SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Numerical Investigation of Operating Conditions that Lead to Flat Flames, Flashback, and Blowout in A Surface-Stabilized Combustion Burner

Carlos E. Arrieta[1,*], Mario Luna-DelRisco[1], Arley Cardona[2,3], Jorge Sierra del Río[2], Alejandro Ruiz Sánchez[2], Lisandra Rocha-Meneses[4], Jhojan Stiven Zea Fernández[1]

[1] Facultad de Ingeniería, Grupo de Investigación en Ingeniería en Energía, Universidad de Medellín, Medellín, Colombia
[2] Department of Mechatronics Engineering, Research Group-MATyER, Instituto Tecnológico Metropolitano, Medellín, Colombia
[3] Department of Mechanical Engineering, Universidad de Antioquia, Medellín, Colombia
[4] Biomass & Bioenergy Research Group, Center for Sustainable Energy and Power Systems Research, Research Institute of Sciences and Engineering, University of Sharjah, 27272 Sharjah, United Arab Emirates

ARTICLE INFO

Article history:
Received 5 September 2022
Received in revised form 6 October 2022
Accepted 6 November 2022
Available online 1 April 2023

Keywords:
Surface-stabilized combustion; Numerical simulation; Two-dimensional model; Flame stabilization

ABSTRACT

Surface-stabilized combustion burners or surface-radiant burners use perforated ceramic plates, ceramic foams, or metal fibers to stabilize a premixed flame. These burners are the most straightforward alternative to have both, the benefits of the reactant preheating technique and a great amount of heat transferred by radiation from the burner to the load. However, in its design, one of the greatest difficulties is to predict the flame stability limits; especially under operating conditions that lead to flashbacks and blowouts. This work presents a computational methodology based on the finite volume method with a two-dimensional domain to predict the flame curvature towards the unburned and burned gas that occurs before flashback and blowout, respectively. In the methodology, continuity, momentum, energy, and chemical species equations are solved to obtain the increase in the surface area of the flame. It was observed that this value can be used as a criterion to predict whether an operating condition is stable. When comparing the numerical results with experimental results reported in the literature, good predictions of the operating conditions that lead to flashbacks and blowouts are observed.

1. Introduction

In recent years, the worldwide concern about high consumption of fossil fuels and large amount of polluting emissions [1] have stimulated scientific interests in new combustion techniques [2-5]. In the group of emerging technologies, surface-stabilized combustion burners are one of the most promising devices because, in addition to respond to the aforementioned needs, they exhibit excellent fuel-flexibility features [6-9].

Surface-stabilized combustion burners are burners that use perforated ceramic plates, ceramic foams, or metal fibers to stabilize a premixed flame; generally, a lean premixed flame. The operation principle is shown in Figure 1. If the unburned mixture velocity is kept in certain limits with respect

---

[*] *Corresponding author.*
E-mail address: carrieta@udemedellin.edu.co (Carlos E. Arrieta)

https://doi.org/10.37934/cfdl.15.4.106113

to the laminar burning velocity, a flat flame is obtained on the burner outlet plane. As a result, the burner surface heats up. Part of this energy is then transferred by radiation to the load and the other part preheat the unburned mixture [10,11].

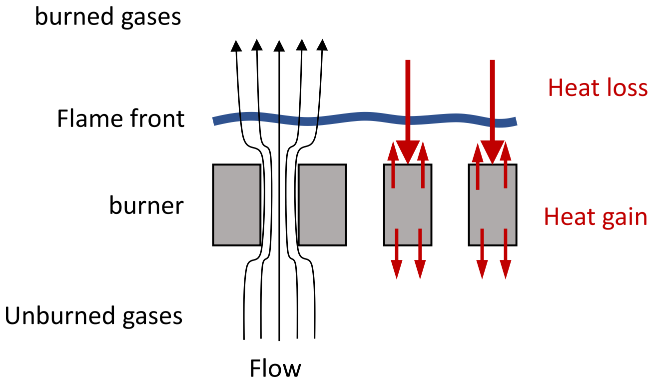


Fig. 1. Operation principle of a surface-stabilized burner

Although the operation principle is simple, one of the greatest difficulties in the design of these burners is to predict the unburned mixture velocities that lead to the operation mode described above. If the output velocity is too high, it is necessary to implement complicated aerodynamical strategies to stabilize the flame. When this is not possible, the flame just blows out. On the other hand, at low output velocities the flame reaches the burner. If the preheating temperature is too high, the mixture penetrates the burner leading to flashback.

