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Convective heat transfer around vertical jet fires: An experimental study

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ABSTRACT

The convection heat transfer phenomenon in vertical jet fires was experimentally analyzed. In these experiments, turbulent propane flames were generated in subsonic as well as sonic regimes. The experimental data demonstrated that the rate of convection heat transfer increases by increasing the length of the flame. Assuming the solid flame model, the convection heat transfer coefficient was calculated. Two equations in terms of adimensional numbers were developed. It was found out that the Nusselt number attains greater values for higher values of the Rayleigh and Reynolds numbers. On the other hand, the Froude number was analyzed only for the subsonic flames where the Nusselt number grows by this number and the diameter of the orifice.

1. Introduction

The jet fires occur when a pressurized fuel, usually in form of a gas or a vapor, escapes through a safety valve, a crack or a hole, forming a relatively high pressure jet. These fires have a very turbulent flame with a substantial momentum, which generates a very high rate of heat flux. This type of accident is classified as potentially dangerous, since a domino effect is observed in 50% of all cases where a jet fire is involved [1].

The jet fires are diffusion flames where fuel and air are initially separated, before getting mixed at the release point of the fuel. By increasing the exit velocity of the fuel, flame length increases. Before reaching the maximum length, the flame begins to show some fluctuations in the upper part. By increasing the fuel mass flow rate further, fluctuations spread to the entire body of the flame and the turbulent regime is reached. Diffusion flames can be controlled by the inertia forces or buoyancy forces. In the case of fuel escaping at high speed, often sonic, thermal behavior of the flame is determined primarily by the inertia forces and the phenomenon is dominated by forced convection, as typically occurs in the jet fire accidents. On the other hand, density differences generated by the combustion, namely the buoyancy forces, control the phenomenon in the case of low escape velocities.

Several researchers have studied the jet fires and published experimental results, mainly related to the temperature distribution and the radiated heat. In one of the first studies, Brzustowski et al. [2] measured the center line temperature of laboratory scale propane flares and reported a maximum temperature of about 1500 K. The fraction of radiant heat was also studied by these investigators. They found that the type of fuel, the jet exit velocity and wind speed determine the value of this fraction. Lowesmith et al. [3] reported higher values of the fraction of radiant heat, in jet fires involving higher hydrocarbons. They observed that considerably more soot is produced with increasing carbon number, generating higher emissions and greater fractions of radiation. On the other hand, wind speed provokes a higher rate of air entrainment and improves quality of combustion, inducing lower values of the fraction of heat radiated [2]. The influence of the jet exit velocity over this fraction will be discussed in details in following sections of the paper. Becker and Yamazaki [4], conducting experiments with small scale propane flames, presented axial and radial distributions of temperature. The maximum temperature measured by these researchers was about 1700 K. McMurray [5] proposed a procedure called the integrated combined point source method, to evaluate the heat flux incident on an object and found a good agreement between predictions of the method and experimentally obtained data employing real scale flares. Sonju and Hustad [6]

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Nomenclature

d	orifice exit diameter [m]
g	gravitational acceleration [m/s^2]
h	convection coefficient [W/(m^2 °C)]
k	thermal conductivity [W/(m °C)]
L	length of the visible flame [m]
m	fuel mass flow rate [kg/s]
Q_{conv}	convection heat transfer rate [MW]
T	temperature [°C]
U	fuel exit velocity [m/s]

Greek letters

α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [1/°C]
ν	kinematic viscosity [m^2/s]

Nondimensional groups

Fr	Froude number [U^2/gd]
Nu	Nusselt number [hL/k]
Ra	Rayleigh number [$g\beta\Delta T L^3/\nu\alpha$]
Re	Reynolds number [Ud/ν]

studied the average temperature of methane and propane jet fires and reported that methane fires presented higher temperatures than the propane fires. These authors also experimentally analyzed the emissive power of the flame, employing the solid flame model. Pfenning [7] conducted experiments with natural gas jet fires, with lengths up to 20 m, and measured a maximum temperature of 1250 K. Chamberlain [8], using large and laboratory scale natural gas flares, studied the influence of the gas exit velocity on the fraction of radiated heat. Carrying out experiments with methane and generating a flame length of about 20 m, McCaffrey [9] reported a maximum temperature of 1220 K on the center line and using the solid flame model calculated the fraction of radiated heat. Santos and Costa [10] studied the maximum temperature with small scale vertical jet fires of propane and ethylene.

