

Experimental Investigation of Flame/Plate Impingement at Variable Height and Inclination

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Abstract

Flame impingement is widely employed in industrial heating applications, where burner configuration significantly influences flame behavior and heat transfer. This study experimentally investigates the effects of burner-to-plate distance ($H/D = 1, 3, \text{ and } 5$) and plate inclination angle ($0^\circ, 20^\circ, \text{ and } 40^\circ$) on the characteristics of a premixed propane flame impinging on a flat aluminum plate. A high-speed camera operating at 240 frames/s was used to capture flame images, while MATLAB-based digital image processing was applied to quantify the projected flame area, flame boundary fluctuations, and RGB color intensities. The results show that increasing both H/D and plate inclination promotes flame spreading and increases the projected flame area owing to enhanced flame development and surface attachment. Flame fluctuations also increase with burner-to-plate distance and inclination angle, indicating reduced flame stability caused by stronger buoyancy effects and aerodynamic instabilities. RGB analysis revealed higher green and blue intensities at larger H/D and inclination angles, suggesting improved premixed combustion with limited soot formation. These findings demonstrate that burner spacing and plate inclination strongly influence flame dynamics and provide useful guidance for optimizing industrial flame-heating systems to improve combustion efficiency and thermal performance.

Keywords: Flat Plate, Fluctuation, Impinging Flame, Inclination Angle, Premixed Flame

1. Introduction

One effective heating technique is flame jet impingement heat transfer, which has been extensively used in domestic applications and industry, including drying, the glass and metal industries, kitchenware, and other heating devices. Impinging flame streams powered by hydrocarbons are another common technique utilized in direct flame heating. Investigating the heat transfer properties of the impinging flame jet is crucial for improving the design of combustion machinery and increasing energy utilization efficiency [1].

By impinging one or more hot flame jets on the object, the turbulent forced heat transfer rate increases, allowing the exposure time to be shortened. The heat transfer rate and mass flow rate of an impinging jet can be altered by modifying parameters such as the Reynolds number of the jet (or jet array), the nozzle geometry, the use of corrugated surfaces, and the presence of pulsating flows [2].

Researchers have conducted many experimental and numerical studies to identify the most important factors affecting flame collisions. For instance, Li et al. [3] examined flame behavior on an inclined surface using a gas burner. They further explored

the effects of this inclination on temperature, heat flux, and velocity distribution using a heat flux meter, infrared thermography, and particle image velocimetry (PIV). The findings of the study indicate a notable increase in flame attachment length as the surface inclination angle was raised from 15° to 20° . This increase subsequently led to a rapid rise in temperature, heat flux, and flame-spread parameters. The combined use of PIV revealed that increasing the inclination angle from 15° to 20° produced a discernible velocity disparity between the upstream and downstream areas of the flame.

The heat transfer phenomenon resulting from the impingement of a methane-air flame on a wedge-shaped object was investigated by Parida et al. [4]. A series of experiments was conducted to investigate several parameters, including the Reynolds number of the flame jet, which ranged from 800 to 1500. Additionally, the dimensionless distance between the nozzle tip and the impinging surface was varied from 2 to 6, while the wedge angle was set at either 90° or 120° . The results indicate that the horizontal edge in the x-direction undergoes more significant heating effects compared to the inclined wing in the y-direction at the impinging zone. In the Reynolds number range 800 to 1500, increasing the non-dimensional

nozzle tip distance from 2 to 4 reduces efficacy in the impinging zone by 5 to 10%. Moreover, at a radial distance of "4d," there is a significant 50% decrease in the heating impact. It is worth noting that the impinging zone experiences the most pronounced heating effect.

The influence of an impingement plate on the heat-transfer properties of the impinging flame-jet system was studied by Zhao et al. [5], [6]. The three materials used to create the impingement plates were brass ($k = 61 \text{ W/mK}$), bronze ($k = 26 \text{ W/mK}$), and stainless steel ($k = 14.9 \text{ W/mK}$). It has been found that the brass plate, which has the highest thermal conductivity, produces a local heat flux significantly greater than that of the stainless steel plate, which has the lowest thermal conductivity, under comparable flame-jet experimental conditions. In addition, it was found that using a low-conductivity impingement plate would lead to greater heat-transfer suppression and greater accumulation of unburned fuel at the stagnation point. The differences between the maximum local heat fluxes of the impingement plates were found to be rather small (the maximum difference was only 8%).

Costa and Malico [7] investigated the impact of a turbulent flame impinging array on a cylinder surface numerically. They asserted that the Reynolds number of the flow, the excess air coefficient, and the temperature of the reactants are the most influential parameters governing heat transfer between the flame and the impinged surface. In contrast, surface conditions and flame-surface distance are the least influential.

