Effect of Wall Heat Losses on Flame Propagation in Micro-Chambers

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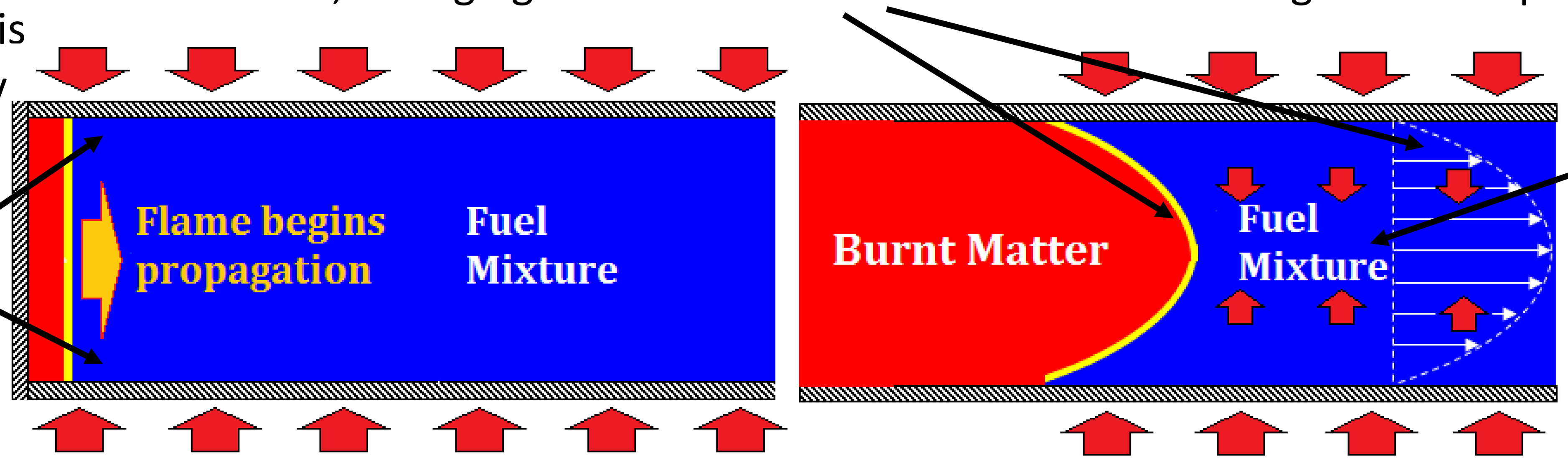
Motivation and Objectives

- Analyses of flame propagation in micro-channels and tubes [1,2] have reported spontaneous flame acceleration, which in turn could lead to a deflagration-to-detonation transition (DDT).
- Within the scenario of the flame acceleration and DDT, the role of the wall conditions was found to be highly important, e.g. friction forces at the pipe walls as well as jet-like flows generated by wall-placed obstacles drive the accelerative flame propagation, unlimited in time [1-3].
- However, thermal effects at the walls were usually neglected by assuming no heat transfer at the pipe surface, namely, adiabatic boundary conditions.
- The present work aims to explore numerically the thermal effect of the chamber walls on the flame propagation. By assuming constant wall temperatures, energy losses at the pipe surface are incorporated into the analysis.

Flame Propagation in Channels and Tubes with Warmed Walls

Initially, the fuel mixture is preheated by the walls, facilitating burning ...

Later, the fuel mixture flow produced by thermal expansion of the burning matter is restricted at the walls, enlarging the flame front surface and accelerating the flame propagation.