The above-mentioned studies were performed with subsonic jet fires. However, in the case of accidents in which a jet fire is involved, very often a sonic exit velocity of fuel is reached [11–13]. Therefore, the study of sonic jet fires is very important from the standpoint of risk analysis and recently several works analyzing this type of jets have been published. In one of them, Gómez et al. [11] observed that the temperature along the center line of the flame varies considerably in vertical jet fires of propane. The geometric characteristics of both sonic and subsonic jet fires were experimentally studied by Palacios et al. [12]. Gómez et al. [13], using the solid flame model, calculated the fraction of heat radiated from vertical sonic jet fires.

As a summary, it appears that heat transfer by radiation from jet fires has been studied by different authors, but in the technical literature there is very limited amount of work published studying the convection heat transfer from a jet fire. In one of the earlier studies, Conolly and Davies [14] experimentally determined convection heat transfer coefficient at the stagnation point of a blunt body immersed in the flames of several common fuel gases. A review, over heat transfer characteristics of isothermal turbulent air and flame jets impinging on surfaces was presented by Viskanta [15]. The review focused on applications in the field of material processing and the author underlined the lack of fundamental knowledge over the relative importance of radiative and convective components in jet flame impingement heat transfer. In a more recent review over jet fire hazards, Lowesmith et al. [3] analyzed heat transfer around an engulfed object in offshore oil and gas installations where generally sonic release velocities are observed.

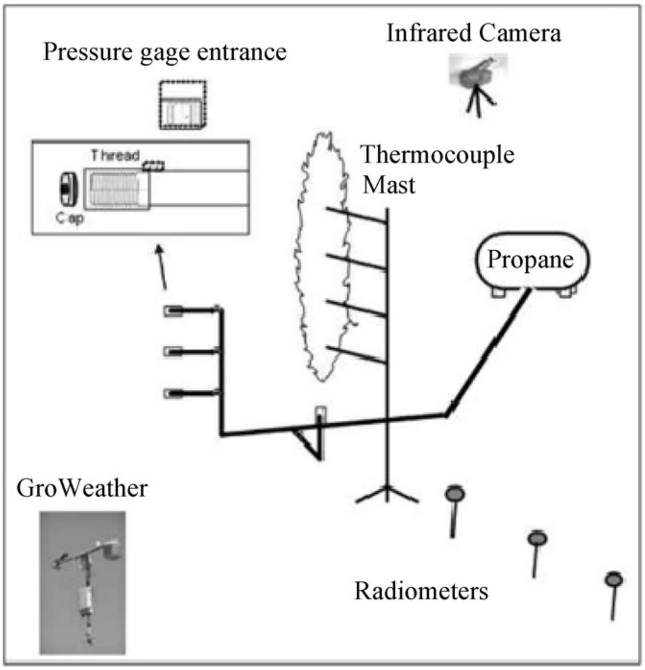

Fig. 1. Experimental set-up.

This paper presents the results of an experimental analysis on the convection heat transfer phenomenon in jet fires. The domino effect involved in jet fires is generally initiated through impingement of flames over the other equipments around the fire [11–13,16,17]. Consequently, heat transfer by convection could be as important as heat transfer by radiation, as a cause of major accidents originated from jet fires, specifically considering the values of the fraction of radiant heat in this type of fires; reported as 0.07 by Gómez et al. [13] and as between 0.17 and 0.246 by Markstein [18].

