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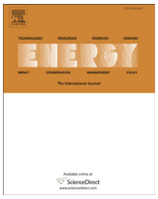

On flame propagation in narrow channels with enhanced wall thermal conduction

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ABSTRACT

The influence of orthotropic wall materials, which have enhanced thermal conductivity in the axial direction, on the flame speed is explored via an analytical model in a parallel plate microcombustor. The model accounts for 2D conjugate heat transfer (both in wall and gas) and fuel species transport in the micro-channel. The effects of heat loss, orthotropic wall thermal conductivities, and wall thickness on the flame speed are explored. The results indicate that as the axial thermal conductivity of the wall is increased, the allowable heat losses to the ambient by the burner also increased. Thicker walls showed increased benefit to the thermal conductivity tailoring than thinner wall designs; both in increased flame speeds as well as the ability to tolerate higher heat losses without extinction. Total heat recirculation is shown to be the primary parameter to control the flame speed.

1. Introduction

Microcombustion has been actively studied in recent years, a detailed summary of the work in this area of combustion can be found in Ref. [1]. Microcombustion finds application in small, portable power systems [2,3], nano/pico satellite propulsion systems and fuel reforming [4]. Spalding [5] studied non-adiabatic flames and demonstrated that when heat losses were accounted for, two flame speeds were possible. Weinberg [6] then proposed heat recirculating burners in which the lean flammability limit could be extended along with occurrence of superadiabatic flame temperatures which he called “excess enthalpy” burners. More recent studies in this area have focused on important topics such as fuel-air mixing [7], the role of catalyst on sustaining combustion [8,9], conjugate heat transfer between fluid and combustor wall [10–13], porous media burners [14], flame dynamics [15,16] and exergy analysis [17]. Other experimental studies in simple burners have demonstrated fundamental phenomena such as enhanced flame speed [18,19] and spinning flames [20].

The key aspect of microcombustors however, is the thermal coupling between the fluid and wall which yields most of the interesting phenomenon. Quasi-1D modelling of this aspect was conducted in past work [21,22] and has shed light on several important features of these flames. However, this requires the assumption of a constant *Nusselt* number (for coupling fluid and wall's heat transfer). This assumption was shown to be inaccurate in the near vicinity of the flame by Veeraragavan et al. [23,24] using 2D heat transfer modelling of the problem and also by Watson and Bergthorson [25]. Veeraragavan and Cadou [26] further developed a 2D conjugate heat transfer model which combined the fuel species transport equation to the two energy equations (gas and wall) analytically to solve for the flame speed. This model removed the need to assume a constant *Nusselt* number by accounting rigorously for conjugate heat transfer in 2D. Like the previous work done in this area, this model could predict the influence of design parameters such as wall thickness, material properties and heat losses on the flame speed.

From a practical standpoint such as for power applications, microcombustor powered TPV (thermophotovoltaic) systems [2,3,27–29] and TE (thermoelectric) devices [1] that employ solid state conversion of radiation/heat to power are preferred to minimise viscous and mechanical losses associated with miniaturised turbo-generators. Recent work on micro gas turbine systems also aim at thermal management to increase reliability [30]. For both TPV and TE systems, it is essential to achieve high, isothermal wall temperatures to improve the efficiency of the system [1]. This needs to be driven by a strongly anchored flame with high thermal output. Researchers have attempted wire insertion as a method to increase thermal conduction within the channel and report enhanced flame stability and thermal output [31]. One approach in

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Nomenclature

α_{th}	thermal diffusivity of gas
Cp	specific heat capacity of gas
d	channel half width
Ea	activation energy
h	heat transfer coefficient
κ	dimensionless thermal conductivity
k	thermal conductivity of gas
λ_n	Eigenvalue
Le	Lewis Number
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
θ	dimensionless temperature
ρ	density of gas
Re	Reynolds number
Ru	universal gas constant
S_L	laminar flame speed
$S_L{}^*$	dimensionless laminar flame speed
τ	dimensionless wall thickness ratio
t	wall thickness
T	temperature
U	flow velocity
ω	dimensionless Reaction rate
x	dimensional axial coordinate
x^+	dimensionless axial coordinate
y	dimensional transverse coordinate
y^+	dimensionless transverse coordinate
Y_f	Normalised fuel mass fraction
Ze	Zeldovich number

