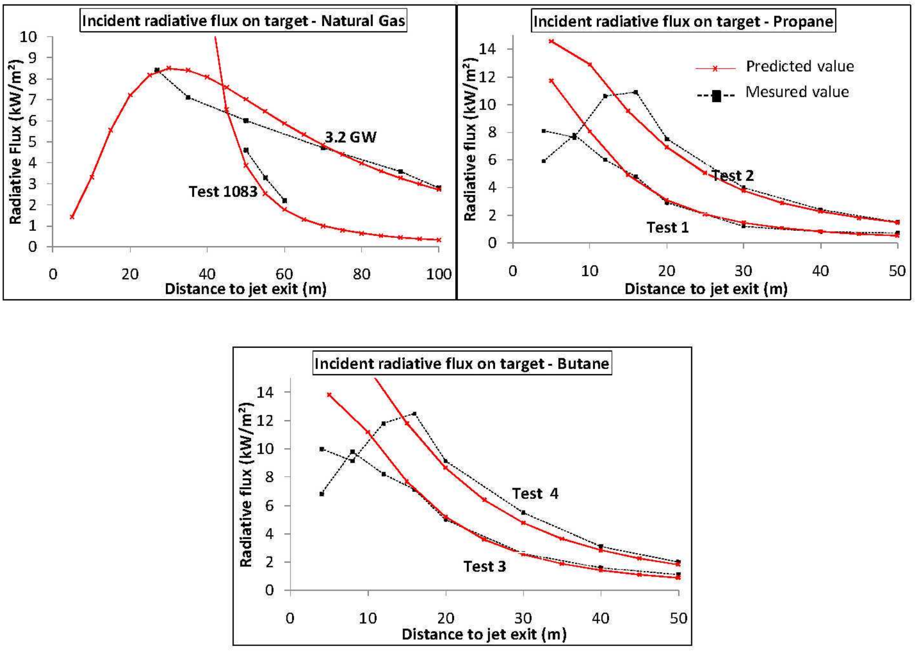

Figure 4. Comparison between measured and predicted results.

Table 2. Comparison between measured and predicted flame length.

	Flame length (m)	
	Measured	Predicted
Test 1083 [1]	33	30
3,2 GW [12]	60	55
Test 1 [10]	16	15
Test 2 [10]	24	25
Test 3 [10]	16	15
Test 4 [10]	23	20

and the second model is the commonly used Phast v6.5 (DNV software) jet fire module of the Cook model [3], which is recommended by DNV [13] for releases of combustible liquids. The Cook model assumes the flare flame shape to be of a cone shape. The cone characteristics are based on semi-empirical correlations. Table 3 presents the mass flow rates in propane and butane released jet fires and the Fig. 5 shows the comparison between the results obtained by both models in terms of the incident radiative flux from the jet exit.

Table 3. Scenario assumptions.

Scenario	Mass flow rate [kg/s]
1	15
2	50

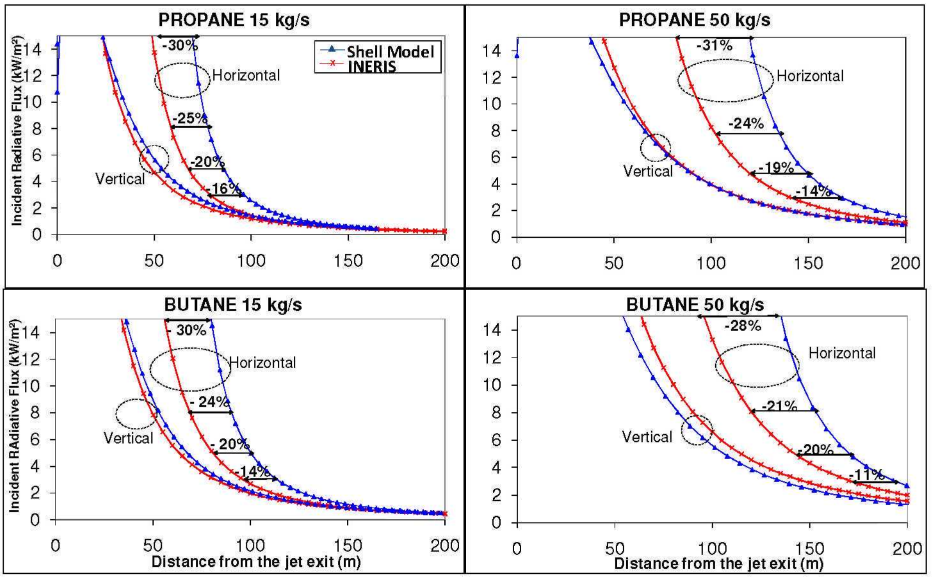

Figure 5. Comparison of incident radiative flux between INERIS and Phast prediction.

