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Experimental Investigation of Premixed LPG-Air Emission Profile During Flame Impingement Process[1]

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Abstract

In the present study, emission profile of premixed 90% propane-10% butane flame, namely LPG (Liquified Petroleum Gas) was experimentally investigated. The fuel was mixed in premixed chamber which then ignited through 2 mm nozzle diameter. The fuel flow was controlled via solenoid valve installed upstream the burner body. This valve is synchronized with high-speed camera and thus, the flame kernel propagation can be captured. In this experiment, the effect of equivalence ratio, initial pressure, and separation distance (H/D) on combustion emissions and flames that produced from a mixture of LPG-air fuel was investigated. The flue gas analyser probe was installed inside the contained flame impingement test allowing to record CO, CO_2, and unburnt HC data. The variation of the equivalence ratio used in this study are 0.8, 1.0, and 1.2. For variations in initial pressure used, 1 bar, 1.2 bar, and 1.4 bar. Variation of separation distance (H/D) that will be used are 4.5, 5.5, and 6.5. The result of this experiment shows that CO increases with increase in equivalence ratio, and initial pressure of premixed gas. For separation distance CO level decreases as the plate progressively moves away from the nozzle. CO and CO_2 concentration increases as the equivalence ratio and initial pressure increases. The highest average CO concentration was 183 ppm that was found in ER 1.2 with the lowest H/D. Highest mean CO_2 concentration was found in the same ER with the highest H/D, which was 4267 ppm.

Keywords: premixed flame, flame impingement, emission profile

Abstrak

Penelitian ini difokuskan pada studi pengaruh jarak tumbukan api terhadap emisi yang dihasilkan dari pembakaran LPG-udara secara *premixed*. Bahan bakar dan udara dicampur pada tabung premixed sebelum dialirkan melalui nozzle dengan diameter 2-mm. Aliran bahan bakar dan udara diatur melalui *solenoid valve* yang dipasang tepat sebelum burner. Rambatan api sampai terjadi proses tumbukan direkam dengan menggunakan high-speed camera. Emisi CO, CO_2, dan HC yang tidak terbakar diukur dengan flue gas analyser yang dipasang di atas *nozzle burner*. Pada paper ini, campuran bahan bakar dan udara (*equivalence ratio*) yang digunakan adalah 0.8, 1.0, dan 1.2 dengan tekanan awal campuran 1, 1.2, dan 1.4 bar. Jarak tumbukan bervariasi dari H/D 4.5, 5.5, dan 6.5 dengan H adalah jarak dari nozzle burner ke plat tumbukan dan D adalah diameter nozzle. Dari penelitian tersebut, didapatkan data bahwa konsentrasi CO dan CO_2 meningkat seiring dengan peningkatan equivalence ratio dan tekanan awal campuran. Jarak tumbukan H/D memiliki efek sebaliknya dengan berkontribusi negatif seiring dengan berkurangnya nilai H/D.

Kata kunci : Emisi CO_2, pembakaran, rambat api, profil emisi

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1. INTRODUCTION

Despite of massively implementation of electrical mobility as well as renewable energy utilization, combustion is still playing a dominant role on existing engineering devices. As example, chemical energy conversion through combustor in aviation fleet, material processing, and heat generation from various low-carbon fuel. The fact that, maturity of this technology, relatively high efficiency process, and high energy density contained by the fuel, combustion process contributes to the rise of global average temperature due to its unavoidable product of carbon dioxide. Moreover, incomplete combustion process leads to produce another product, carbon monoxide, which is harmful for the human's health. Incomplete combustion may take place due to several causes such as lack of reactants, insufficient ignition energy or temperature and obstruction during combustion process (Chien dkk., 2016; Wei dkk., 2022). To address the incomplete combustion due to obstruction, in this case specific to flame impingement, a basic physic of such phenomena are presented in (Dong dkk., 2002, Foat dkk., 2001; Zhang dan Bray, 1999; Chander dan Ray, 2005). A regime showing the flame shape during the impingement based on its equivalence ratio and stretch rate are presented in (Zhang dan Bray, 1999). The regime contains lean-extinction limit, disc region, ring-like flame, unresolved region, disc & ring region which are governed by the radial flow velocity of the impingement jet. This type of characterization was also studied by (Foat dkk., 2001). Some key findings were the instability of fuel-rich flame, turbulence structure due to certain flow conditions, holes in the flame sheet, and as the equivalence ratio increase the turbulence wrinkle flame surface disappear. On the other hand, characterization in term of heat transfer was studied by changing the plate angle (Dong dkk., 2002). The main findings were the maximum heat flux position is shifted away as the inclination angle reduced, local heat flux are more sensitive to the inclination angle in streamline direction, and inclination angle reduce average heat transfer capabilities. In real engineering application, flame impingement appears such as in material processing (Shao dkk., 2018; G. K. Malikov dkk., 2001) and typical burner/combustor representing jet-engine combustor (Okafor dkk., 2021; He dkk., 2022; Fan dkk., 2023).