Zhang et al. [8] investigated the temperature distribution beneath an inclined ceiling due to a gaseous fuel jet flame in both upward and downward directions. Different source-plate heights of 0.475 m, 0.57 m, 0.665 m, 0.76 m, and 0.855 m, as well as different inclination angles of 5° , 8° , 20° , and 30° , were taken into consideration. The findings show that when the inclined direction is perpendicular to the long side of the fire source, the burner direction has little effect on the characteristics of temperature attenuation. Conversely, the temperature rise for upward flow and downward flow is affected in opposite ways by the inclination angle.

To investigate the heat transfer properties of a premixed methane-air flame jet impinging on a hemispherical surface, Hua [1] conducted an experimental and numerical study. Investigated was the influence of the burner-to-plate distance ($H/D = 1-6$) on the heat transfer properties. The distribution and average heat flux on the impingement surface were determined using CFD to model a laminar methane-air flame impinging on a hemispherical surface under various operating conditions. He discovered that the burner nozzle-to-plate distance significantly affects the heat-transfer characteristics of the impinging flame jets, with the highest thermal performance occurring when the premixed flame cone contacts the impingement surface.

Zhu et al. [9] studied the flame extension length and temperature profile of a ceiling jet experimentally in an inclined tunnel with the flame touching the ceiling. The jet fires were established at the exit of the circular stainless steel. The results demonstrate that the asymmetrical distribution of unburned fuel after impingement can be explained by correlations among

flame-free height, inclination angles, the height between the fire source and the ceiling, and the lengths of the flame extensions along the ceiling in both directions. In addition, the source's initial momentum influences the ceiling jet's temperature profile, whereas the flames have minimal initial momentum.

Tripathy et al. [10] conducted an experiment in which they theoretically analyzed heat-transfer characteristics by examining heat-propagation phenomena in methane-air-premixed turbulent flames impinging on planar surfaces. This study examined the impact of the Reynolds number, distance between the plate and the nozzle, and equivalence ratio on the phenomenon under investigation. It has been observed that as the H/d ratio decreases from 12 to 8, the maximum heat flux near the stagnation area increases. The heat flow around the stagnation point decreases as the H/d ratio drops from 8 to 4. Moreover, it has been demonstrated that as the distance from the target plate increases, the location of the maximum value of local heat flux approaches the stagnation point.

Hou [11] conducted an experimental investigation to ascertain the combined effects of heating height and oblique angle on the temperature field, thermal efficiency, and the flame structure of a laminar Premixed methane-air flame impinging on a planar surface. The oblique angle and heating height significantly influence the flame structure, temperature distribution, and thermal efficiency. The high-temperature zone moves closer to the major flow region as the angle of inclination decreases from 90° to 60° , according to the data. The burner operates at its best when $\theta=60^\circ$ and $H=12 \text{ mm}$, as indicated by the largest high-temperature zone and the highest thermal efficiency. In general, thermal efficiency decreases as the oblique angle decreases; however, this trend holds only for lower heating heights.

The influence of the mixture equivalence ratio, Reynolds number, and nozzle diameter on the stagnation-point heat transfer of a laminar methane/air flame impinging on a flat surface was investigated numerically and experimentally by Chander and Ray [12]. They discovered that the H/D ratio is inversely related to the maximum heat flux at the stagnation point. When H/D grew further from the inner reaction zone's end, the heat flow in the axial direction decreased. At higher H/D values, the heat flux at the stagnation point rose once again.

All of the preceding demonstrates that flame impingement on planar surfaces is of significant interest across a variety of applications. Consequently, it has been the subject of numerous research articles. As stated previously, the nature of the combustion process and the many interfering variables make it difficult to provide a single physical description of the overall process. Thus, every combustion process requires its own set of data for creating the most realistic description of the corresponding physical behaviors. Moreover, some parameters, such as plate height and inclination, are more influential than others on the physics of flame/plate impingement. Therefore, additional experimental and theoretical analyses are necessary to achieve a more complete understanding of the process. Examples of these areas are the influence of multi-flame impingement, flame impingement on porous surfaces, and the influence of horizontal flame impingement on a vertical plate. In addition, the current work presents initial results from an ongoing field investigation, including experimental tests

conducted on a flat aluminum plate for comparison with previously published work. The remaining results focus on the impact of plate material and other base parameters on the flame-plate impingement dynamics.

2. Experimental Methodology

2.1 Experimental Setup

The experimental investigation was conducted on a TVPLC combustion test platform located in the combustion laboratory of the mechanical engineering department at the College of Engineering, Mustansiriyah University. The test rig comprised a Bunsen burner, an air-fuel supply system controlled by an electronic system, precision flow meters, computer control, and an adjustable plate holder. Results are shown in Fig. 1, and additional schematic diagrams and a photograph of the experimental setup are included.