Until a few years ago, numerical simulations of surface-stabilized burners were carried out considering one-dimensional models [12,13]. They predict with great precision the position of the flame front for given values of porosity of porous media, gas flow and equivalence ratio, as can be observed in the work of Lammers *et al.,* [14,15]; one of the most cited works in the literature. However, one-dimensional models do not reproduce very well some flame behaviours that may indicate that the system is about to reach unstable conditions. Recently, Kishroe *et al.,* [16,17]. performed a numerical study of porous media burners with a three-dimensional model. Like the results obtained with one-dimensional models, the three-dimensional model predicted with great precision the experiments carried out under the same operating conditions. However, it was also reported that this model allows to predict flame behaviours that are important to identify flame stability range, such as cellular structures on the flame. The main drawback of three-dimensional models is the high computation cost. For example, Kishroe *et al.,* reported computational domains that exceeds four million of control volumes.

In this work, numerical simulations of methane-air premixed flames on a surface-stabilized combustion burner were carried out to identify the reliability of two-dimensional model for predicting operating conditions that may lead to flashback. Although two-dimensional models are not expected to be capable of reproducing some three-dimensional behaviours, they computational cost is not much greater than that of one-dimensional models [18-21]. Additionally, they offer important results for the design process of surface-stabilized combustion burners, which are discussed in this paper, such as the ability to identify whether certain unburned mixture velocity leads to a flat flame operation condition. The experimental data to validate the results were reported by the authors in a previous study [1]. The results indicate that the numerical approach implemented in this work allows to predict the flame stability in a surface-stabilized combustion burner.

2. Numerical Model

Figure 2 shows the cross section of the burner surface or burner port. Gray rectangles represent the solid part of the burner port and the spaces between them represents the burner holes or pores. The flame has been represented in a wave form, since experimental tests have reported that the flame always tends to have this behaviour. That is why a minimum curvature value is defined. This allows to identify whether a flame can be considered as a “flat flame”. The definition of this curvature value will be shown later.

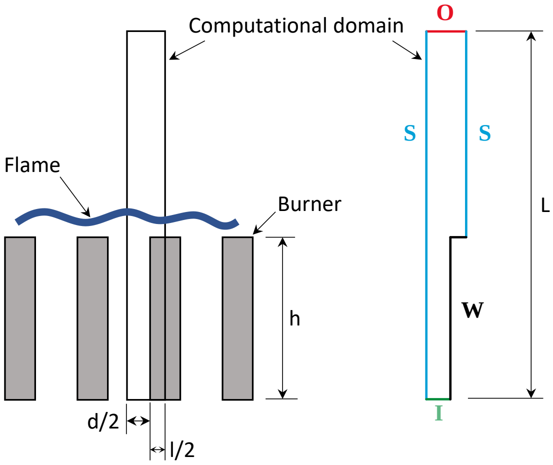


Fig. 2. Computational domain

In Figure 2, a rectangle has been drawn to represent the computational domain. The pores are considered as if they were slots and only half of one of them is studied taking advantage of the symmetry of the system. In previous study [2], the geometric properties of the burner are discussed. From this information is possible to obtain that diameter of the holes (d) is 1 mm and the distance between the holes (l) is 0.3 mm. Additionally, the thickness of the burner, h, is 25 mm.

Boundary conditions were defined as I: velocity inlet, W: solid phase, S: symmetry, and O: pressure outlet. The total height of the calculation domain (L) is 30 mm, which is considered long enough since the reaction occurs very close to the burner.

