UNIVERSITY OF NOVI SAD
Technical Faculty "Mihajlo Pupin"
Zrenjanin, Republic of Serbia

IIZS
Conference

PROCEEDINGS

of the XIV International Conference on

Industrial Engineering and Environmental Protection IIZS 2024

Zrenjanin, Serbia, October 3-4, 2024.

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Technical Faculty “Mihajlo Pupin”
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INTRODUCTION

Department of mechanical engineering and Department of environmental protection of Technical Faculty "Mihajlo Pupin", Zrenjanin, has organized the XIV International Conference Industrial Engineering and Environmental Protection – IIZS 2024.

The topics of scientific conference «IIZS 2024», cover the fields of Industrial Engineering and Environmental protection: Mechanical Engineering, Energetics and process technique, Designing and maintenance, Oil and gas engineering, Health and environmental protection, Environmental management, Occupational safety and Engineering management.

The main goals of the conference are: fostering innovation and expanding knowledge for engineers in industry and environmental protection; supporting researchers in presenting their current research results; establishing new contacts with premier national and international institutions and universities; popularizing the Faculty and its leadership role in our society and immediate environment, to attract a high-quality young individuals to study at our Faculty; cooperating with other organizations, public companies, and industry; initiating the collection of ideas for solving specific practical problems; interconnecting and establishing business contacts; introducing professional and business organizations to the results of scientific and technical research; and presenting scientific knowledge and exchanging experiences in industrial engineering.

We would like to express our gratitude to the partners of the IX International Conference "IIZS 2024" – Aurel Vlaicu University of Arad, Faculty of Engineering, Arad, Romania; University St. Kliment Ohridski, Technical Faculty, Bitola, Macedonia; University Politehnica Timisoara, Faculty of Engineering, Hunedoara, Romania; University of East Sarajevo, Faculty of Mechanical Engineering, East Sarajevo, B&H, Republic of Srpska; and University of Giresun, Faculty of Engineering, Giresun, Turkey – for their support in organizing this event. We are also grateful to all the authors who have contributed their papers to the scientific meeting "IIZS 2024".

We would like to extend our special thanks to the Ministry of Education, Science and Technological Development, Republic of Serbia, and the management of Technical Faculty “Mihajlo Pupin”, University of Novi Sad, for supporting the organization of the Conference "IIZS 2024".

The IIZS Conference has become a traditional annual meeting for researchers from around the world. We are open to and grateful for any useful suggestions that could help make the next, XV International Conference on Industrial Engineering and Environmental Protection even better, both organizationally and programmatically.

Chairman of the Organizing Committee
Asst. Prof. Jasna Tolmač, PhD

Zrenjanin, October 3-4, 2024.

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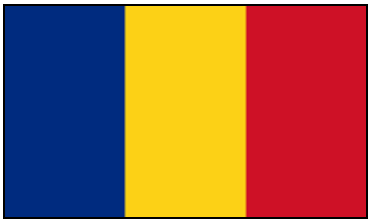

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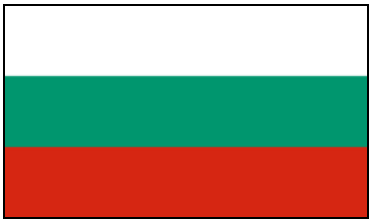

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EXPERIMENTAL STUDY OF FIRE HAZARDS FROM SMALL-SCALE METHANE FIRES

Research paper

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Abstract: This paper presents an experimental study on the flame dynamics and radiation properties of small-scale methane fires, with a focus on safety implications in laboratory settings. The experiments were conducted using a methane sand burner to simulate various heat release rates (HRR) ranging from 3 kW to 10 kW. Key parameters, such as flame height and total heat flux, were measured and compared with estimations derived from the Heskestad and McCaffrey models. The results demonstrated good agreement between the experimental measurements and model predictions up to 8 kW, with significant discrepancies arising beyond this point. The study also highlights the nonlinear relationship between HRR and measured incident total heat flux, with the largest increases observed between 3–5 kW and 7–8 kW. The findings should be interpreted with caution due to external influences, such as flame tilting caused by minor airflow in the laboratory. Obtained results provide valuable insights for assessing fire hazards in small-scale methane fires and improving safety protocols.
Key words: pool fires, methane, flame length, incident thermal radiation

INTRODUCTION

Despite efforts toward transitioning to cleaner energy, fossil fuels, including oil and natural gas, still account for a significant portion of global energy consumption. Hydrocarbon use remains a dominant force in global energy markets, influencing both economic and environmental outcomes. United States, China, and other leading industrial nations account for half of global oil use, with much of the world's oil being traded between regions rather than consumed at the source [1]. The reliance on hydrocarbons adversely affects environmental sustainability and calls for the urgent need for energy transition strategies [2]. These insights reflect the complex balance between the economic benefits of hydrocarbons and the environmental challenges they pose, emphasizing the importance of integrating sustainable energy practices.