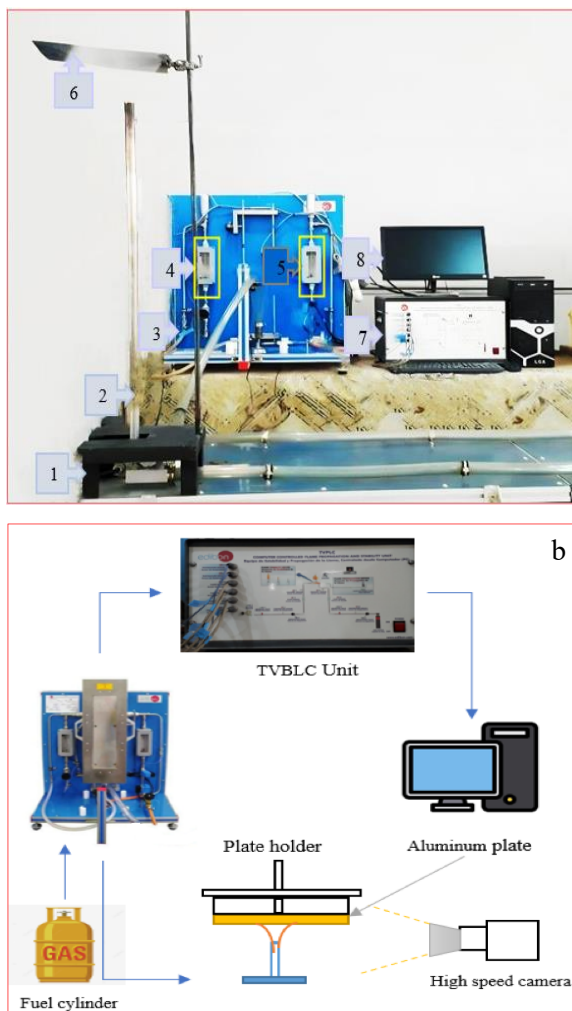


Figure 1. a) Test rig components: (1) Plate holder, (2) Burner, (3) TVPLC Unit, (4) Air flow meter, (5) Fuel flow meter, (6) Plate, (7) CIB, (8) PC. b) Schematic diagram.

A Bunsen burner made the premixed propane-air flame with a nozzle diameter of 12 mm. The height of the burner tube was set to 850 mm to ensure stable flame development before impingement. In all experiments, the gas supply (propane and

air) was maintained at flow rates of 0.06 L/s and 0.28 L/s respectively [13],[14]. The combustion conditions were kept constant, so any changes in flame characteristics were due to variations in the distance between the burner and the plate and in the plate's angle of inclination.

The impingement surface was a flat aluminum plate of size 20 mm × 20 mm × 4 mm. The burner was mounted on a movable stand providing independent control of the distance from the burner to the plate and the angle of inclination. The digital protractor, with an accuracy of ±0.1° and a measurement range of 0–180°, was used to measure the plate's inclination.

2.2 Experimental Design

The effect of geometric parameters on flame impinging characteristics was studied by a two-factor factorial experimental design. In this study, the following independent variables were taken into account:

- The distance between the burner exit and the impingement surface (H) and the burner nozzle diameter (D) were used to define the dimensionless distance between the burner and plate, which were 1, 3, and 5.
- Plate inclination angle (θ) = 0°, 20°, and 40°.

The nine experimental configurations were created from these variables. The remaining operating parameters (burner geometry, fuel type, flow rates, ambient laboratory conditions, camera position, etc.) have been held constant across all experiments to isolate the effects of the parameters under investigation.

2.3 Flame Imaging and Data Acquisition

The video footage of the flame was captured using a high-speed smartphone camera (12 MP, f/1.8) with a frame rate of 240 frames per second (fps). In all the tests, the camera was positioned orthogonal to the flame axis and at a fixed distance from the burner to reduce the perspective distortion and get a uniform spatial resolution.

Data from each experiment were collected within 2-3 s, resulting in 480-720 image frames per experiment. The recorded field of view was sufficient to see the whole of the flame from the nozzle of the burner to the impingement surface, and the flame under each experimental condition could be analyzed. Before the videos were converted into individual JPEG images for subsequent digital image processing, they were all saved as MP4 files.

2.4 Digital Image Processing

Analysis of the images was performed with a MATLAB R2019b-based program developed for this study. The purpose of the image processing was to determine the flame geometry, the time dependence, and the luminosity of the flame from the recorded high-speed images.

The following sequence in processing was used:

- Taking snapshots of the video.
- Cropping each image to isolate the area of the image that the flame is in.