Heat transferred by the walls

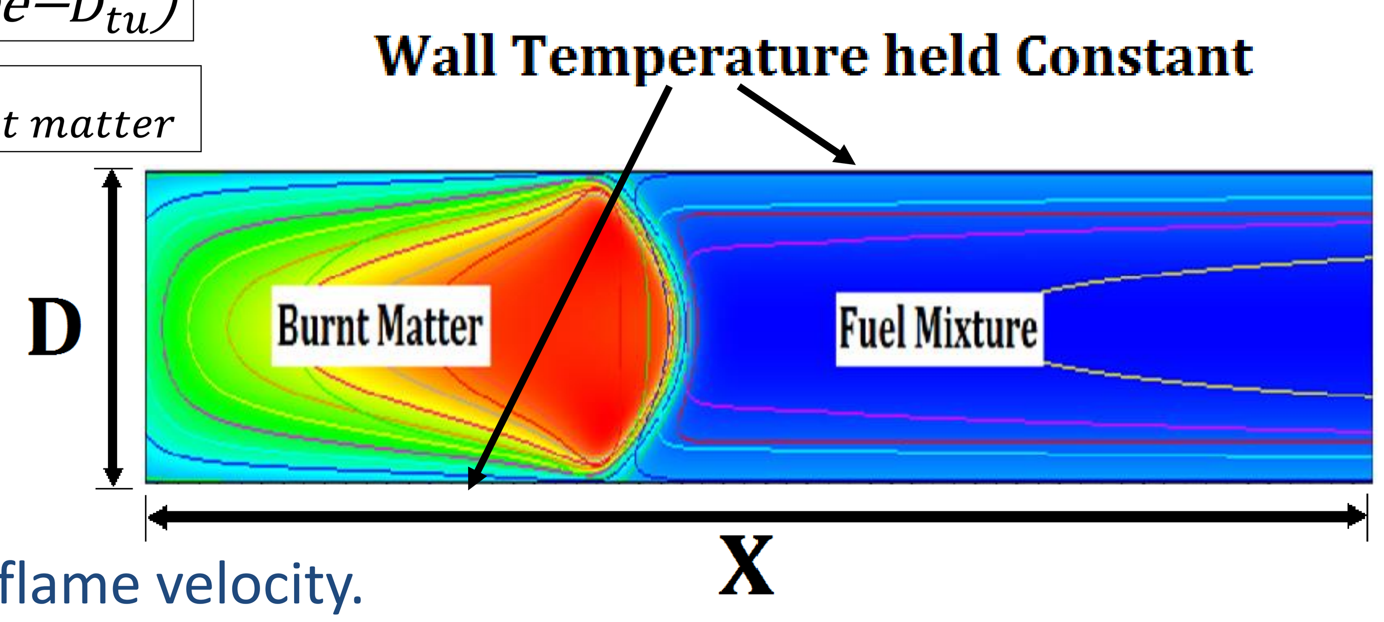
However, heat gained by the fuel mixture modify the thermal expansion, and consequently, the flame acceleration mechanism.

Methodology

- A fully-compressible, finite volume "in-house" code is used to perform this investigation. It solves a complete set of hydrodynamic and combustion equations, including transport processes such as diffusion, viscosity, heat conduction, and the Arrhenius chemical kinetics.
- It is second order accurate in time, fourth order in space for the convective terms, and second order in space for the diffusive terms. The solver is adapted for parallel computations and available in Cartesian and Cylindrical axisymmetric versions, with a self-adaptive structured grid.
- The parametric study includes non-slip channel and tube configurations of variable width, where the flame front is propagating from a closed end to an open one.
- The presented results and discussions are based on the following scaled parameters:

Channel/tube width:	$D\ (Channel{-}D_{ch},\ Tube{-}D_{tu})$
Thermal expansion ratio:	$\Theta = \rho_{fuel\ mixt.}/\rho_{burnt\ matter}$
Scaled flame tip position:	$R_t = 2X/D$
Scaled flame tip velocity:	U_{tip}/S_L
Scaled time:	$\tau = 2t\,S_L/D$
Flame thickness:	$L_f = \upsilon/S_L Pr$