Before checking mesh independence, computational domain consisted of 334 control volumes, as shown in Figure 3(a). To improve readability, just a portion of the numerical domain is shown. Since the flame is expected to be very thin, it is necessary to refine the mesh especially in those areas where reactions occur. That is the reason why once the independence of the mesh has been achieved, the mesh is denser towards the burner surface and its size increases progressively as it moves away from the burner, as it is shown in Figure 3(b). It was observed that with a size of control volumes greater than 18000 the solution does not present significant changes.


(a) (b)

Fig. 3. Computational domain (a) Before mesh independence (b) After mesh independence

ANSYS-Fluent was used to perform the numerical simulations. Steady state equations related to conservation of mass, momentum, energy, and species were solved simultaneously [22]. Radiation at the burner surface was considered using a user defined function (UDF). Surrounding temperature was assumed to be 25 °C. A laminar, segregated, double precision solution model is used to solve the governing equations mentioned above. Density, Specific heat, thermal conductivity, and viscosity of the unburned mixture are calculated using the ideal gas mixture law. As described in Ref. [2], the material of the porous media consists of alumina (Al_2O_3).

To determine the source terms of species in the energy equation, the conservation of chemical species equation must be solved. Since the fuel used is methane, the Westbrook and Dryer two-step reaction mechanism was used in this work. In this case, reactions are too fast, which leads to inequalities in the time scales of the system and therefore the solution diverge. To solve this problem, the stiff chemistry solver method is used.

Calculations were initialized with the velocity inlet conditions of the methane-air mixtures described in Ref. [2]. Figure 4 shows the velocity contours of one operating condition. Running pre-mixed combustion simulations is often difficult. To get the reactions to start, it is necessary to perform simulations with the cold mixture until the momentum equation is solved and subsequently, a temperature of 2000 K is stablished in the control volumes downstream of the burner. As a convergence criterion, constant value of the residuals and temperature 1mm downstream of the burner outlet and a report of heat flux balances close to zero were considered.

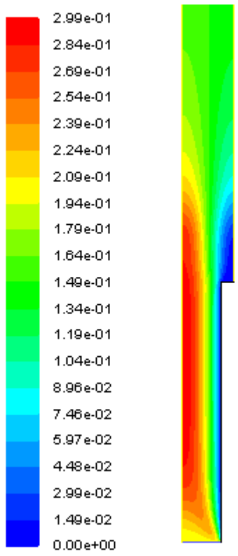
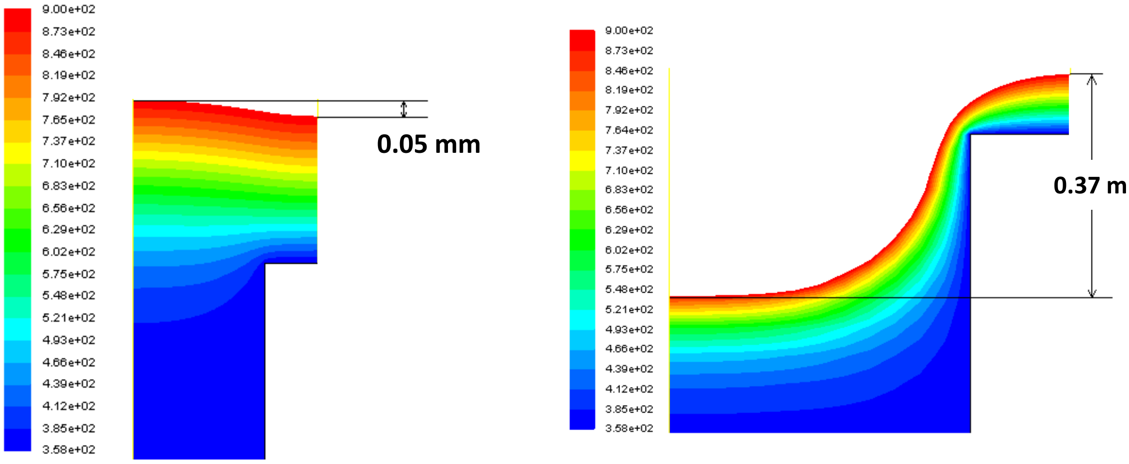