Subscripts

a	activation
ad	adiabatic
E	environment
$free$	associated with a freely propagating flame
F	flame
f	fuel
g	gas
w	wall
11	streamwise direction
22	transverse direction

order to improve on this is to use orthotropic materials for the combustor wall. Orthotropic materials have different thermal properties along different orientations. Hence, using such materials (for e.g. pyrolytic graphite as demonstrated in recent work [32]) it is possible selectively increase or lower wall thermal conduction in certain directions to cause uniform spreading of the heat in the combustor's wall. However, the influence of selectively tailoring the thermal conductivity on flame propagation has not been thoroughly investigated in literature as yet but has been suggested as a suitable method to improve the combustor performance [33]. Very recent experimental evidence also supports this concept [34]. Therefore, this work extends the previous analytical model [26] (with 2D conjugate heat transfer) to include orthotropic wall thermal conductivity in the wall and studies the importance of increasing the axial thermal conductivity to increase flame stability (withstand higher heat losses) and flame speeds. Preliminary findings of the work in this paper was presented at the *Australian Combustion Symposium* [35].

2. Problem formulation

Fig. 1 shows a schematic sketch of the problem studied, i.e., a pre-mixed flame propagating in an infinitely long, 2D channel with the wall made of an orthotropic thermally conductive material surrounded by air. The origin is at the centre of the flame. The model simplifies the flow portion by assuming constant density and constant velocity (Plug flow) and focuses on the enhanced 2D conjugate heat transfer. The model also assumes a flat flame and simplified 1-step reaction kinetics. These are justified for the scope of this paper as follows: 1) Constant density and plug flow has been assumed in numerous models by other researchers as simplifications that enable obtaining an analytical solution [22,36], these simplifications, however, limit the validity of the results for engineering applications, 2) Simplified 1-step reaction kinetics has also been used extensively in literature in order to either obtain an analytical solution [22,36] or avoid high computational cost [33,37] for numerical solutions where the emphasis is on steady flames and design point operation, and 3) the planar flat, thin flame assumption that allows the development of planar jump conditions across the flame front has also been used in literature [22] and is accurate for submillimeter scale channels for hydrocarbon-air flames as demonstrated in simulations by Norton and Vlachos [33,37] where the flame is not bifurcated or angled within the channel. It is well known that each of these assumptions has implications on the validity of the predictions of simplified models such as the one presented in this work. However, the aim and scope of the present work is to illustrate the effect of tailored wall thermal conduction (orthotropic walls) on the flame speed. Therefore, the results and conclusions drawn from this work would be a useful guide for expected trends in flame speed variation with increased axial thermal conduction in the wall.

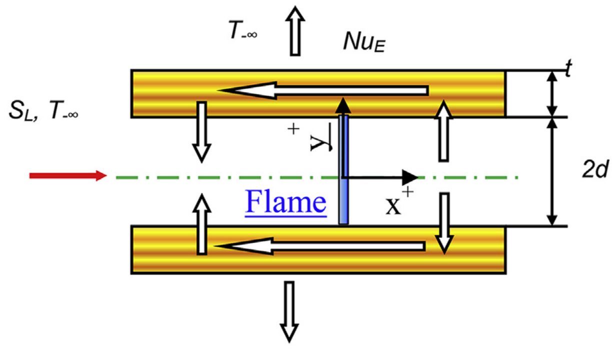

Fig. 1. 2D Parallel plate burner with enhanced axial structural thermal conduction.

The gas transport equations using the dimensionless variables defined in Table 1 (based on previous work [26,35]) are:

$$Pe_{free}S_L{}^*\frac{\partial\theta_g}{\partial x^+} = \frac{\partial^2\theta_g}{\partial x^{+2}} + \frac{\partial^2\theta_g}{\partial y^{+2}} + \omega\delta(x^+) \tag{1}$$

$$Pe_{free}S_L{}^*\frac{\partial Y_f}{\partial x^+} = \frac{1}{Le}\left(\frac{\partial^2 Y_f}{\partial x^{+2}} + \frac{\partial^2 Y_f}{\partial y^{+2}}\right) - \omega\delta\left(x^+\right) \tag{2}$$

Equation (1) is the energy balance and Eq. (2) is the species mass