Safety incidents involving hydrocarbon fuels in the process industry come in various forms. Each of these incidents has distinct radiation characteristics, but they share the common factor of having devastating effects on nearby people and property. Tayab et al. (2023) provided a detailed analysis of over 50 process safety events, showing that failures in risk identification and asset integrity contributed to many incidents [3]. Similarly, Aslam et al. (2023) analyzed the effects of human factors, noting that over 30% of storage tank incidents are linked to human errors, particularly during critical activities such as flushing and purging hydrocarbon systems [4]. Study by Nolan (2011), showed that large incidents often escalate when hydrocarbons cannot be isolated from the source [5]. The integration of updated safety practices, continuous training, and better leadership during crises are critical to reducing the frequency and severity of incidents in the hydrocarbon industry.

Hydrocarbon events in the process industry are categorized based on the nature of the release and subsequent events such as fires, explosions, or toxic releases. These events often originate from the release of hydrocarbons in gaseous, liquid, or mist form, with gas

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releases posing the highest risk due to their potential to create vapor clouds that can lead to explosions or jet fires.
Pool fires are one of the most common fire hazards in the process industry, particularly in chemical and hydrocarbon processing facilities. Pool fires are a type of diffusion flame, where fuel and oxidizer mix at the onset of flame. In pool fires, fuel is vaporized from a liquid pool and then combusted in the air, creating a diffusion flame characterized by its dependence on heat and mass transfer processes.
The aim of this paper is to investigate the flame dynamics and radiation properties of methane flames in a laboratory setting, with a focus on safety considerations. Methane flames are not typically categorized as pool fires since pool fires usually involve liquid fuels that evaporate and burn as diffusion flames above the liquid surface. Methane, being a gas at standard conditions, does not form a liquid pool like hydrocarbons such as gasoline or heptane. However, under certain conditions, methane flames can be considered comparable to pool fires, particularly when examining combustion characteristics, heat transfer, and flame dynamics.

MATERIAL AND METHODS

Experiments were performed with calibration burner used for ISO 13927 [6]. Burner design is shown on the Fig. 1 [6].

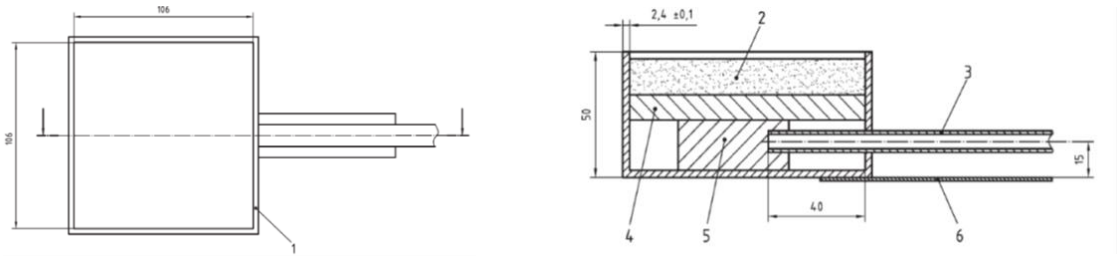

Fig. 1. *Methane burner used for performing experiments [6]*

where: 1. is square stainless-steel pan, 2 sand (with grain size approximately 1 mm to 2 mm), 3. is the stainless steel tube for methane conduit (inner diameter 8 mm), 4 and 5 are isolating ceramic-fiber blankets and 6. is handle for manipulation of burner.
The burner was connected to double rotameters (Influx, UK) calibrated for methane flow and then to a methane cylinder (250 bar). The cylinder was equipped with a double regulator. For safety reasons, a double flame arrestor system was used. One rotameter had a flow range between 0-18 l/min, while the other had a range of 0-2.8 l/min. A three-way valve was used to direct the methane flow from the gas cylinder to either of the flowmeters. For the experiments, only the flow meter with a higher range was used. According to the producer's recommendation, the flow through the flowmeters was limited to 2 bar. The configuration is shown in Fig. 2.