The present study focuses on the effect of the impingement plate distance in which affects the emission profile (CO, CO_2, and unburnt HC). Reported the CO profile decreases as the plate moves farther the flame. The flame was non-premixed methane-air through 2 mm nozzle outlet (Chien dkk., 2016). The measured CO was based on the ratio of impingement distance H/D, H is the distance between nozzle tip to the plate and D is nozzle diameter. H/D was varied from 1.5 to 13.5 and its effect on the CO was observed increase significantly as the plate moved closer to the nozzle tip. The effect of equivalence ratio on emission profile was investigated numerically by taking premixed biogas-hydrogen fuel blend (Wei dkk., 2022). The chemical kinetics and transport parameter, quenching distance, wall heat flux and thermochemical states of CO/NO were presented too. Studied the plate temperature effect on heat transfer and emission profile (Li dkk., 2010). The plate temperature has a significant effect on the flame impingement heating where the heat flux is suppressed as the plate temperature increase. Moreover, the key finding is the plate temperature affects the CO/NOx emission significantly. As the plate temperature increase, the combustion process is enhanced and thus lowering CO. On the other hand, it increases the NO_x production. Other study, involving the effect of equivalence ratio, showed that CO emission increase as the equivalence ratio increase (Mishra, 2004). The same trend for CO_2 was observed too while it is in opposite way for the NO_x emission. The same result was obtained by (Sakai dkk., 2020). Nevertheless, as far as the author knowledge, these presented studies are focused on the final result which indeed provide us valuable insight in how the impingement plate affect the emission profile. Furthermore, the detail mechanism in how the flame propagates and hit the plate are not covered yet. It is suspected that the physical mechanism of such phenomena may contribute to the emission profile.

2. EXPERIMENTAL SETUP

The present investigation was conducted in a co-flow burner fueled by 90% propane and 10% butane, namely as LPG (Liquified Petroleum Gas). As shown in Figure 1, the fuel mixture (LPG + air) is premixed in the mixing chamber. Prior ignited, its pressure is controlled via pressure transducer (P2) in the flow-manifold. A solenoid valve is installed upstream the burner and synchronized with the high-speed camera trigger system. This system allows to observe flame kernel development as well as flame impingement mechanisms. The tests were performed for equivalence ratio 0.80, 1.05, and 1.20. The initial pressure was varied for 1.0, 1.2, and 1.4 bar while the H/D is 4.5, 5.5, and 6.5. A flue gas analyzer probe was installed inside the test section to record the emission profile of CO, CO_2, and unburnt hydrocarbon. This result was then plotted against impingement distance at constant initial pressure. In addition, it was also checked at constant equivalence ratio.

