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Mechanisms of stabilization and blowoff of a premixed flame downstream of a heat-conducting perforated plate

Kushal S. Kedia *, Ahmed F. Ghoniem

Department of Mechanical Engineering, Massachusetts Institute of Technology, 77-Massachusetts Avenue, 3-342, Cambridge, MA 02139, USA

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ABSTRACT

The objective of this work is to investigate the flame stabilization mechanism and the conditions leading to the blowoff of a laminar premixed flame anchored downstream of a heat-conducting perforated-plate/multi-hole burner, with overall nearly adiabatic conditions. We use unsteady, fully resolved, two-dimensional simulations with detailed chemical kinetics and species transport for methane-air combustion. Results show a bell-shaped flame stabilizing above the burner plate hole, with a U-shaped section anchored between neighboring holes. The base of the positively curved U-shaped section of the flame is positioned near the stagnation point, at a location where the flame displacement speed is equal to the flow speed. This location is determined by the combined effect of heat loss and flame stretch on the flame displacement speed. As the mass flow rate of the reactants is increased, the flame displacement speed at this location varies non-monotonically. As the inlet velocity is increased, the recirculation zone grows slowly, the flame moves downstream, and the heat loss to the burner decreases, strengthening the flame and increasing its displacement speed. As the inlet velocity is raised, the stagnation point moves downstream, and the flame length grows to accommodate the reactants mass flow. Concomitantly, the radius of curvature of the flame base decreases until it reaches an almost constant value, comparable to the flame thickness. While the heat loss decreases, the higher flame curvature dominates thereby reducing the displacement speed of the flame base. For a stable flame, the gradient of the flame base displacement speed normal to the flame is higher than the gradient of the flow speed along the same direction, leading to dynamic stability. As inlet velocity is raised further, the former decreases while the latter increases until the stability condition is violated, leading to blowoff. The flame speed during blow off is determined by the feedback between the growing recirculation zone and the cooling burner plate.

1. Introduction

Perforated-plate burners are widely used in domestic and industrial heating equipments. Flame anchoring as well as dynamic stability mechanisms in such burners have been active research areas in combustion. Flame stabilization generally, and specifically on perforated-plate burners, and its blowoff remain poorly understood because of the complex multi-physics nature of the problem and the significant challenges it poses to experimental, analytical and numerical investigations. A perforated-plate burner flame is composed of a periodic array of bell-shaped flames connected with U-shaped flames downstream of the hole and the heat-conducting plate, respectively. We have recently developed a time accurate, two-dimensional numerical simulation tool to study perforated-plate stabilized laminar premixed flames, incorporating detailed chemical kinetics and species transport mechanisms [1,2]. In this paper, we use this tool to elucidate the flame stabilization and blowoff mechanisms in methane-air flames anchored on heat conducting perforated-plate burners. We highlight the role of flame curvature and heat exchange with the burner.

Previous studies have focused on the mechanisms of stabilization and blowoff of inverted flame downstream of a single thin rod or a twin-slot burner. The results of these studies are not directly applicable to perforated-plate stabilized flames because of significant flame-wall interaction in the latter, although some similarities are expected. Aerodynamic stretching, preferential diffusion effects due to non-unity Lewis number, conductive heat loses to the burner plate, as well as volumetric heat loss via radiation have been suggested as physical mechanisms that impact stabilization and blowoff. However, there still exists strong disagreement and contradictory hypothesis in the literature on these mechanisms even for flames downstream of a single thin rod or a twin-slot burner.

* Corresponding author.
E-mail address: kushal@mit.edu (K.S. Kedia).

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Nomenclature

d	thickness of the burner plate
D	diameter of the inlet hole
K_B	total stretch at the flame base
L_f	total length of the typical bell-shaped flame
m_B	mass burning flux at the flame base = $\rho_B S_B$
q_p	heat flux at the burner plate at $z/D = 0$ and $r/D = 1$
r	Radial coordinate
S_B	flame base displacement speed
S_c	flame consumption speed
S_T	flame tip displacement speed
t	time
T_{ad}	adiabatic flame temperature
$0.8 \times T_{ad}$	temperature contour used to define the flame location
T_B	flame base temperature
T_p	temperature of the burner plate at $z/D = 0$ and $r/D = 1$
u	streamwise velocity
U	mean inlet velocity of the reactants far upstream
v	radial velocity
$v_{r,B}$	strain at the flame base; $\frac{1}{r}\frac{\partial(rv)}{\partial r}$
z	streamwise coordinate

Greek symbols

γ_B	radius of curvature of the flame base
ρ_B	density at the flame base
ψ_B	flame stand-off distance above the burner plate
ψ_T	location of the flame tip above the burner plate
ω	volumetric heat release rate
ζ	location of the stagnation point above the burner plate