Fig. 4. Velocity contours

3. Results

Some results of the calculations are shown in Figure 5. This figure shows the temperature distribution in the flame for a flat flame (stable) operation condition. Since the lines are curved, the flame is assumed to be curved. To define whether a flame is flat, the increase in the surface area is calculated. To accomplish this, the curved flame is assumed to be conical, while a perfectly flat flame is assumed to be a circular surface parallel to the burner surface [23]. Therefore, the increase in the surface area can be calculated as follows:

$$S_{increment} = \frac{\pi l \sqrt{l^2+\delta^2}}{\pi l^2} \quad (1)$$



(a) (b)

Fig. 5. Temperature contours

Where δ is the difference between the upper part of the flame and the lower part of the line at 900 K, as shown in Figure 6. Here, the flame is considered flat (stable) if the increase in surface area, $S_{increment}$, is less than 1 for flames that exhibit a positive curvature and less than 1.5 for flames that exhibit a negative curvature. It was observed that, generally, operating conditions that exceed a value of 1 towards the burned gases lead to blow out, as shown in Figure 5(a). On the other hand, it was observed that operating conditions that exceed a value of 1.5 towards the burned gases lead to blow out, as shown in Figure 5(a).

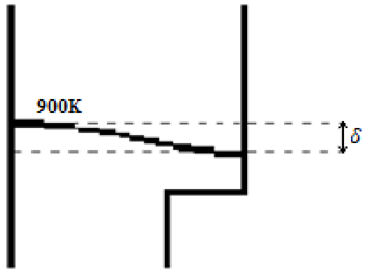


Fig. 6. Schematic representation of flame curvature

Figure 7 shows the mole fractions of the species in the preheating zone and in the reaction zone for the operating condition that leads to flashback discussed in Fig. 5(b). It is observed that oxygen and methane are consumed within the burner, indicating that the flame is about to penetrate de burner.

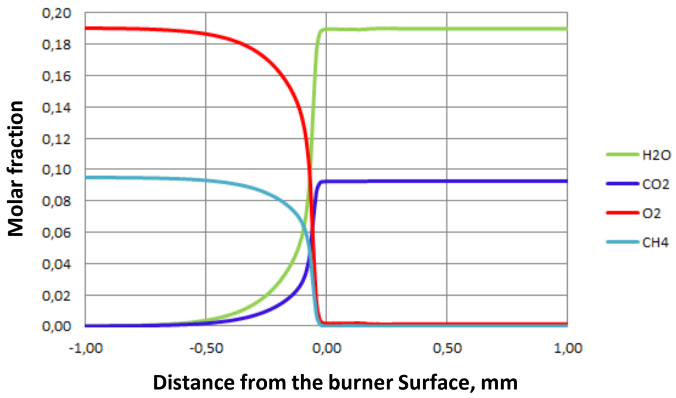


Fig. 7. Species profile

Finally, Figure 8 shows the stability diagram obtained numerically (num) and experimentally (exp). Again, experimental results are obtained from Ref. [2]. It is observed that following the criterion of $S_{increment} > 1$ and $S_{increment} > 1.5$ to predict blowout and flashback, respectively, reproduce very well the experimental results.