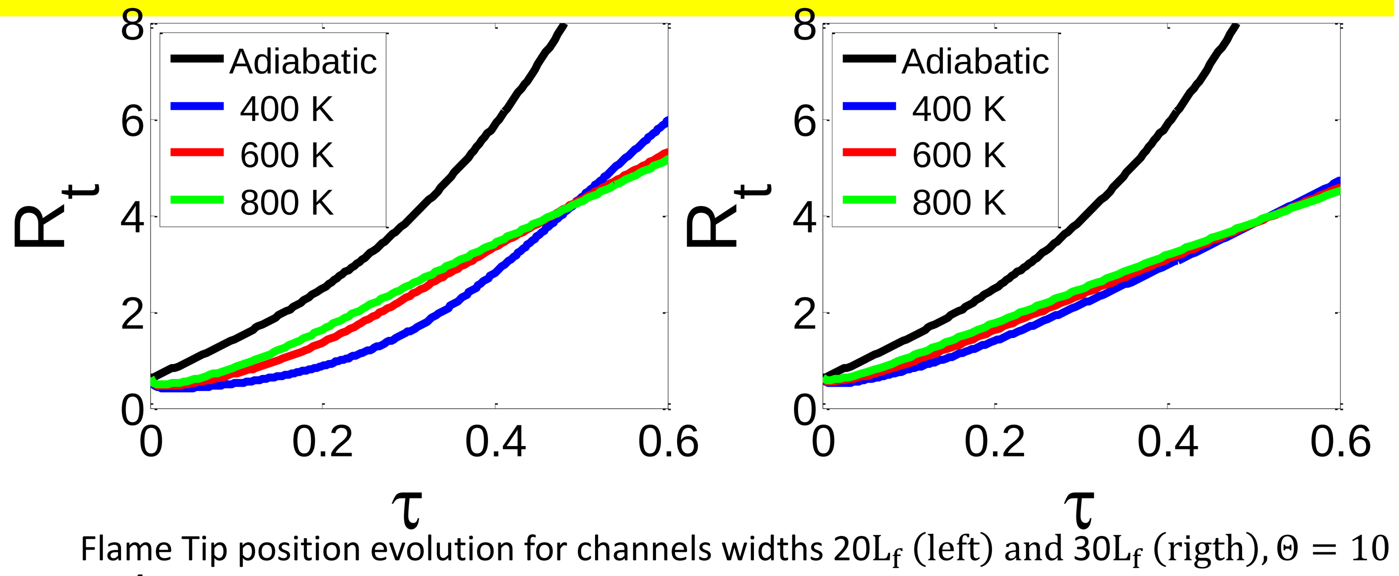
with U_w the total burning rate, S_L the normal flame velocity.