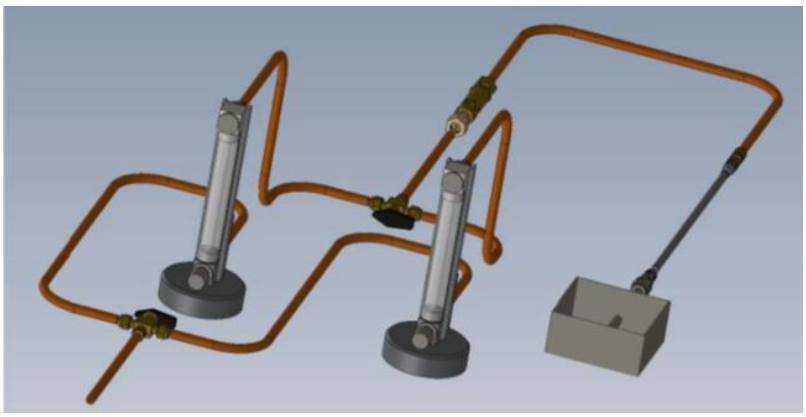

Fig. 2. *System for conveying methane to the burner* [7]

Experiment was performed for heat release values from 3 kW to 10 kW. The relationship between the heat release rate and the corresponding methane flow is shown in the Fig. 3.

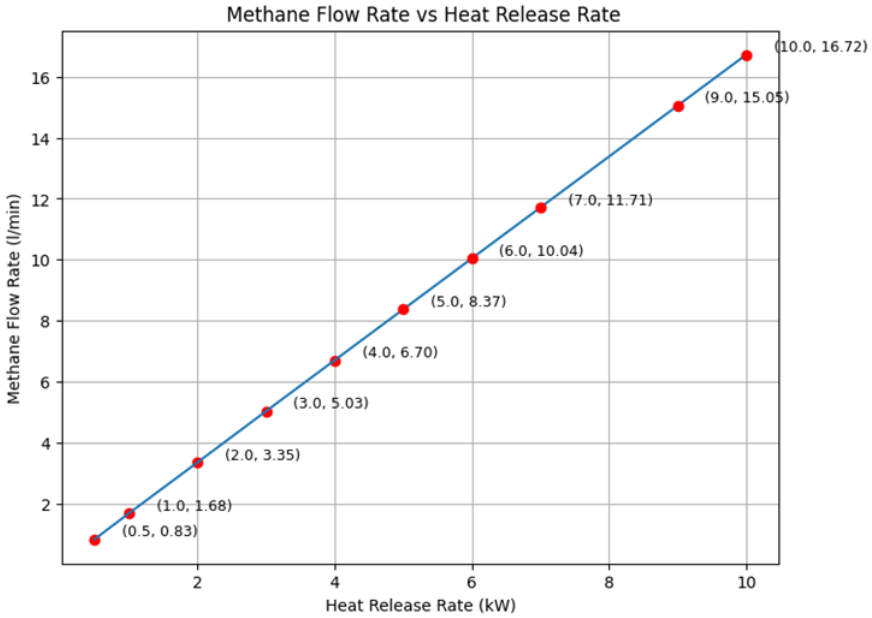

Fig. 3. *Methane flow rate vs Heat release rate*

For heat flux measurement, a calibrated water-cooled Schmidt-Boelter (thermopile type) heat flux meter (Medtherm, USA) was used. The measurement range of the heat flux meter is set to 100 kW/m². The heat flux meter was connected to a data processing device and then to a computer, allowing for immediate readings of the incoming thermal radiation. Data were displayed at a frequency of 1 Hz. The instrument was zeroed to show 0 kW/m² for ambient thermal radiation. The heat flux meter was continuously cooled through 6 mm barbs. Demineralized water with a flow rate in the range of 200-300 ml/min was used for cooling. The cooling loop of the heat flux meter was closed with an appropriate immersion pump. The heat flux meter was clamped to a vertical holder. This allowed the adjustment of the heat flux meter by height. The height of the heat flux meter could be adjusted, and for the experiments in this study, the thermopile part of the flux meter was set at a height of 15 cm, measured from the edge of the burner and at distance of 17 cm. The installation during the experiment is shown in Fig. 4. This configuration enabled continuous measurement of incoming thermal radiation.