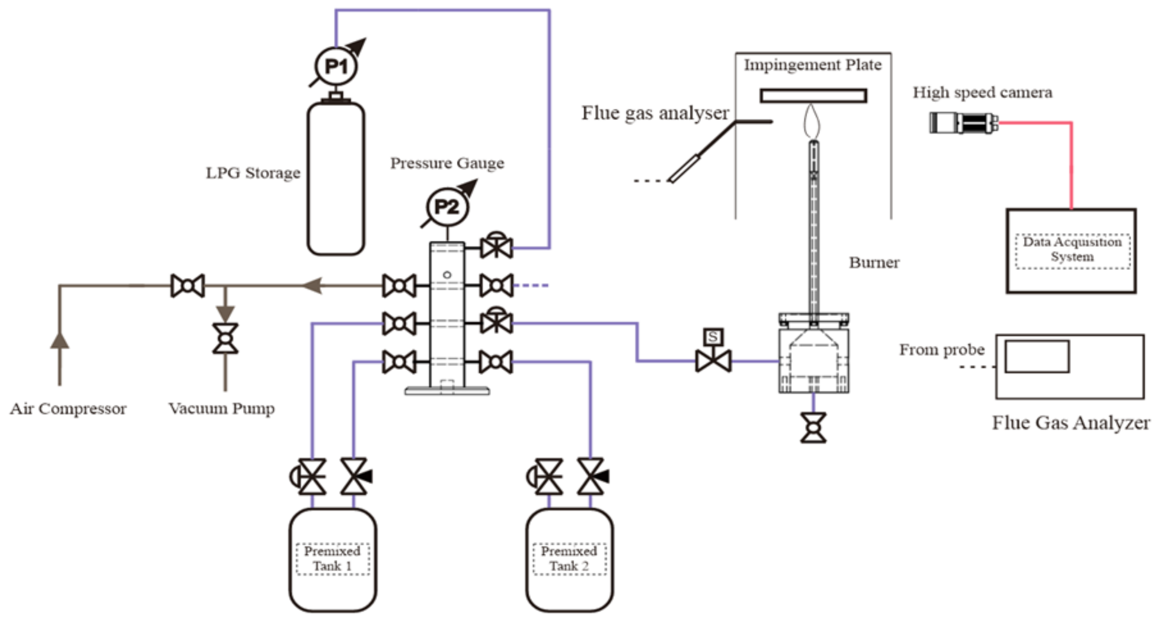


Figure 1. Experimental set-up of LPG-Air flame impingement test

3. RESULTS

Figure 2 to 7 show the preliminary result of the present study where it was found that as the plate moved closer to the nozzle tip end, the CO emission increased. The initial pressure tends to affect on the same sense. As the pressure increase, the emission increase. All these finding can be explained as quenching phenomena. As the flame is obstructed, its temperature is suppressed and, in this situation, certain chemical process may not take place due to insufficient temperature reaction. As a consequence, unburnt fuel concentration may increase and what we observed clearly showed that the CO increased. On the other word, the combustion process is toward incomplete combustion.

Figure 2 shows diversity of CO concentration that affected by H/D ratio for three different initial pressure. It is seen that the higher the position of plate CO emission of the combustion became lower. CO concentration increases with the increasing of initial pressure. Figure 3 provides 2 charts in Fig. 3(a), (b), and (c) respectively, for ϕ = 0.8, 1, 1.2. It can be seen from this chart the highest CO emission was produced at the lowest H/d (4.5) and it slightly decreased when impinging plate was moved away further from the tip of nozzle. But there is no difference between H/d 4.5 and 5.5 in the result of CO concentration at lean and stoichiometric mixture. It means that separation distance will only has a big impact if there is a bigger space between each H/d since each H/d is only 2 mm apart.

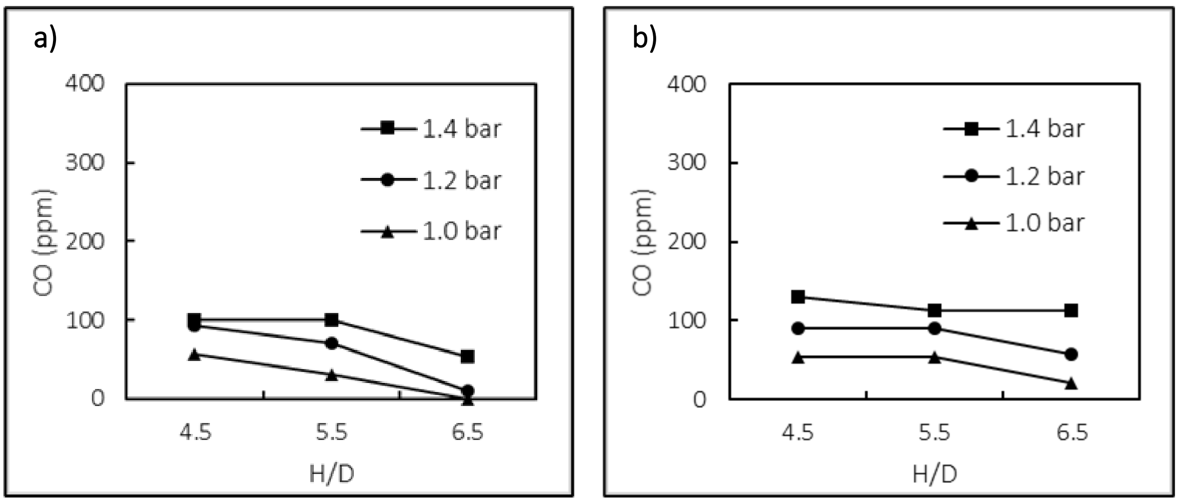


Figure 2. CO emission at various impingement distance for equivalence ratio (a) 0.8; (b) 1 and (c) 1.2