2. Experimental set-up

A series of experiments was carried out in the Can Pedró Safety Training Center, near Barcelona. The experimental set-up, shown in Fig. 1, allowed to generate vertical jet fires, both subsonic and sonic. Commercial propane, contained in the pressurized tank, was used as the fuel and vaporized while flowing through the pipe. Tests were conducted with six different orifice exit diameters: 10, 12.75, 15, 20, 25.5 and 30 mm. The mass flow rate of propane was calculated from the gas pressure measured 5 cm upstream of the release point. This measurement was taken as the upstream stagnation pressure of the flow and the experiments were performed at steady-state conditions, after a very short initial transient period. The temperature distribution along the flame axis was obtained by thermocouples of type B and S. The error of the B type thermocouples was 0.5 K over 1070 K and for S type thermocouples, 1.5 K, according to the data provided by the supplier. The temperature at the exit of the orifice was also measured using an uncoated K-type thermocouple. Three Schmidt–Boelter type heat flow sensors were used to measure the rate of heat radiated by the flame. The estimated experimental uncertainty with this measurement was ±3% with 95% of confidence level. The main geometric characteristics of the flame were determined by studying the images taken during the experiments by an AGEMA 570 infrared thermografic camera and two video cameras (for visible images). Fig. 2 presents an infrared image of a vertical jet fire. In these experiments, visible flame lengths ranging between 2.2 and 8.1 m were obtained, while the net heat released was measured between 2.76 and 19.78 MW

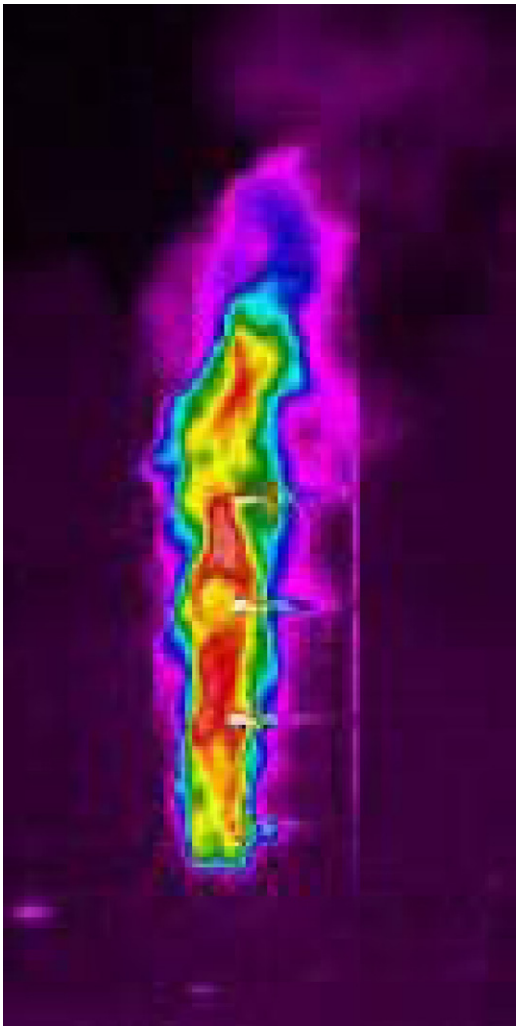

Fig. 2. An infrared image of a vertical jet fire.

and the surface emissive power between 47.6 and 103.3 kW/m^2. During the experiments also a field point module, as a data acquisition system, and a meteorological station were employed. More detailed information about the experimental facility can be found elsewhere [11–13,17].

3. Results and discussion

Heat transfer in jet fires occurs mainly by convection and radiation. The contribution of each one of these mechanisms depends on the fuel exit velocity and characteristics of the fuel such as composition and the phases involved in the exit conditions, among others. Having gas, liquid or two-phase flow at the orifice is directly related to the luminosity of the flame and has a particular influence over the rate of heat radiated [2,8,9,19].

In the present study, the thermal radiation emitted by propane jet fires was calculated, using the geometric properties of the flame, atmospheric transmissivity and the intensity of radiation incident on radiometers placed at various distances from the flame. Then, the rate of heat transfer by convection was evaluated, by subtracting the heat radiated by the flame out of the net heat released during combustion. As shown in Fig. 3, the rate of convection heat transfer increases with the length of the flame. This trend is consistent with the results reported by different authors [5,13,20–22]; they all observed that longer flames are generated by providing higher fuel mass flow, namely increasing the net heat released during combustion. On the other hand, Sonju and Hustad [6] as well as Gómez et al. [13] reported that a greater amount of net heat release results in an increase of heat radiated per unit surface area of the flame. However, increasing the net heat released, the fraction of heat radiated remains almost constant at a value of 0.07 according to the analysis by Gómez et al. [13], confirming the results presented in Fig. 3. The value of this fraction can reach 0.13 with large flames, according to Lowesmith et al. [3].