One of the earliest theories on flame blowoff was proposed by Lewis and von Elbe [3,4]. These pioneering studies extended the flame stretch theory of Karlovitz et al. [5] and postulated that blowoff occurs when a critical velocity gradient in the nozzle near the burner plate is reached in the unburnt mixture. A schematic diagram showing the velocity gradient is shown in Fig. 1a. The criterion was formulated in terms of a critical value of the Karlovitz number, $K_b = \eta_0 g_b / S_{u0}$, where η_0 is the characteristic length of the preheat zone, g_b is the velocity gradient near the burner plate and S_{u0} is the adiabatic burning velocity. This critical value depends on the configuration used to stabilize the flame, and its value ranges between 1.3 and 2.0 for wire stabilized flames, 0.7 and 3.0 for pilot stabilized flames, and 1.5 and 11 for bluff-body stabilized flames [6]. Lewis and von Elbe assumed that the velocity gradient at the flame base is almost the same as the velocity gradient near the exit of the burner plate. Edmondson and Heap [7] provided additional support for the theory of Lewis and von Elbe by performing experimental analysis of blowoff of inverted methane-air flames stabilized on thin plates. Reed [6] extended Karlovitz's flame stretch concept to flame blowoff on burners with no secondary air dilution.

Flame curvature, flow non-uniformity resulting in finite strain, and unsteady flame motion, all contribute to flame stretch [8–10]. In the literature, the theory based on Karlovitz's flame stretch is commonly referred to as the flame stretch theory of blowoff. In this theory, the flow non-uniformity (strain) is assumed to be the dominant component of stretch and flame base curvature is neglected. Hence we will refer to this theory as the 'critical velocity gradient theory'. Ignoring curvature is a weak assumption in cases where the curvature at the flame base is strong compared to the strain, especially near blowoff conditions. Melvin and Moss [11] analyzed the 'critical velocity gradient theory' and concluded that it is largely unsatisfactory.

The 'critical velocity gradient theory' was also challenged by Kawamura et al. [12,13]. They proposed that the flame area increase factor (in the Lagrangian sense) due to the strong positive curvature at the flame base (which is concave towards the products) is responsible for blowoff. They demonstrated that a critical value of area-increase factor, which they define as $A_b = \eta_0 / R_b$, where R_b is the radius of curvature of the flame base, correlates better with flame blowoff than the Karlovitz number, K_b, used by Lewis and von Elbe. We refer to this area-increase theory as the 'curvature theory'.

Kawamura et al. [12] performed experiments to determine conditions of blowoff for laminar, two-dimensional inverted flames stabilized on a twin-slot rectangular burner and investigated the possibility that a universal critical number could be used to predict blowoff under a wide range of conditions. Figure 1b shows a cross-sectional area of the burner. Figure 1c shows the measured critical values of K_b and Fig. 1d shows the critical values of A_b for different equivalence ratios and stabilization plate thicknesses, d. We note that $1 < K_b < 10$ whereas $1 < A_b < 2$. For a given equivalence ratio, the variation of the critical value of K_b is larger for different plate thicknesses as compared to the variation of the critical value of A_b. Moreover, the order of magnitude of the critical value of A_b is unity across the range of ϕ and d investigated in the experiment. Kawamura et al. concluded that the blowoff of inverted flames can be predicted better by the area-increase factor (corresponding to the 'curvature theory') than by the Karlovitz number (corresponding to the 'critical velocity gradient theory'). However, the figures also show that K_b and A_b have significant variation with thicker plates, demonstrating that both theories fail as the plate thickness increases. The distance between the neighboring holes in a typical perforated plate is comparable to the size of the holes, and it is equivalent to the plate thickness in the twin-slot rectangular burner configuration. Thus, the stabilization plate thickness is large in such perforated-plate burners.

Both theories described above share the objective of formulating a global blowoff criterion for premixed inverted flames in terms of either K_b or A_b. However, flame blowoff is likely to result from the combined effect of the flame response to the aerodynamic field as manifested by stretch, the mixture properties such as the Lewis number, the boundary conditions such as heat transfer and secondary air dilution, if present. A more fundamental understanding of flame stabilization and blowoff is needed, sidestepping the aim to formulate a global blow-off criterion. For instance, the role of heat transfer to the burner plate in flame stabilization and blowoff remains unclear. Trevino et al. [14] argued that heat transfer to the plate is necessary for the stabilization of inverted flames. On the other hand, Sung et al. [15] demonstrate the existence of solutions where inverted flame can stabilize without heat loss to the thin stabilizing rod. However, they emphasize that the conclusions of Trevino et al. may still be valid when the flame stabilizes close to the rod. Kawamura et al. [12,13] concluded that the heat loss plays an insignificant role in the flame blowoff mechanism. Furthermore, they proposed, without proof, that for a stable flame, the gradient of the flame base displacement speed normal to the flame is greater than the gradient of the flow speed along the same direction above the burner plate, providing a dynamic stability mechanism. In this paper, we demonstrate the validity of this hypothesis using