- Improving the image for better visibility of the flames.
- Subtracting background noise from a flame by thresholding.
- Applying morphological filtering to remove single noise pixels and sharpen the edges of the flames.
- Measurement of flame geometric parameters like projected flame area.
- Approximate calculation of the variations on the flame front, using comparison of frames.
- Measurement of average RGB color intensities to evaluate the intensity of combustion of flames.

The number of frames analyzed for each experimental condition was approximately 500 frames to ensure that measurements were statistically representative.

2.5 Flame Characterization

The processed images were then used to calculate three quantitative flame parameters;

- Flare area (A^*): The area of the flame was defined by the number of pixels of each image that were segmented into the flame and then divided by the flame area measured at the burner exit. This normalization will minimize the influence of the camera position and nozzle geometry.
- Flame fluctuation (F^*): The fluctuation of the flame was measured as the deviation of the flame area projected on the image sequence frame to frame. A positive value indicates flame expansion, while a negative value indicates flame contraction. The average size of the fluctuations was an indicator of the flame stability under different impingement conditions.
- In addition, the intensity of the red (R), green (G), and blue (B) portions of each segmented flame image was averaged to determine the color intensity of the flame. The RGB color components give qualitative information about the chemical composition of the flames and the combustion behavior of the flames. The red channel typically is correlated with soot formation, and the green and blue channels correlate with chemiluminescent radicals produced during combustion.

2.6 Data Analysis and Experimental Uncertainty

Approximately 500 images were processed for each experimental setup, and the mean values of flame area, flame fluctuation, and RGB intensities were calculated. Multiple random flame oscillations were analyzed for a number of images, which was sufficient to enable a reliable comparison of the average values.

The main experimental errors were measurement error by the digital protractor (0.1°), the spatial resolution of the image (0.141 mm/pixel), positioning of the camera, and segmentation in the digital process of the image. A series of experiments was conducted to reduce the systematic errors, with the camera position and the burner operating conditions constant in the experimental program, while the laboratory environment was kept constant. Moreover, the same image processing parameters

were used in all experimental cases to ensure the uniformity and repeatability of the flame characteristics obtained [15], [16].

As a result, it has been used in the current work for high-speed imaging. For tracking combustion, a 12MP iPhone high-speed camera with an $f/1.8$ aperture and 240 fps imaging rate is employed. A (66 mm 120 mm) image area is produced by the camera's 464 x 848-pixel resolution and (0.14117 mm/pixel) pixel density settings. This region enabled the complete capture of the flame from the nozzle to the plate. For each test, an MP4 file with a 2- to 3-second imaging duration is produced during recording. This file is then converted into individual JPG frames, yielding 480–720 frames per test. A custom MATLAB image-processing code is then used to enhance, process, and analyze these images. The steps involved in processing images may be summarized as follows: data analysis; morphological operations for feature extraction; image enhancement, including cropping to preserve the region of interest; and thresholding for noise reduction.

3. Results and Discussion

Fig. 2 shows experimental images of the flame impinging on a flat aluminum plate at different inclination angles ($\theta = 0^\circ$, 20° , and 40°) and H/D ratios (H/D = 1, 3, and 5). From this figure, it can be seen that the flames in the images appear to be double; in fact, each is a single flame, but its reflection on the plate gives the impression of double flames. This case has been considered throughout the digital image processing operations, but its effect on the images has been omitted from this figure. It can be seen that both the angle and height of the plate are effective in determining the shape of the flame and, thus, its features. This is consistent with the results of [17]. Moreover, at the same height, the flame size increases with increasing plate inclination angle. The length of the flame in the upward direction is greater than that in the downward direction. This is due to a physical reason: an asymmetric distribution of unburned gases before impingement, which is consistent with the results of the research [9], [18].

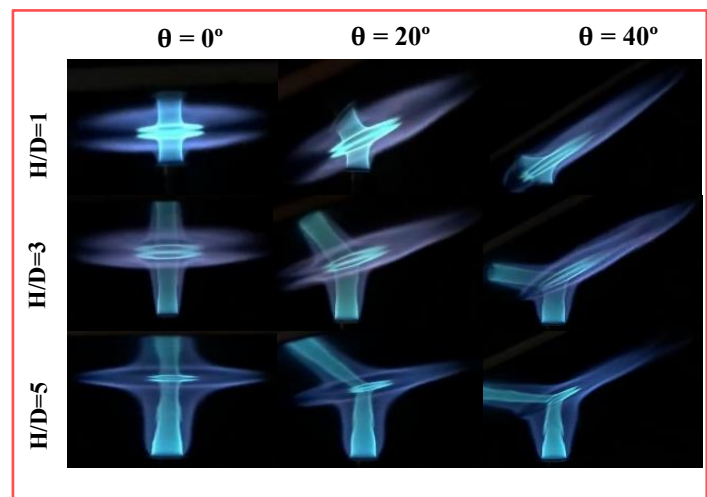


Figure 2. Images of flame impingement on a flat aluminum plate, for the present work.