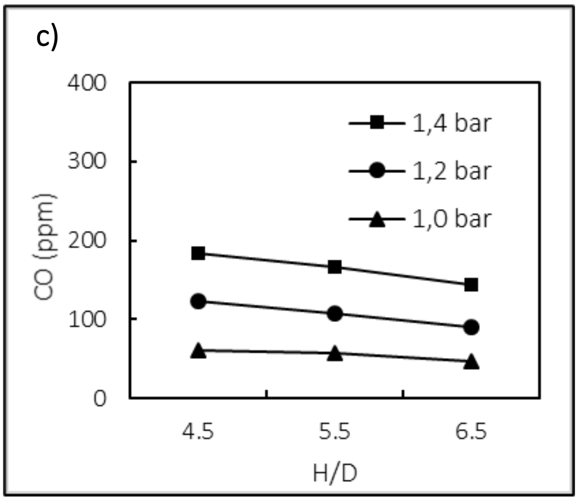
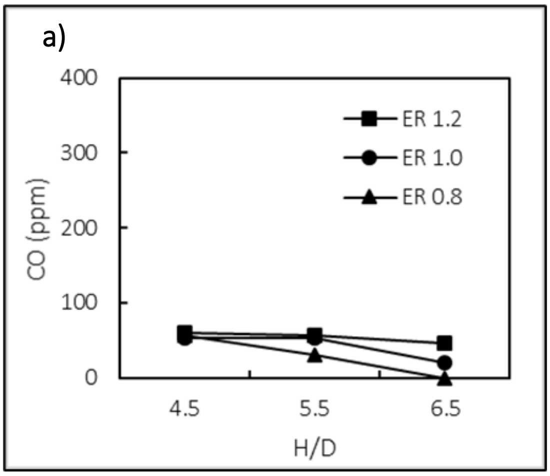
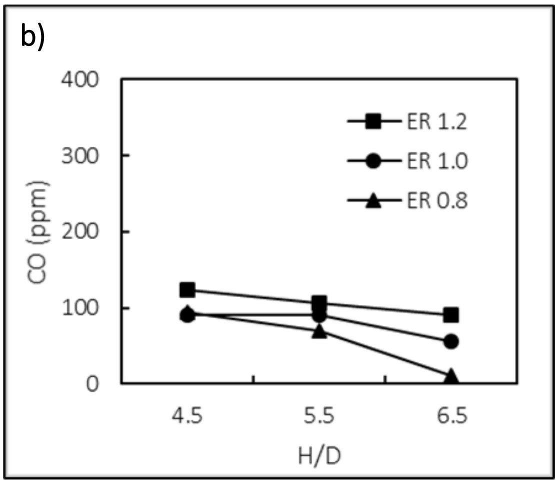


Figure 2. CO emission at various impingement distance for equivalence ratio (a) 0.8; (b) 1 and (c) 1.2 (lanjutan)

Figure 3 also shows the variation of CO but each line indicates different equivalence ratio. These charts explained increasing equivalence ratio affect CO growth in the same pressure. Highest emission produced is 183 ppm and it happened when the combustion has the biggest initial pressure and so does equivalence ratio. From all charts embedded in this study it can be concluded mixture of gas has the biggest leverage in the production of CO emission.





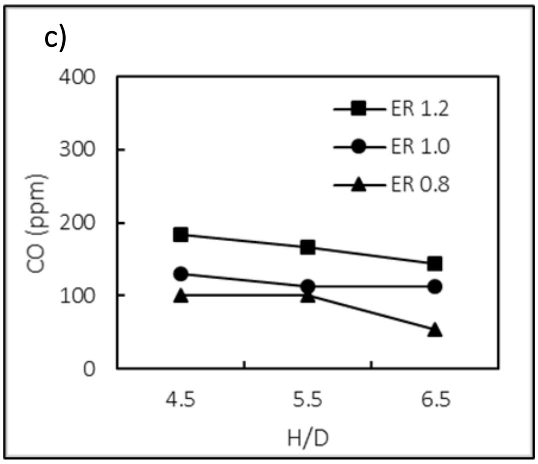


Figure 3. CO emission at various impingement distance for various initial pressure (a) 1 bar; (b) 1.2 bar and (c) 1.4 bar

CO_2 has been approved as a result of complete combustion. In this research CO and CO_2 were both taken at the same time due to the measurement of flue gas analyzer. Figure 4 shows how initial pressure gives its effect on CO_2 emission. It is seen that increase in separation distance tends to reduce CO_2 concentration. It can be caused by the decrease of actual equivalence ratio due to excess air intake and lowered CO_2 concentration (Mishra, 2004). CO_2 level increases with increase in initial pressure for all separation distance. This is caused by the number of fuel particles increases by the increasing of pressure as described in ideal gas law.