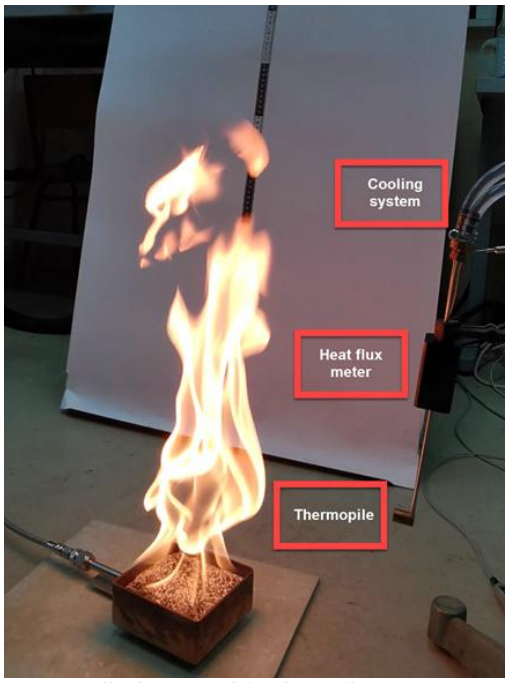

Fig. 4. *Installation used for heat flux measurement*

An aluminum meter was used to measure the flame length. It was attached to the back side of the sand burner.

RESULTS AND DISCUSSION

Flame height

Flame height is defined as the distance from the burner to the flame tip. From the very beginning, it was clear that measuring the flame height would be a very difficult task. A methane diffusion flame has a complex morphology dictated by turbulence. The flame has an irregular shape, with numerous small flames detaching from the main flame vertically and laterally. This is especially noticeable at higher fuel flow rates. See Fig. 4.

Fig. 5. *Two frames for the same HRR illustrating the pulsating nature of the turbulent methane flame*

Due to the pulsatory nature of the flame, it was difficult to precisely measure the flame height. Therefore, multiple measurements were collected for each heat release rate, and the results are reported in a normalized box plot Fig. 5. Mean values are indicated on the right side of the Gaussian distribution curve for each of the tested heat release rates.

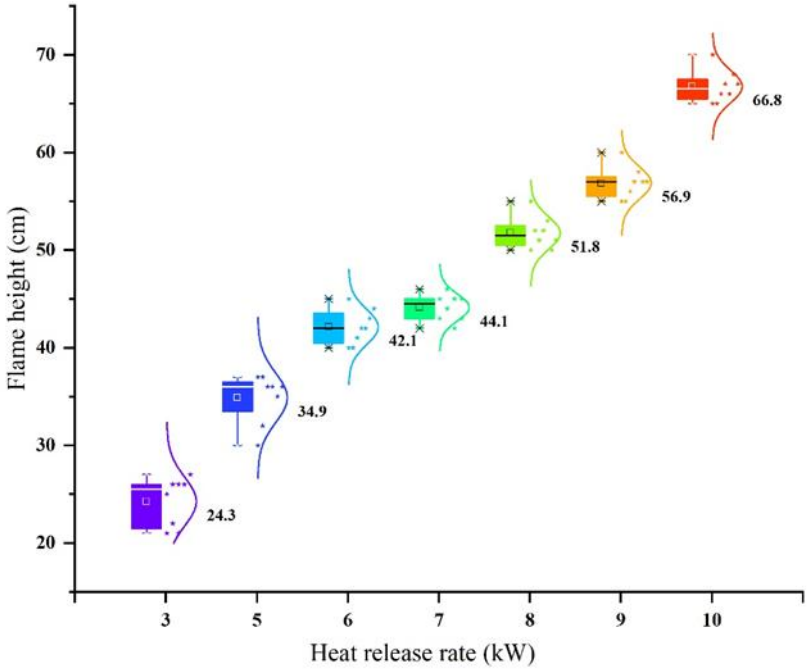

Fig. 6. *Measured flame height and corresponding HRR*

In the next step, the obtained values were compared with those derived from models found in the literature. For the comparison, the following two models were used: the Heskestad virtual origin model [8], and the model developed by McCaffrey [9].
Both models require the perimeter of the pool as an input, as they are used to describe pool fires. In the experiments, as previously mentioned, a square burner was used. Therefore, the equivalent diameter was calculated using the following formula:

$$D_{eq} = \sqrt{\frac{4A}{\pi}} \tag{1}$$

where: D_{eq} is the equivalent diameter (m) and A is the area of the burner (m²). Hence, for the square burner used (10 x 10 cm), the following equivalent diameter was applied for further calculations:

$$D_{eq} = \sqrt{\frac{4 \times 0.01}{\pi}} = \sqrt{\frac{0.04}{3.14159}} \approx \sqrt{0.01273} \approx 0.113\,\mathrm{m} \tag{2}$$

Heskestad's model [8] is based on the concept of a "virtual origin" of the flame, which adjusts the flame height based on the heat release rate and the plume's behavior near the flame base. According to this model, the flame height is given by:

$$h_f = 0.235 \cdot Q^{2/5} - 1.02 \cdot D \tag{3}$$

where: h_f is the flame height, Q is the heat release rate and D is the diameter of the fire source.