Fig. 3 illustrates the change in flame area over time during impingement on the aluminum plate at different heights and

inclination angles. The flame area is normalized by the flame's projected area after the nozzle exit to eliminate the effects of nozzle diameter and camera position on the results. The figure clearly shows that the average flame area is directly proportional to both variables: the inclination angle and the plate height. As height increases, flame area gradually increases, and the area's fluctuation increases at higher heights. This is because of the increased flame height [19], [20].

Flame boundary fluctuations are evaluated using digital processing of the experimental images, and the results are shown in Fig. 4 for the aluminum plate. Flame size fluctuations are evaluated across 500 images for each case, with the difference in size between successive images assessed through

digital processing. It is assigned the letter (F^*) for expressing the fluctuation normalization with respect to nozzle diameter, i.e., flame size at the tip of the nozzle. A positive value of F^* indicates an increase in flame size, while a negative value indicates a decrease. Fig. 4 shows that flame fluctuations increase with increasing inclination angle at a fixed height. This is due to an increase in the tangential driving force, which spreads the flame over the plate [21]. Additionally, size fluctuations are directly proportional to the plate height [22]. This is evident at $H/D=5$, compared with the other heights. Another proof of the proportionality between flame size fluctuations and plate angle and height is the average fluctuation shown in Fig. 4, which clearly demonstrates this proportionality.