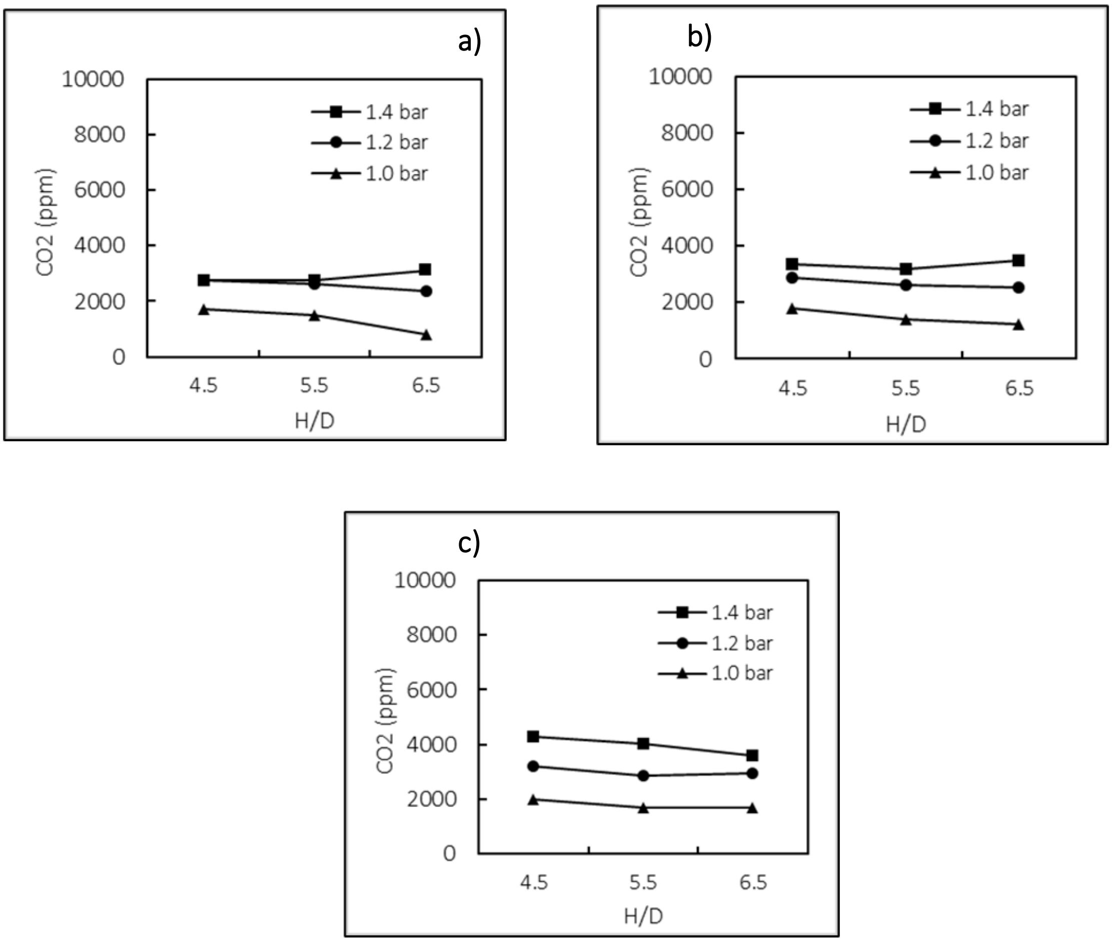


Figure 4. CO_2 emission at various impingement distance for equivalence ratio (a) 0.8; (b) 1 and (c) 1.2

Figure 5 shows equivalence ratio effects on CO_2 concentration level. It is seen that equivalence ratio increased followed by an increase in CO_2 levels. Equivalence ratio represents the ratio between fuel and air contained in the premix gas mixture. So as if LPG ratio gets bigger will then it will affect the amount of CO_2 gas produced in the post-combustion phase.

Figure 6 shows effect of initial pressure on HC emissions at several separation distances at various equivalence ratios. It is seen that the effect of separation distance is negligible on HC emission. Separation distance does not have a big role because the table shows inconsistent HC rates. In this case the increase in pressure affects the concentration of HC. Where the greater the initial pressure, the concentration of HC increases. But the lowest HC concentration was obtained at 1.2 bar.

Figure 7 shows effect of equivalence ratio on HC emissions at several separation distances at various initial pressure. As shown in the charts as the equivalence ratio increases, HC concentration decreases. This is caused by lean mixture can reduces burning rate of gas mixture and forms thick quenching layer near impinging plate surface (Sakai dkk., 2020). From all of the charts can be concluded that to reduce HC emission from combustion reaction, the combustion process must be carried out by determining the proper gas pressure and air – fuel mixture.

From all emission gases that had been taken, it can be concluded that a low-emission combustion really needs to be considered in all aspects of its expenditure. CO, CO_2, or HC, all of these gases must be controlled so that each gas concentration does not exceed reasonable limits so that the combustion reaction can be more efficient and does not pollute the surrounding environment.