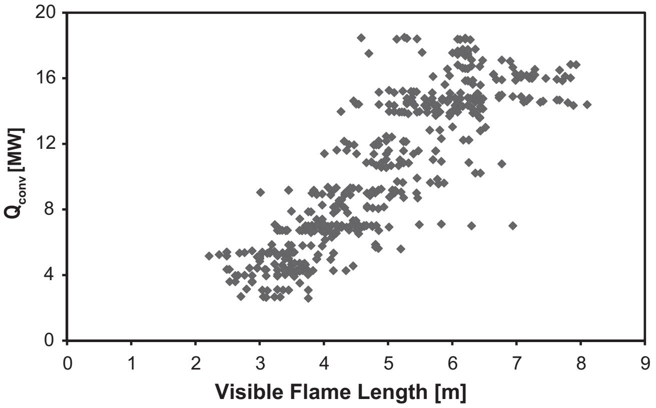

Fig. 3. Heat flow rate by convection as a function of the flame length.

The degree of dispersion observed in Fig. 3 is the result of highly turbulent flames with constant movement. Considerable scattering is very common in this type of experiments, as reported by several authors [2,4,6,9,11,13].

Analyzing infrared images, it was concluded that in vertical jet fires, in the absence of wind, the flame shape can be approximated to a cylinder with a height equal to the length of the flame, not including the lift-off zone, and with a diameter equal to the average diameter of the jet. This approach has been used by several authors previously [6,8,9,12]. Considering this cylindrical geometry and data presented in Fig. 3, the convection heat transfer coefficient around the flame was calculated. Fig. 4 shows that this coefficient assumes larger values, with increasing mass flow rate. Mannan and Lees [23] reported a value of 250 W m^{-2} K^{-1} for the coefficient of heat convection for a methane jet fire, assuming a flame temperature of 1500 K. The experimental value presented by Conolly and Davies [14], for a propane fire, was 465 W m^{-2} K^{-1}. These values, as shown in Fig. 4, agree in order of magnitude with convection coefficient values obtained in case of orifices of small diameter. The experimental uncertainty over these results was estimated to be ±11%. On the other hand, the value given by Lowesmith et al. [3], 80 W m^{-2} K^{-1}, appears to be lower than all these values. This

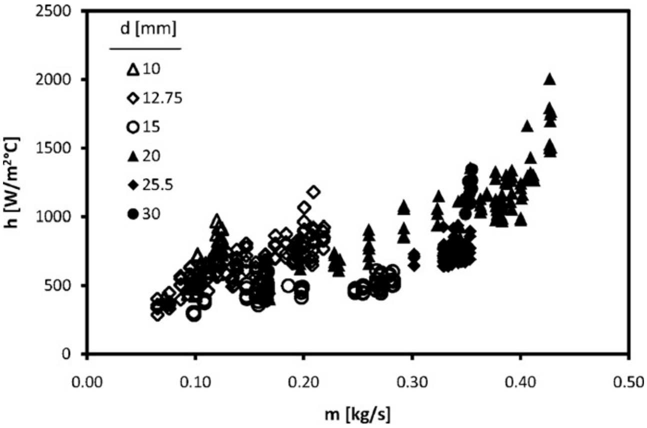

Fig. 4. Variation of convection heat transfer coefficient with mass flow rate.

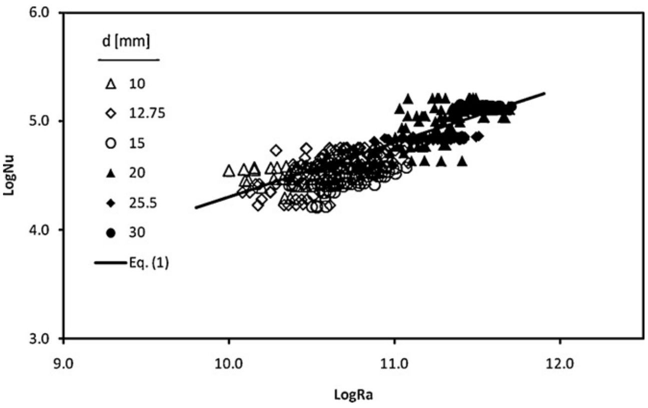

Fig. 5. Nusselt number against Rayleigh number.

difference can be attributed to the fact that these authors considered the heat convection coefficient around an engulfed object and published a value of 0.6–0.7, for the fraction of heat radiated. Consequently, the heat transfer rate by convection and the corresponding heat convection coefficients were relatively lower.