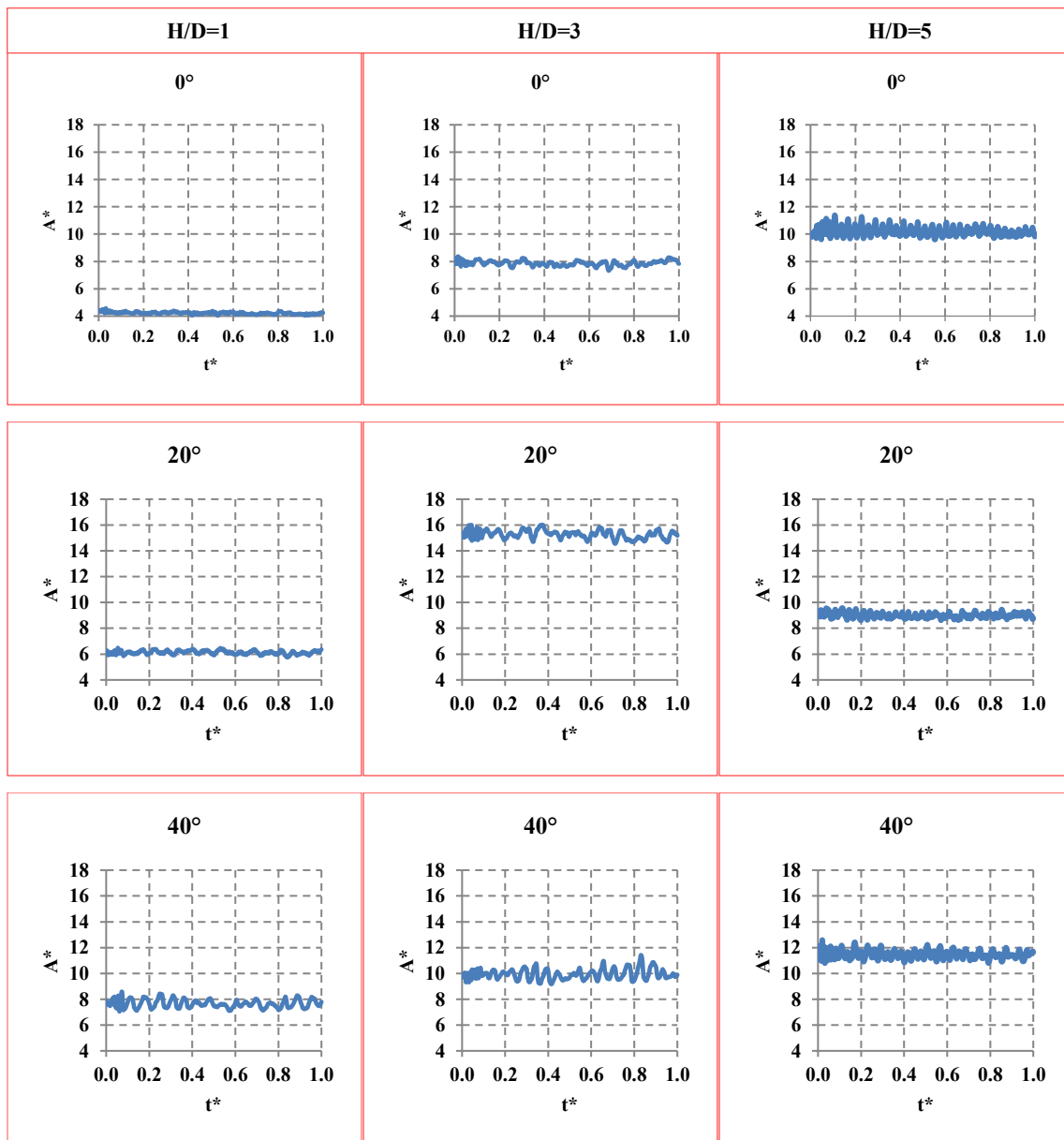


Figure 3. Temporal variation of flame area upon impingement on a flat aluminum plate.

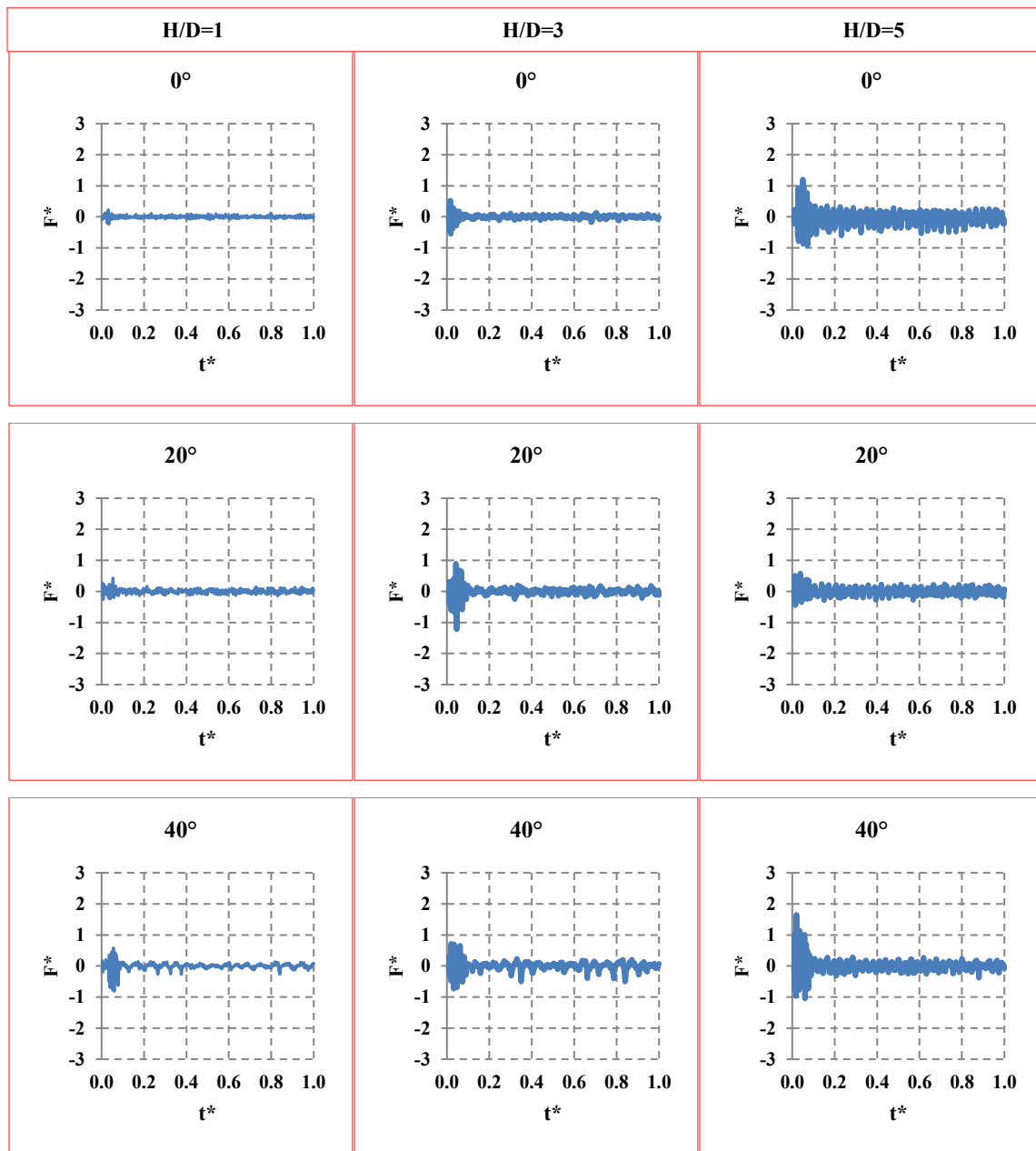


Figure 4. Temporal variation in flame size fluctuations upon impingement on the flat aluminum plate.