The new model significantly reduces the incident radiative flux related to horizontal jet fire when comparing with the values obtained using Phast v6.5. The difference is between -25% and -15% for the 8 kW/m² threshold and reaches -30% for the 15 kW/m² flux. This is due to the fact that the model flame shape takes proper account of the balance between the initial jet momentum and the buoyant forces, given bent shape to the flame, increasing the distance between the flame and the target and so that decreasing the incident radiative flux. On the other hand, the radiative flux related to vertical jet fire and computed by both models are relatively close (no more than +15% of discrepancy).

CONCLUSIONS

The calculation of jet fires effects is essential when assessing the safety of high-pressure processing of flammable materials. A new model has been developed for the jet fires occurring in large-scale industrial accidents.

Unlike more complex modeling approaches as CFD model, this model provides the capability to yield satisfactory predictions of the radiative flux from the jet fire with a little computer run time. Both at small and large scale, the predictions are in good agreement with the measurements for far field. Furthermore, the results computed with this model have been compared with those computed with semi-empirical approach based on the Cook's model [3]. This highlights a smaller incident radiative flux from the horizontal jet fire. A discrepancy up to 25% can be noticed. If this model is validated at large-scale, it can then be used to assess safe separating distances in industrial sites.

Further work remains to be performed to validate this model, and to assess the ability of the model to predict a wider range of fires types, especially for horizontal and inclined jet fires. Large scale experiments with the horizontal and inclined releases will be carried out in the near future to validate this new model.

REFERENCES

1. Johnson, A.D., Brightwell, H.M., and Carsley A.J., "A Model for Predicting the Thermal Radiation Hazards from Large-Scale Horizontally Released Natural Gas Jet Fires," *Trans IChemE* 94 Part B: 157-168 (1994).
2. Chamberlain, G.A., "Developments in Design Methods for Predicting Thermal Radiation from Flares," *Chem Eng Res Des.* 65**:** 299-309 (1987).
3. Cook, J., Baharami, Z., and Whitehouse, R.J., "A Comprehensive Program for Calculation of Flame Radiation Levels", *J. Loss Prev.Process In.,* 3: 150-155 (1990).
4. Hébrard, J., and Lacome, J.M., "Evaluation of Two-Phase Flow Models for Accidental Release and Comparison with Experimental Data", *Proceedings of the 11th International Conference Multiphase Flow in Industrial Plants* 747-759, 2008.
5. Gómez-Mares, M., Muñoz, M., and Casal, J., "Axial Temperature Distribution in Vertical Jet Fires," *Journal of Hazardous Material* 172: 54-60 (2009).
6. Hann, D., and Mungal, M.G., "Direct Measurement of Entrainment in Reacting/Nonreacting Turbulent Jets," *Combustion and Flame* 124: 370-389 (2001).
7. Becker, H.A., and Yamazaki, S., "Entrainment, Momentum Flux and Temperature in Vertical Free Turbulent Diffusion Flames," *Combustion and Flame* 53: 123-149 (1978).
8. Ricou, F.P., and Spalding, D.B., "Measurements of Entrainment by Axisymmetrical Turbulent Jets," *J. Fluid Mech.* 11: 21-32 (1961).
9. American Petroleum Institute, "Guide for Pressure Relieving and Depressing Systems", *API Recommended Practice* 521, Appendix A, 1973.
10. Bertrand, J.P., and Durussel, T., *Compte-rendu des Essais Réalisés à l'Institut TOTALGAZ.* Ressons-sur-Matz, 2005.
11. Delichatsios, M.A., "Smoke Yields from Turbulent Buoyant Jet Flames," *Fire Safety Journal 20:* 299-311 (1993).
12. Cleaver, R.P., Cumber, P.S., and Fairweather, M., "Predictions of Free Jet Fires from High Pressure, Sonic Release", *Combustion and Flame* 132: 463-474 (2003).
13. *JFSH (Jet Fire) Theory Document,* DNV Software, 14-20, 2005.