The relationships among the dimensionless numbers involved in the phenomenon were also analyzed. Eq. (1) presents the correlation developed between Nusselt and Rayleigh numbers,

$$\mathrm{Nu} = 0.057\,\mathrm{Ra}^{0.545} \tag{1}$$

Definitions of the dimensionless numbers used in this paper are provided in the nomenclature. The experimental values of Nusselt and Rayleigh numbers, obtained using different hole diameters, as well as the Eq. (1) are displayed in Fig. 5. The flame height was used as the characteristic length in this part of the analysis and Eq. (1) presented a correlation coefficient of 0.737.

Eq. (2) is the relationship obtained between the Nusselt number and the Reynolds number,

$$\mathrm{Nu} = 0.0000486\,\mathrm{Re}^{1.43} \tag{2}$$

This equation has a correlation coefficient of 0.560 and is presented together with the experimental values in Fig. 6. Although the correlation coefficient is fairly low, the tendency between the Nusselt and the Reynolds numbers is very clear. It should be emphasized that in this part of the analysis the Reynolds number is of the orifice, namely the characteristic length is taken as the diameter of the fuel outlet. In the sonic regime, the real nozzle diameter and the sonic velocity at the exit temperature were used. In analysis of the jet fires, the fuel exit velocity is of great importance, appearing in the Reynolds number. Several authors [2,8,9,19] reported that increasing this velocity decreases the fraction of heat radiated, consequently enriches convection heat transfer. The trend presented in Fig. 6 is in full agreement with these results. As shown in the figure, the Nusselt number takes higher values with increasing Reynolds number, indicating that the values of the convection heat transfer coefficient increase with the fuel exit velocity. These authors observed that at high velocities the degree of air–fuel mixture and, as a result, the quality of combustion improve, creating a blue flame, less bright, in some cases almost transparent. A flame with these characteristics emits less heat by radiation and provokes higher heat transfer rates by convection. Brzustowski et al. [2] also deduced that at high fuel velocities, a greater amount of oxygen flows into the flame, decreasing the concentration of the condensed species, subsequently, causing a reduction of the radiation and an enrichment of the convection.

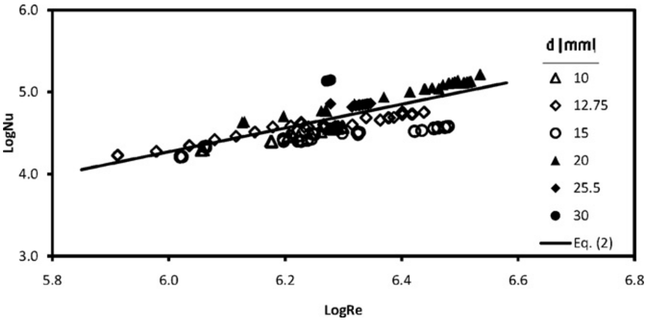

Fig. 6. Nusselt number against Reynolds number.

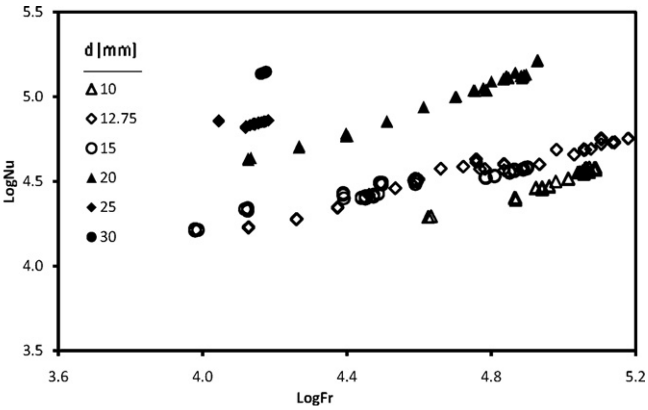

Fig. 7. Nusselt number against Froude number.

On the other hand, all the Reynolds numbers presented in Fig. 6 are encountered in the range of 8.5×10^5–3×10^6, indicating that all the flames analyzed were in the fully turbulent regime, considering that for propane the critical Reynolds number is 8.5×10^3 [24].