The average flame area shown in Figure 5 confirms the nearly linear relationship between flame expansion and plate inclination angle. The increase in projected area can be attributed to the reduction in normal momentum after impingement. Instead of being reflected directly away from the surface, a larger fraction of the flame momentum is redirected tangentially along the inclined plate. This flow redirection increases the flame attachment length and enlarges the visible combustion zone. Similar observations have been reported for inclined impinging flames, where larger inclination angles promote greater flame spread and an increased heat-transfer area.

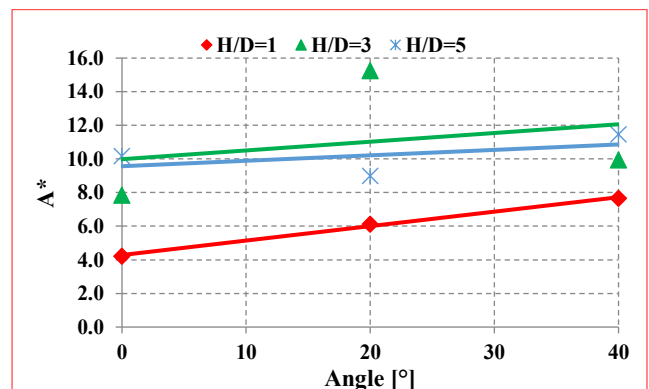


Figure 5. Variation of average flame area with plate angle at different heights.

Besides, from Fig. 6, it can be inferred that the flame experiences some fluctuation, or flicker, which is a characteristic of the flame. However, the amplitude of this fluctuation indicates the flame's stability.

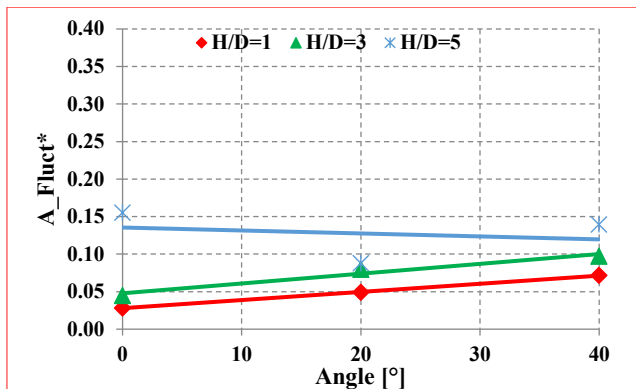


Figure 6. Effect of plate angle and height on the average fluctuation in flame size.

From Fig. 6, the proportionality between the fluctuation of flame size and the plate angle and height is clear. But this is not the case when $H/D = 3$. It is inversely proportional to the inclination angle. Flame illumination, expressed in the RGB color system, is of practical importance in combustion investigations. The R, G, and B intensities give indications about the nature of the combustion products and, in turn, the combustion process itself. For instance, the red (R) channel in the flame increases with increasing soot content, whereas the green (G) and blue (B) channels are directly connected to the concentrations of the C_2^* and CH^* radicals in the combustion products [23]-[24]. Therefore, they have been calculated in the present work to evaluate the effect of flame/plate impingement on the combustion process and combustion products at the set conditions.

Fig. 7 shows the effect of plate inclination angle on the average red, green, and blue color intensity of the flame luminescence (R-mean), (G-mean), and (B-mean) upon impinging an aluminum plate, respectively, at variable plate height. From the figure, it can be seen that R-Mean is proportional to the plate angle and increases with increasing height from $H/D = 1$ to 3, but decreases at $H/D = 5$. However, the influence of the inclination angle on R-Mean is a bit more intricate. Furthermore, the figure shows that the B-Mean and G-Mean are proportional to the inclination angle and height.

Overall, the results demonstrate that burner-to-plate distance primarily governs flame development before impingement, whereas plate inclination controls flame spreading after impingement. Increasing either parameter enlarges the projected flame area and increases flame fluctuations, reflecting stronger interactions between aerodynamic forces, buoyancy effects, and flame attachment along the heated surface. These findings provide valuable guidance for the design of industrial flame-heating systems, where optimization of burner spacing and impingement angle can improve heating uniformity while maintaining flame stability and combustion efficiency.