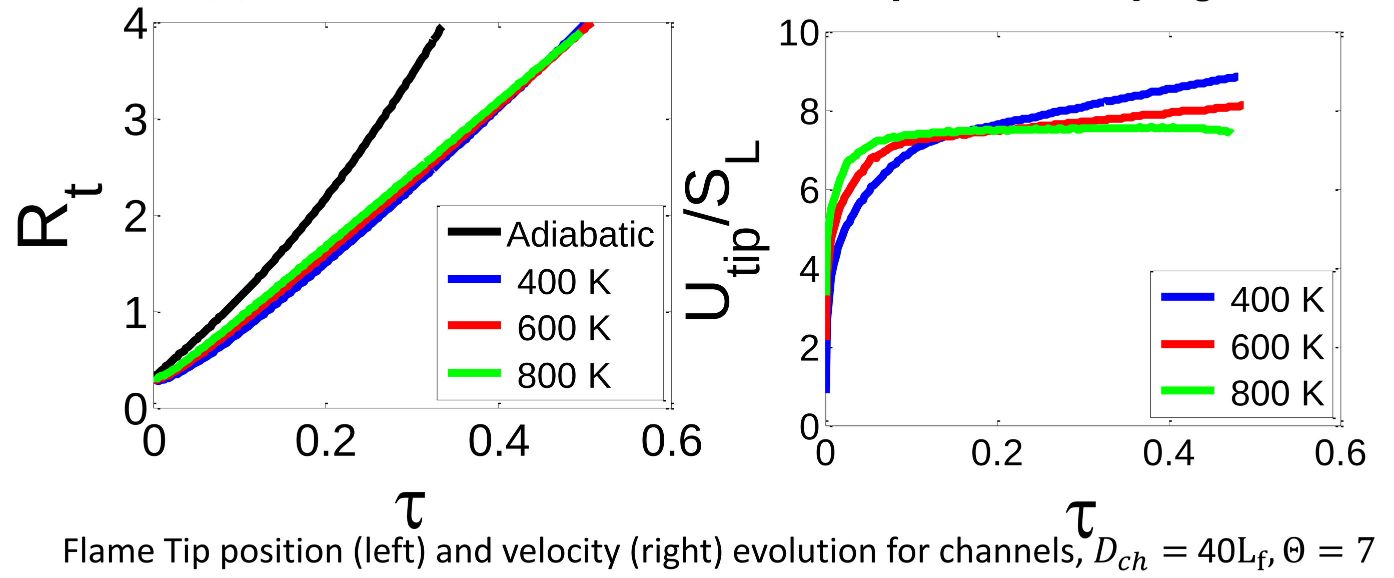
Results and Discussion

Wall Temperature Effect

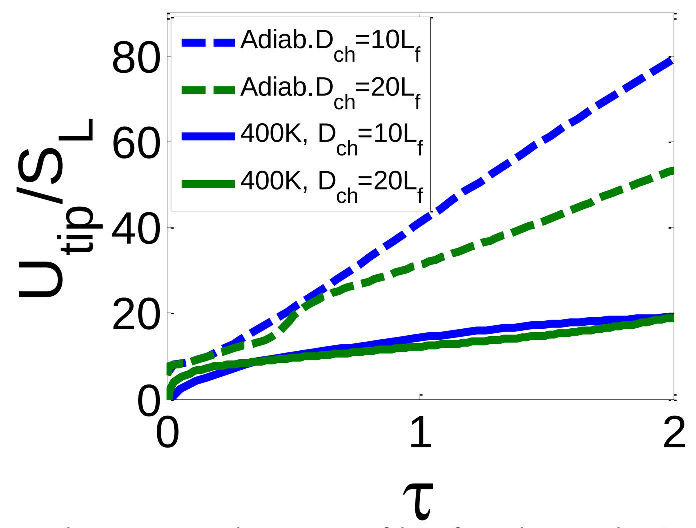
- Flame propagation in channels with isothermal walls, cold or warm, is weaker than that observed in adiabatic walls, since a part of the energy released in the combustion process is lost.
- Comparing the flame propagation profiles obtained in different wall channel temperatures, two trends can be noted: at the beginning, the warmer walls promote combustion as compared to the colder ones, but later the flame propagation is surprisingly faster in the colder channel walls.
- The switch is produced when heat transferred to the fresh gas in the radial direction decreases the thermal expansion ratio (that drives flame acceleration), thereby reducing the flame velocity. Also, this is the reason why larger flame velocities occur when heat is not lost at the walls at all, in the adiabatic case.



Flame Tip position evolution for channels widths $20L_f$ (left) and $30L_f$ (rigth), $\Theta = 10$



Flame Tip position (left) and velocity (right) evolution for channels, $D_{ch} = 40L_f, \Theta = 7$