The McCaffrey model divides the flame into three distinct regions: continuous flame, intermittent flame, and buoyant plume, each with different behaviors. When predicting the flame height for a highly turbulent fire from the onset, like it is the case in this study, it is essential to account for both the continuous flame region and the intermittent region. Thus, for highly turbulent flames starting from the sand burner head, the intermittent region's equation:

$$h_f = C \cdot Q^{2/5} \tag{4}$$

where C is an empirical constant, gives the prediction for the flame height before transitioning into the buoyant plume.

Experimentally obtained results were compared with the estimations from the two aforementioned models. The results are summarized in Fig. 6.

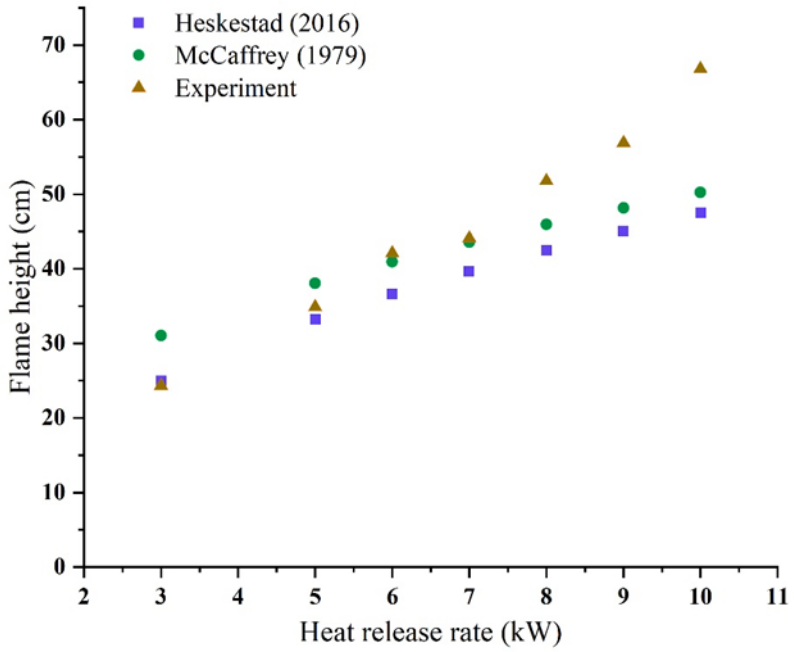

Fig. 7. *Flame height vs. HRR: experimental results and model estimates*

As can be seen from the figure, there was good agreement between the experimental results and the models up to a heat release rate of 8 kW. For heat release values of 6 and 7 kW, the experimental results were almost identical to the McCaffrey model. However, for a heat release rate of 7 kW, the experimentally obtained values began to diverge, and the difference between the models and experimental results increased. Therefore, for HRR values in the range between 3 and 8 kW, both models provided a reasonable estimate for flame height. For lower HRR values (3 to 5 kW), the Heskestad model provided accurate estimates, while for higher HRR values, the McCaffrey model performed better. For all tested HRR values, the intermodel agreement was satisfactory, with a decreasing trend in differences as the tested HRR increased.

Thermal radiation hazard

Measured thermal radiation values are presented as box normal plot in Fig. 7.