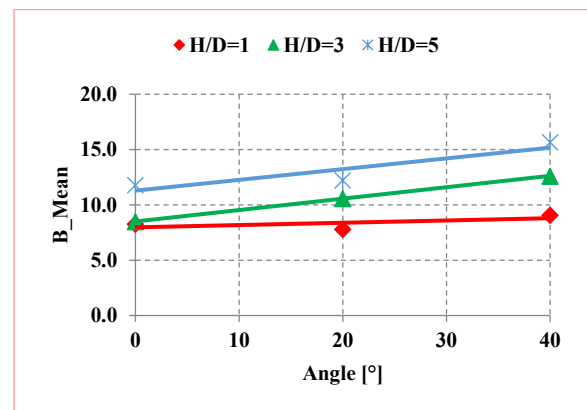
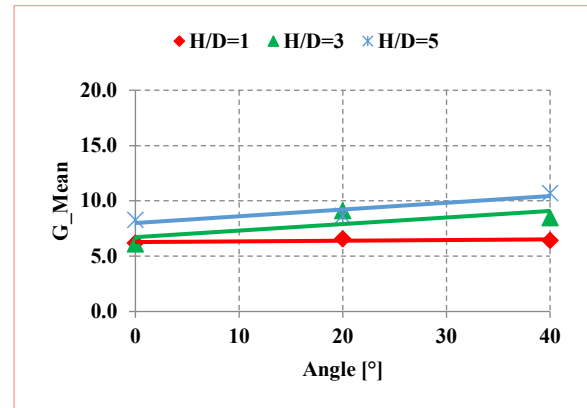
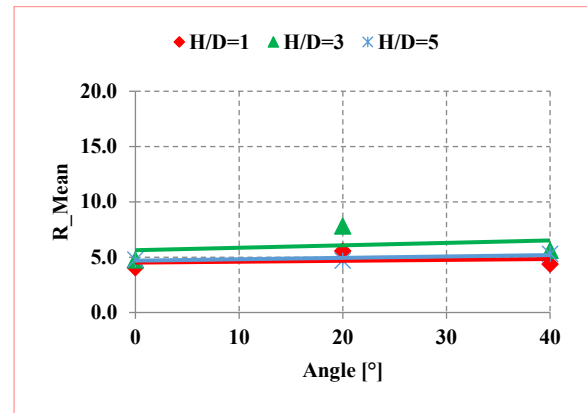


Figure 7. Effect of plate angle and height on flame illumination.

4. Conclusion

The experimental study focuses on the flame behavior of a premixed propane flame focused on a flat plate of aluminum for different burner-to-plate distances (H/D) and plate inclination angles. The high-speed imaging system and MATLAB-based digital image processing were successfully used to quantify the flame characteristics such as flame projected area, flame boundary fluctuations, and RGB color intensity. The selected method proved to be effective and non-invasive in the analysis of the flame dynamics under different impingement conditions.

Experimental results revealed that the geometry parameters are both important in characterizing the flame structure and stability. As the distance from the burner to the plate increased, the flame area and temporal fluctuations increased with an

increase in the length of flame prior to impingement, as a result of the increased buoyancy effects and aerodynamic instabilities. In the same way, the larger inclination angle of the plate enabled the flame to attach and spread around the plate, resulting in an asymmetric flame structure and further increase in the flame area. The flame fluctuations were typically found to increase with the increase of H/D and inclination angle, implying that as the impingement configuration became more suitable for stretching the flame and forming a vortex, the flame became less stable.

Changes in green and blue luminosity with the plate height were examined by flame luminosity analysis to demonstrate the increase of luminosity with inclination angle and height, which would represent the presence of chemiluminescent radicals that would be formed by efficient premixed combustion. The relatively low red intensity validated the combustion of propane with clean burning under the investigated operation conditions with minimal soot formation.

The engineering results indicate that the burner spacing and impingement angle can have a considerable impact on the spreading and stability of the flame as well as the combustion characteristics. The results can be used to develop and optimise industrial flame-heating processes which demand better heat transfer and combustion performance, including drying, metal processing, glass manufacturing, thermal treatment etc.

It is an experimental study on a limited number of burner-to-plate distances, burner inclination angles, burner geometry, and fuel type (propane) for the impingement plate material (Aluminum). Moreover, the investigation did not include measurements of temperature distribution, local heat flux and flow field.

Other operating parameters that could be used for further studies include different equivalence ratios, different burner Reynolds numbers, nozzle geometry, and material of the impingement surface. The use of advanced techniques like Particle Image Velocimetry (PIV), infrared thermography and heat-flux measurements would yield a more comprehensive understanding of the coupled fluid flow, combustion and heat-transfer phenomena involved in flame impingement. Moreover, with the aid of computational fluid dynamics (CFD) simulations it could be used to predict flame behaviour in a much greater range of operating conditions.

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Conflict of interest

The authors declare that publication of this manuscript does not involve any conflicts of interest.

Author Contribution Statement

The first author conducted the research and performed the calculations under the supervision of the second author. Both authors contributed to the discussion and data analysis.

Nomenclature

H/D	Distance between nozzle and plate
θ	Inclination angle
RGB	Red, green, and blue

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