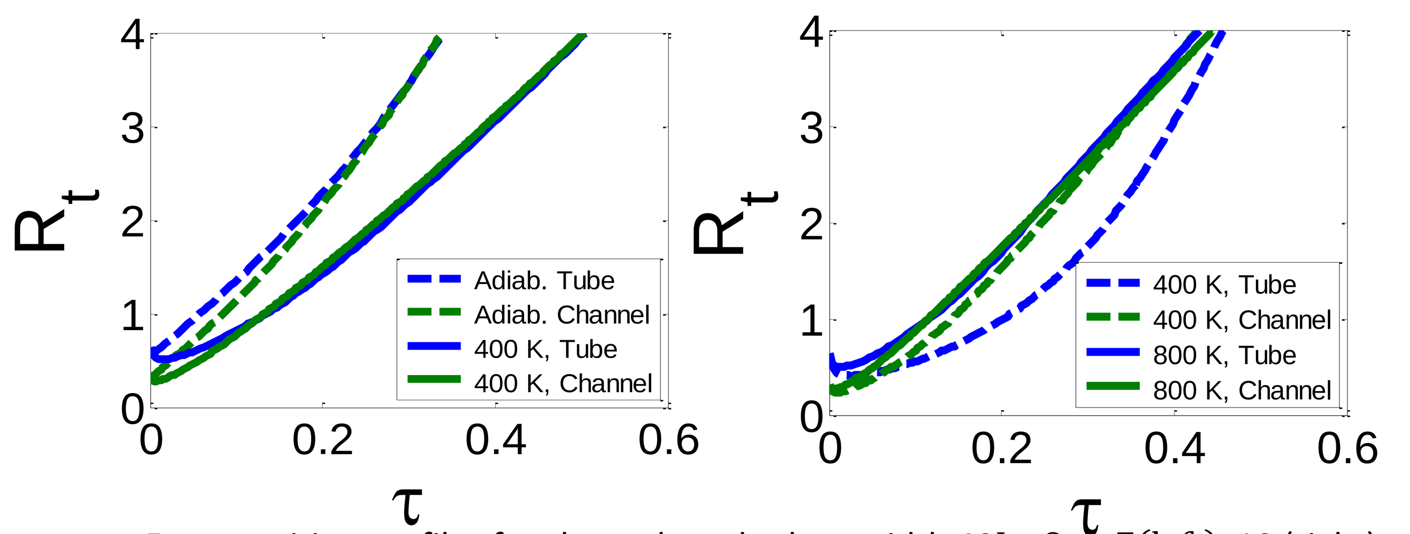
Flame tip velocity profiles for channels, $\Theta = 8$

Channel Width Effect

- Differences observed in the flame propagation velocity regimes at different channel widths became much smaller when considering isothermal wall conditions.
- Intensification of the flame propagation by bending of the flame front is more easily attained in narrower channels. Since the wall temperature is lower than that of the flame front, burning is prevented in there, reducing the front propagation cross section.
- However, this positive forcing is not as strong as the mitigation observed when the thermal expansion is reduced by exchanging heat with the pipe surface.

Channel vs Tube Configurations

- Constant wall temperature conditions produce similar effects to the flame propagation in cylindrical-axisymmetric tubes as in planar 2D channels.
- It is possible to observe the shifting in the velocity trend dominance of colder isothermal walls over warmer ones after a certain time.
- This time interval is nevertheless noted to be longer than that of the planar geometry.



Front position profiles for channels and tubes, width $40L_f$, Θ = 7(left), 10 (right)

Conclusions

- The role of thermal boundary conditions at the walls of channel and tube combustors is scrutinized.
- The effect produced by heat losses at a combustor surface is found to be considerable. Namely, the exponential state of flame acceleration, the role of a channel/tube width, and the difference between 2D and cylindrical geometries are mitigated as compared to that with adiabatic walls.
- Heat transferred to the fresh mixture initially enhances burning, but then is shorty overcome by a consequent reduction of the thermal expansion, mitigating the flame acceleration.

References

1. V. Bychkov *et al.*, Phys. Rev. E 72, 046307 (2005).
2. V. Akkerman *et al.*, Combust. Flame, 145, 206-219 (2006).
3. D. Valiev *et al.* Combust. Flame, 157, 1012-1021 (2010).

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