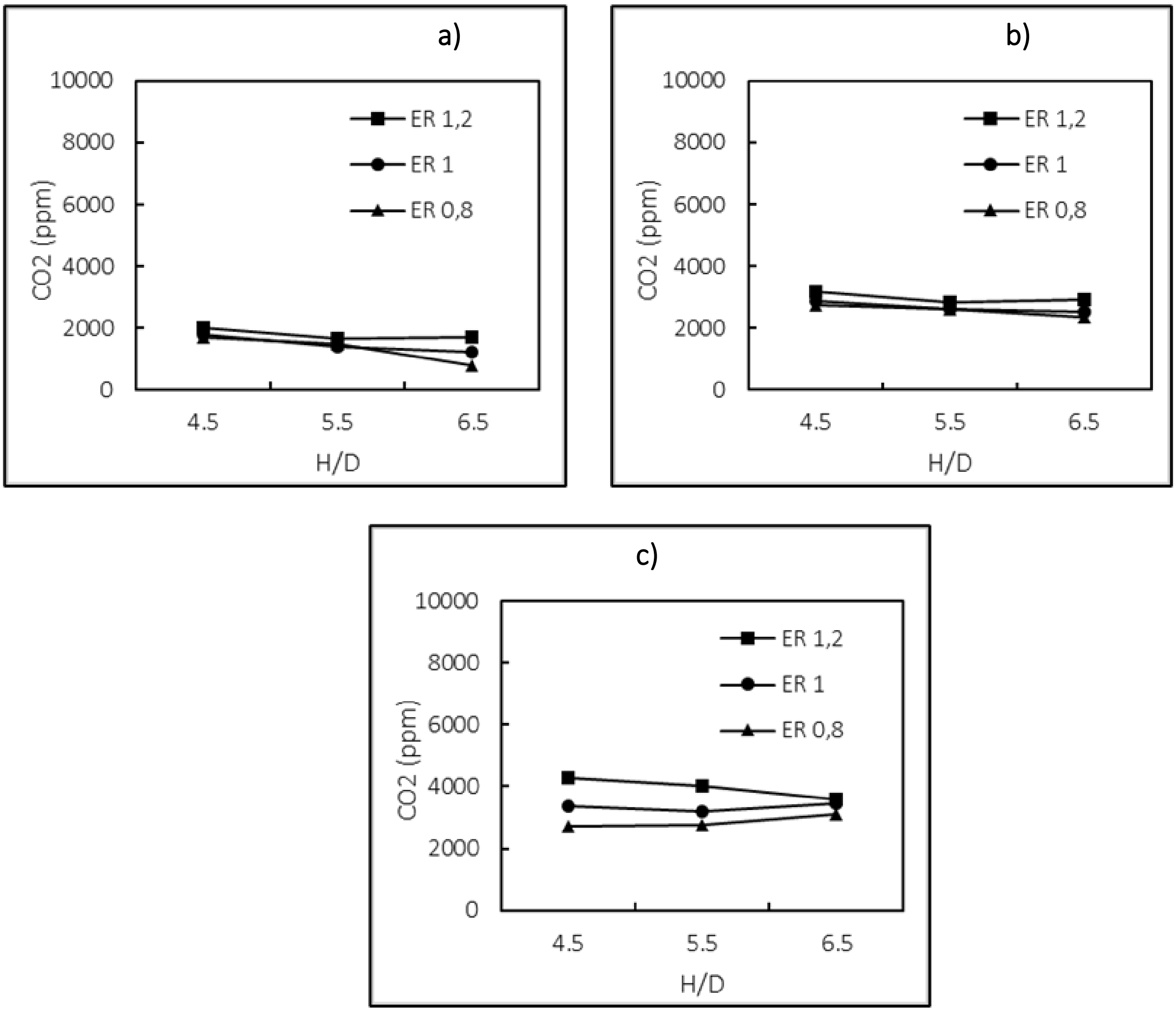
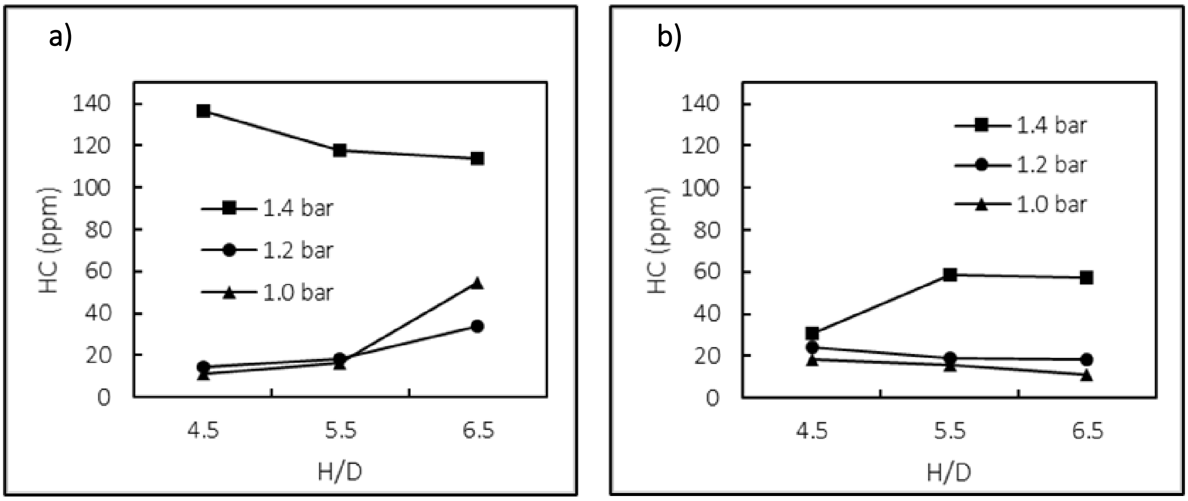