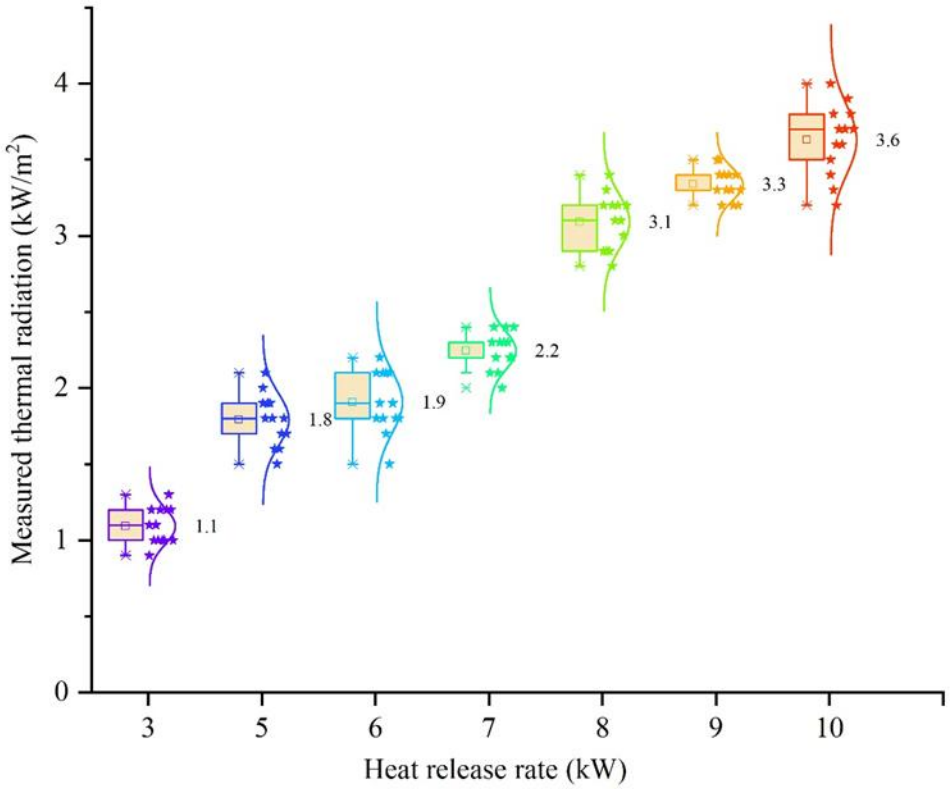

Fig. 8. *Measured total heat flux from flame vs. HRR*

As was expected, the measured total heat flux increased with increasing HRR. However, this increase was not regular. The largest changes in the measured total heat flux occurred between an HRR of 3 and 5 kW, and between 7 and 8 kW. The obtained values should be interpreted with caution due to the pulsating nature of the flame and flame tilting, which may have potentially affected the measurement process.

According to the NFPA 59A Standard [10], a heat flux level of 5 kW/m² is often used to determine hazard distances for human exposure to radiant heat from fires. In the European Union, the permissible exposing heat flux levels for radiant heat from fires are primarily outlined in the EN 1473 standard [11]. According to EN 1473, 1.5 kW/m² is threshold set for unshielded areas of critical importance where individuals without protective clothing may be exposed. The obtained results comply with NFPA 59A but not with the regulations outlined in EN 1473. However, it is important to note that distance from the direct flame significantly affects human thermal exposure. Therefore, while exposure at higher HRR may exceed the threshold set by EN 1473, the incident radiation at greater distances is considerably lower and considered acceptable. The main hazard from this type of laboratory flame arises from the stochastic nature of the flame. This includes highly unpredictable flame morphology (such as flame detachment) and, in particular, flame tilt, which can be induced by even minor disturbances in the surrounding airflow. These adverse events, especially at higher methane flow rates, should be regarded as primary safety concerns.

CONCLUSION

This experimental study examined the flame dynamics and thermal radiation properties of small-scale methane fires. The results demonstrated that both the Heskestad and McCaffrey models provide reasonable estimates of flame height for heat release rates (HRR) ranging between 3 and 8 kW. For lower HRR values, the Heskestad model was more accurate, while the McCaffrey model performed better at higher HRR values. Beyond 8 kW, the experimental

values began to diverge from the model predictions. This can be attributed to the complexity of flame behavior at elevated fuel flow rates.
Additionally, the thermal radiation measurements showed an expected increase in total incident heat flux with higher HRR. However, the increase was nonlinear, with significant changes observed between 3 and 5 kW, and 7 and 8 kW. Although the obtained heat flux values complied with the NFPA 59A standard, they exceeded the limits outlined in EN 1473. However, the incident radiation at greater distances from the flame is expected to be significantly lower, reducing the overall hazard.
The study emphasized the importance of considering flame morphology, particularly the stochastic behavior and flame tilting caused by minor airflow disturbances, as critical safety concerns in laboratory settings. These findings contribute valuable insights for improving safety protocols in handling flammable gas fires and assessing fire hazards in controlled environments.

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