Motivation & Objectives

- Due to wall friction, propagation speeds of flames in tubes/channels can grow by several orders of magnitude. Such a flame acceleration may subsequently result in a deflagration-to-detonation transition (DDT). The DDT stays behind countless disasters in mines and power plants; and it can be utilized, constructively, in novel energy efficient setups such as pulse-detonation engines.
- For decades, there was a limited theoretical understanding of the DDT mechanism because of the common opinion that flame acceleration is impossible without turbulence: the lack of knowledge about turbulence and turbulent flames prevented a rigorous DDT formulation to be developed.
- It was next realized that turbulence plays a supplementary role in the acceleration scenario such that even laminar flames can accelerate and initiate detonation due to wall friction [1,2].
- Based on this constructive idea, conceptually-laminar, rigorous formulations to quantify the flame acceleration scenario in channels and tubes have eventually been developed and validated [3,4].
- However, the formulations [3,4] employ a set of assumptions; this thereby leads to the intrinsic limitations of the formulations, which have not been properly identified so far.
- Identification of the intrinsic limitations and accuracy of the formulations [3,4] and quantification of their validity domains constitute the overall goal of the present work.

Analytical Formulations of Flame Acceleration in Channels/Tubes

- The formulations [3,4] are based on the following approximations: (i) zero flame thickness; (ii) incompressible, near-isobaric combustion process; (iii) plane parallel flame generated flow in the fuel mixture; (iv) the average flame-generated flow velocity is related to the total burning rate as: \( U_w = \Theta(1-U_\infty) \), and \( S_l \), the normal flame velocity
- The exponential state of the flame acceleration is exhibited \( U_w \propto \exp(\Theta_s t/l) \).
- Flame evaluation equation: \( w_0(0, r) - w_1(q, \tau) = \frac{1}{1 + \frac{U_\infty}{U_w}} \left( \frac{\partial w}{\partial \tau} + \frac{1}{\Theta} \frac{\partial w}{\partial r} + \frac{1}{\Theta} \frac{\partial w}{\partial \Phi} \right) \)
- Plane-parallel Navier-Stokes equation, 2D and cylindrical-axisymmetric

Flame Acceleration in Cylindrical Tubes

- The major result of the 2D formulation [3] is a coupling of the flame acceleration rate \( \sigma \) to the thermal expansion ratio \( \Theta = \gamma_i / \gamma_o \), and a flame propagation Reynolds number \( Re = RS_l/l_v \), where \( \mu = \mu_0 - \sinh(\mu_0 - \Theta_0) \), \( \eta = \eta_0 - \sinh(\eta_0 - \Theta_0) / (2(\mu_0 + \sigma)) \)
- This equation can be solved analytically in the limit of \( \mu \gg 1 \), and \( \Theta > 1 \) with the acceleration rate

Flame Acceleration in 2-D channels

- The major result of the 2D formulation [3] is a coupling of the flame acceleration rate \( \sigma \) to the thermal expansion ratio \( \Theta = \gamma_i / \gamma_o \), and a flame propagation Reynolds number \( Re = RS_l/l_v \), where \( \mu = \mu_0 - \sinh(\mu_0 - \Theta_0) \), \( \eta = \eta_0 - \sinh(\eta_0 - \Theta_0) / (2(\mu_0 + \sigma)) \)
- This equation can be solved analytically in the limit of \( \mu \gg 1 \), and \( \Theta > 1 \) with the acceleration rate

Conclusion

- Formulations [3,4] are revisited. Their intrinsic limitations are identified in the form of domains in a Re-\( \Theta \) diagram. While the formulations are accurate for large Re and \( \Theta \), the accuracy deteriorates at other conditions. Finally, this analysis is supported by numerical simulations; see the figure on the right. Here, the exponential (circles) regime of flame acceleration is separated from a non-exponential regime (triangles) by the solid line associated with a threshold thermal expansion ratio.

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