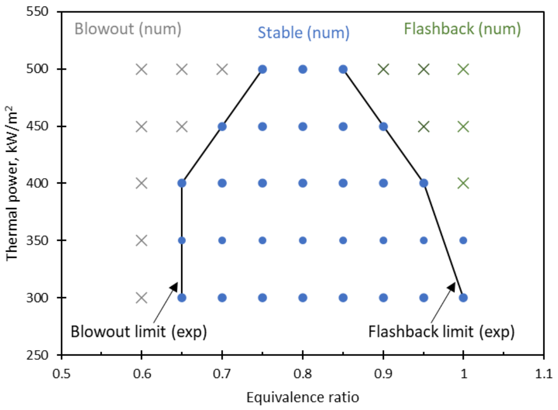


Fig. 8. Stability diagram

4. Conclusions

In this work, a computational methodology based on the finite volume method with a two-dimensional domain is presented to predict the flame curvature towards the unburned gas that occurs before flashback and the flame curvature towards the burned gas that occurs before blowout in a surface-stabilized combustion burner. This allows to identify whether an operating condition can be considered stable, or, in other words, the flame is flat. From the results presented and their discussion, as well as from the background of the literature exposed through the article, it is possible to conclude that the use of a two-dimensional simulation model allowed obtaining profiles of temperatures and species in accordance with those expected based on the results reported in the literature. Additionally, it was observed that the flame curvature can be used as a criterion to predict whether an operating condition leads to flashback or blowout.

Acknowledgement

The authors gratefully acknowledge to “Grupo de Investigación en Ingeniería en Energía” at Universidad de Medellín for their logistical support for the development of this project.

References

[1] Zulkurnai, Fatin Farhanah, Norhidayah Mat Taib, Wan Mohd Faizal Wan Mahmood, and Mohd Radzi Abu Mansor. "Combustion characteristics of diesel and ethanol fuel in reactivity controlled compression ignition engine." *Journal of Advanced Research in Numerical Heat Transfer* 2, no. 1 (2020): 1-13.

[2] Arrieta, C. E., A. García, H. A. Yepes, I. Bedoya, and A. Amell. "An experimental study of combustion stability and emissions characteristics of a surface-stabilized combustion burner fueled with natural gas-syngas blends." In *Journal of Physics: Conference Series*, vol. 1257, no. 1, p. 012018. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1257/1/012018

[3] Medhat, Moataz, Mohamed Yehia, Adel Khalil, Miguel C. Franco, and Rodolfo C. Rocha. "A Numerical Prediction of Stabilized Turbulent Partially Premixed Flames Using Ammonia/Hydrogen Mixture." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 87, no. 3 (2021): 113-133. https://doi.org/10.37934/arfmts.87.3.113133

[4] Janvekar, Ayub Ahmed, Mohd Zulkifly Abdullah, Zainal Arifin Ahmad, Aizat Abas, Mohammad Zuber, Ahmad Kamal Ismail, Ahmed Hussien et al. "Experimental and numerical studies of porous media combustion in micro burner." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 43, no. 1 (2018): 112-120.

[5] Taib, Norhidayah Mat, Mohd Radzi Abu Mansor, and Wan Mohd Faizal Wan Mahmood. "Simulation of Hydrogen Combustion in Neon-Oxygen Compression Ignition Engine." *CFD Letters* 12, no. 12 (2020): 1-16. https://doi.org/10.37934/cfdl.12.12.116

[6] Arrieta, Carlos E., Alex M. García, and Andrés A. Amell. "Experimental study of the combustion of natural gas and high-hydrogen content syngases in a radiant porous media burner." *International Journal of Hydrogen Energy* 42, no. 17 (2017): 12669-12680. https://doi.org/10.1016/j.ijhydene.2017.03.078

[7] Colorado, A., and V. McDonell. "Surface stabilized combustion technology: An experimental evaluation of the extent of its fuel-flexibility and pollutant emissions using low and high calorific value fuels." *Applied Thermal Engineering* 136 (2018): 206-218. https://doi.org/10.1016/j.applthermaleng.2018.02.081

[8] Chen, Xinjian, Junwei Li, Mang Feng, Dan Zhao, Baolu Shi, and Ningfei Wang. "Flame stability and combustion characteristics of liquid fuel in a meso-scale burner with porous media." *Fuel* 251 (2019): 249-259. https://doi.org/10.1016/j.fuel.2019.04.011

[9] Rahman, Mohammad Nurizat, Norshakina Shahril, and Suzana Yusup. "Hydrogen-Enriched Natural Gas Swirling Flame Characteristics: A Numerical Analysis." *CFD Letters* 14, no. 7 (2022): 100-112. https://doi.org/10.37934/cfdl.14.7.100112