Figure 5. CO_2 emission at various impingement distance for various initial pressure (a) 1 bar; (b) 1.2 bar and (c) 1.4 bar.



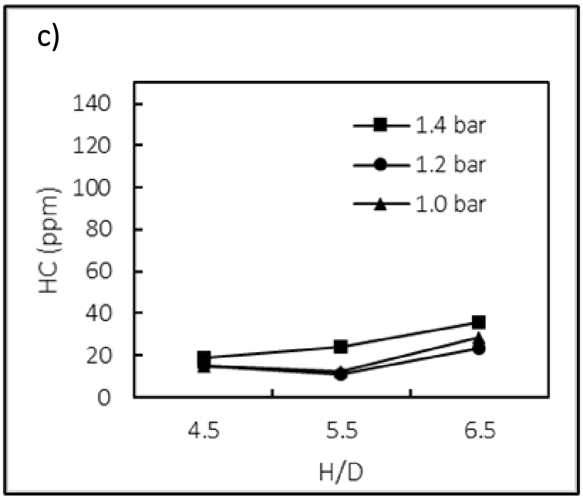
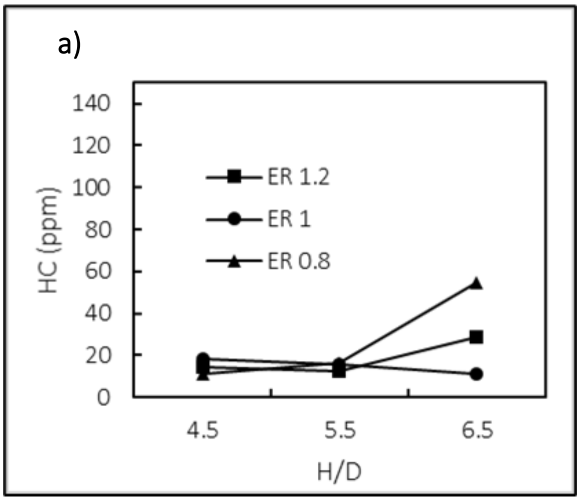
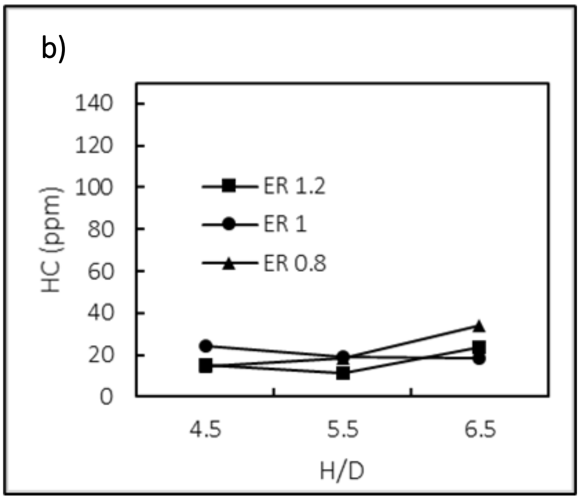


Figure 6. HC emission at various impingement distance for equivalence ratio (a) 0.8; (b) 1 and (c) 1.2





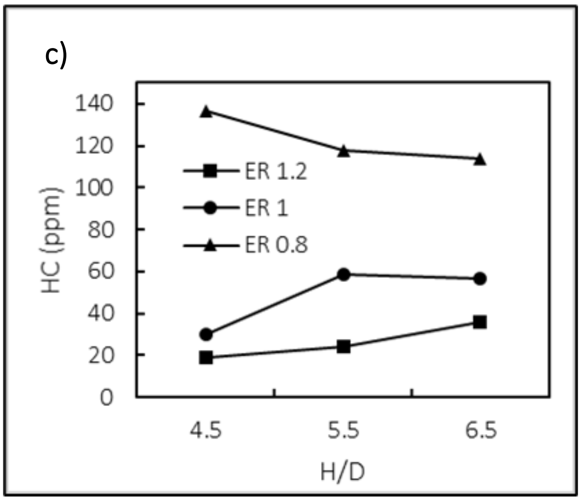


Figure 7. HC emission at various impingement distance for various initial pressure (a) 1 bar; (b) 1.2 bar and (c) 1.4 bar