Depending on the gas pressure before the orifice, the fuel can reach subsonic or sonic exit velocities. In the case of a propane discharge to the atmosphere, a sonic exit velocity is reached when the absolute pressure in the container is greater than 1.74 bar [16]. The data presented in Figs. 3–6 correspond to jet fires produced with sonic and subsonic velocities, while Fig. 7 displays results of only subsonic jet fires. In this figure, the Nusselt number is given as a function of the Froude number. The Froude number represents the ratio of inertial forces to buoyancy forces. Therefore, it is the parameter that determines if the flame is dominated by forced convection or natural convection. As observed in the figure, the Nusselt number takes higher values with bigger values of the Froude number and through larger exit diameters. It is important to mention that the data presented in Fig. 7 correspond only to subsonic jet fires. Once the sonic condition is reached, the fuel velocity and the Froude number assume constant values; they cannot grow further, even increasing the mass flow rate.

Finally, Eq. (1) is compared with commonly known correlations given for natural convection heat transfer around a vertical cylinder. For this phenomenon, Eckert and Jackson [25] and Bayley [26] proposed the following equations, respectively,

$$\mathrm{Nu} = 0.021\,\mathrm{Ra}^{0.4} \tag{3}$$

and

$$\mathrm{Nu} = 0.10\,\mathrm{Ra}^{0.33} \tag{4}$$

Eq. (1) presents a very similar tendency with these correlations, while predicting higher Nusselt numbers for given values of Rayleigh number. This difference can be attributed to the particular physical and experimental conditions where Eq. (1) was developed. Eckert and Jackson [25] originally developed a semi analytical method for turbulent natural convection over a flat plate.

Observing a good agreement between predictions of their method and experimental results, they extended their methodology for vertical cylinders. Bayley [26] presented a theoretical analysis of natural convection heat transfer in turbulent flow and extrapolated the experimental data obtained in small scale equipment, to practical applications and different geometries. Clearly, these equations were developed through different techniques and considerations than the ones employed in this study.

4. Conclusions

A series of experiments was performed to analyze the convection heat transfer phenomenon around vertical jet fires. In these experiments, the temperature variation along the flame axis, the fuel mass flow rate, the geometric characteristics of the flame as well as radiation incident on sensors, installed at defined distances around the flame, were measured. The fuel was provided from a tank of commercial propane and vertical jet fires both in subsonic and sonic regimes were generated. In all experiments the flame was encountered in fully turbulent regime.

The experimental results showed that increasing the mass flow rate of fuel, flame length also increases, resulting in a higher rate of convective heat transfer, as shown in Fig. 3. This result is attributed to the reduction with the emissive power of the flame by radiation. Higher fuel exit velocity increases air entrainment, creates a stronger mixing and, consequently, provides a better quality of combustion, generating a less luminous flame with a low emissivity coefficient and lower rate of radiation. Therefore, since the fraction of heat radiated remains constant, the convection heat transfer is enhanced. As a result of this enhancement, the convection heat transfer coefficient also increases by mass flow rate, as presented in Fig. 4.

Finally, two equations in terms of the dimensionless groups involved in the phenomenon, were developed. The Nusselt number increases with Rayleigh number, as observed in Eq. (1). The characteristic lengths in the Nusselt and Rayleigh numbers were taken as the height of the flame, while as the diameter of the orifice in the Reynolds number. Eq. (2) presents the relationship between Nusselt number and Reynolds number.

This equation indicates that higher fuel exit velocities produce higher values of heat convection coefficient. In case of the subsonic exit velocities, the analysis showed that the Nusselt number increases with increasing Froude number and size of the hole, as seen in Fig. 7.

In conclusion, since domino effect is essentially provoked by impingement of flames over equipments, convection heat transfer contributes significantly to the heat flux reaching the surfaces around a jet fire; this aspect of the phenomenon has not been taken into account by many authors up to now. The experimental results and expressions presented in this paper contribute to a better understanding of convective heat transfer phenomenon associated with vertical jet fires and can be helpful in assessment and prevention of this type of accidents. However, they concern intermediate scale flames, up to 8 m of length, and more experimental data with larger flames is required to test the validity of these results for bigger scales of applications.

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