[10] Echeverri-Uribe, Camilo, and Andrés A. Amell. "Experimental evaluation of the surface-stabilized combustion of a confined porous inert media burner." *Combustion Science and Technology* 192, no. 2 (2020): 335-358. https://doi.org/10.1080/00102202.2019.1565493

[11] Maznoy, Anatoly, Alexander Kirdyashkin, Nikita Pichugin, Sergey Zambalov, and Dmitry Petrov. "Development of a new infrared heater based on an annular cylindrical radiant burner for direct heating applications." *Energy* 204 (2020): 117965. https://doi.org/10.1016/j.energy.2020.117965

[12] Ding, Yi, Daniel Durox, Nasser Darabiha, and Thierry Schuller. "Chemiluminescence of burner-stabilized premixed

laminar flames." *Combustion Science and Technology* 191, no. 1 (2019): 18-42. https://doi.org/10.1080/00102202.2018.1558391

[13] Nemoda, Stevan, Dimosthenis Trimis, and Goran Živković. "Numerical simulation of porous burners and hole plate surface burners." *Thermal Science* 8, no. 1 (2004): 3-18. https://doi.org/10.2298/TSCI0401003N

[14] Lammers, F. A., and L. P. H. De Goey. "A numerical study of flash back of laminar premixed flames in ceramic-foam surface burners." *Combustion and Flame* 133, no. 1-2 (2003): 47-61. https://doi.org/10.1016/S0010-2180(02)00540-0

[15] Lammers, Frederik Albert. *Ceramic-foam surface burners in high-temperature environments*. Technische Universiteit Eindhoven, 2001.

[16] Kishore, V. Ratna, M. R. Ravi, and Anjan Ray. "Adiabatic burning velocity and cellular flame characteristics of H2–CO–CO2–air mixtures." *Combustion and flame* 158, no. 11 (2011): 2149-2164. https://doi.org/10.1016/j.combustflame.2011.03.018

[17] Veetil, Jithin Edacheri, C. V. Rajith, and Ratna Kishore Velamati. "Numerical simulations of steady perforated-plate stabilized Syngas air pre-mixed flames." *International Journal of Hydrogen Energy* 41, no. 31 (2016): 13747-13757. https://doi.org/10.1016/j.ijhydene.2016.06.120

[18] Qian, Peng, Minghou Liu, Xinlong Li, Fubo Xie, Zizhen Huang, Chengyuan Luo, and Xiugen Zhu. "Combustion characteristics and radiation performance of premixed hydrogen/air combustion in a mesoscale divergent porous media combustor." *International Journal of Hydrogen Energy* 45, no. 7 (2020): 5002-5013. https://doi.org/10.1016/j.ijhydene.2019.12.094

[19] Mujeebu, M. Abdul, M. Zulkifly Abdullah, A. A. Mohamad, and MZ Abu Bakar. "Trends in modeling of porous media combustion." *Progress in Energy and Combustion science* 36, no. 6 (2010): 627-650. https://doi.org/10.1016/j.pecs.2010.02.002

[20] Wang, Fei, Xueming Li, Shuai Feng, and Yunfei Yan. "Numerical Study on the Characteristics of Methane Hedging Combustion in a Heat Cycle Porous Media Burner." *Processes* 9, no. 10 (2021): 1733. https://doi.org/10.3390/pr9101733

[21] Arutyunov, V. S., A. A. Belyaev, B. V. Lidskii, A. V. Nikitin, V. S. Posvyanskii, and V. M. Shmelev. "Numerical solution of the problem of surface combustion on flat porous matrix." In *AIP Conference Proceedings*, vol. 2046, no. 1, p. 020075. AIP Publishing LLC, 2018. https://doi.org/10.1063/1.5081595

[22] Tey, Wah Yen, Yutaka Asako, Nor Azwadi Che Sidik, and Rui Zher Goh. "Governing equations in computational fluid dynamics: Derivations and a recent review." *Progress in Energy and Environment* 1 (2017): 1-19.

[23] Slikker, W. J. "Extension of the heat flux method to elevated pressures." *Combustion* (2008).