4. CONCLUSION

This paper presents the effect of flame impingement on the CO_2, CO, and unburnt HC concentration under different impingement distance conditions as well as equivalence ratio. Some key takeaways finding are as follows:

1. CO concentration increases as the initial pressure and equivalence ratio increase, whilst separation distance affects conversely.
2. CO_2 concentration increases as the initial pressure and equivalence ratio increase, whilst separation distance had no significant effect.
3. HC is affected by gas pressure, where the concentration of HC increases with increasing pressure. An exception occurred at a pressure of 1.2 bar. It can be interpreted that the best ignition occurs in the gas combustion process with a pressure of 1.2 bar.

Next work should reveal physical mechanism of flame impingement which leads to increase the emission. High speed imaging should be considered for the next work and presented in upcoming publication.

5. REFERENCES

C. He, J. Jiang, M. Sun, Y. Yu, K. Liu, dan B. Zhang, 2022. Analysis of the NH3 blended ratio on the impinging flame structure in non-premixed CH4/NH3/air combustion. *Fuel*, Vol. 330, 125559.

D. P. Mishra, 2004. Emission studies of impinging premixed flames. *Fuel*, Vol. 83, pp. 1743–1748.

E. C. Okafor, M. Tsukamoto, A. Hayakawa, K.D.K.A. Somarathne, T. Kudo, T. Tsujimura, dan H. Kobayashi, 2021. Influence of wall heat loss on the emission characteristics of premixed ammonia-air swirling flames interacting with the combustor wall. *Proceedings of the Combustion Institute*, Vol. 38, pp. 5139–5146.

G. K. Malikov, D. L. Lobanov, K. Y. Malikov, V. G. Lisienko, R. Viskanta, dan A. G. Fedorov, 2021. Direct flame impingement heating for rapid thermal materials processing. *International Journal of Heat and Mass Transfer*, Vol. 44, pp. 1751-1758.

H. B. Li, H. S. Zhen, C. W. Leung, dan C. S. Cheung, 2010. Effects of plate temperature on heat transfer and emissions of impinging flames. *International Journal of Heat and Mass Transfer*, Vol. 53, pp. 4176–4184.

L. Fan, B. Savard, S. Carlyle, M. Nozari, R. Naaman, B. Fond, dan P. Vena, 2023. Simultaneous stereo‐PIV and OH × CH_2O PLIF measurements in turbulent ultra lean CH_4/H_2 swirling wall‐impinging flames. *Proceedings of the Combustion Institute*, Vol. 39, pp. 2179-2188.

L. L. Dong, C. W. Leung, dan C. S. Cheung, 2002. Heat transfer characteristics of premixed butane/air flame jet impinging on an inclined flat surface. *Heat and Mass Transfer*, Vol. 39, pp. 19–26.

S. Chander dan A. Ray, 2005. Flame impingement heat transfer: A review. *Energy Conversion and Management*, Vol. 46, pp. 2803–2837.

H. Sakai, S. Sato, S. Mori, S. Nogawa, dan K. Nakatani, 2020. Analysis of unburned hydrocarbon generated from wall under lean combustion. SAE Technical Paper 2020-01-0295, p.13.

T. Foat, K.P. Yap dan Y. Zhang, 2001. The visualization and mapping of turbulent premixed impinging flames. *Combustion and Flame*, Vol. 125, pp. 839-851.

Y. Chien, D.E. Martin, dan D.D. Rankin, 2016. CO emission from an impinging non-premixed flame. *Combustion and Flame*, Vol. 174, pp. 16-24.

Y. Zhang, K.N.C. Bray, 1999. Characterization of impinging jet flames. *Combustion and Flame*, Vol. 116, pp. 671-674.

Z. Shao, J. Jiang, dan J. Lin, 2018. Feasibility study on direct flame impingement heating applied for the solution heat treatment, forming and cold die quenching technique. *Journal of Manufacturing Processes*, Vol. 36, pp. 398–404.

Z. Wei, H. Liu, Z. Chen, Z. Liu, dan H. Zhen, 2022. Quenching distance, wall heat flux and CO/NO thermochemical states in the wall vicinity of laminar premixed biogas-hydrogen impinging flame. *Fuel*, Vol. 307, p. 121849.