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Numerical modelling of laminar flames from methanol wicks confined within vertically oriented parallel walls in a mixed convective environment

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ABSTRACT

A numerical investigation of the flame characteristics of steady, laminar diffusion flames sourced by methanol wicks, established over vertically oriented parallel surfaces in a mixed convective flow field is carried out. Two configurations are considered; in the first, both surfaces contain methanol wicks facing each other, whereas in the second, only one of the surfaces contains the wick. In both these configurations, the flow of air is upwards and parallel to the surfaces. The effect of wick separation distance and forced convective air flow velocity on the thermal and reactive flow fields, flame shapes, average mass burning rates, as well as on the conditions leading to flame lift-off are brought out. Numerical model that uses a single-step kinetics for methanol-air oxidation and optically thin radiation sub-model, is employed. It is observed that the average mass burning rates are more sensitive to the separation distance at lower air velocities. As separation distance increases, the air velocity leading to flame lift-off increases, before becoming a constant finally. For lower separation distances, the lift-off occurs at a higher air velocity for single fuel wick case. The flow, temperature and species fields are used to explain the predicted trends.

1. Introduction

Over the last few decades, several studies have appeared in literature on the physical nature of diffusion flames on vertically oriented or inclined condensed fuel surfaces. Most of these studies address fires on a single wall under natural or forced draught conditions, with the main parameter of interest being flames structure, mass burning rates, convective and radiant heat fluxes and velocity vector field in the vicinity of the flame. In comparison, the studies on fires between parallel walls, under various environmental conditions, have been relatively rare. Such fires can be encountered between tall vertical storage racks in malls and warehouses. Another example of parallel wall fires is the burning of hydrogen between the plates of a passive autocatalytic recombiner (PAR) in a nuclear reactor containment building. Although the PAR is intended to passively remove hydrogen and is employed as a safety device for hydrogen removal, it can cause hydrogen to ignite accidentally under certain conditions. This could lead to development of a strong buoyancy induced draught between the plates that further aggravate the problem. Subsequent implementation of appropriate fire protection measures would be difficult. Such issues make the study of parallel wall fires important and interesting. Therefore, simulation of lab-scale flames between two parallel walls is attempted in this study.

Spalding [1] was one of the first to present a theoretical analysis of the vertical burning problem when he obtained a Pohlhausen solution based on several approximations. Kosdon et al. [2] investigated burning of vertical cellulose cylinders by means of a boundary layer type two-dimensional similarity solution. Kim et al. [3] examined various physical processes that influence the burning characteristics of vertical, inclined and horizontal cylindrical fuel surfaces under laminar regime. They also developed a Pohlhausen solution applicable to burning of vertically oriented surfaces, which was an improvement over the solution proposed earlier by Spalding [1]. Tamanini [4] has presented a numerical model for obtaining flame structure and mass burning rates for radiation controlled, turbulent, single vertical wall fires. Fire induced plumes on upright surfaces were investigated in detail by Ahmad [5] and Ahmad and Faeth [6]. Both laminar as well as

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Nomenclature

A	Pre-exponential factor (1/s)
c_p	Specific heat at constant pressure (J/kg K)
D	Mass diffusivity (m^2/s)
E_a	Activation energy (J/kmol)
g	Acceleration due to gravity (m^2/s)
h	Total specific enthalpy (J/kg)
h_{fg}	Latent heat of vaporization (J/kg)
$h_{f,I}$	Enthalpy of formation (J/kmol)
k_G	Global rate constant
k	Thermal conductivity (W/m K)
L	Length of the fuel wick (m)
MW	Molecular weight
$\dot{m}''_f$	Mass burning rate per unit area ((kg/m^2 s)
n	Number of moles
$\hat{n}$	Normal direction
P	Pressure (N/m^2)
$\dot{q}'''_R$	Radiation heat loss (W/m^3)
R_u	Universal gas constant (J/kmol K)
T	Temperature (K)
t	Time (s)
u, v	x and y velocity components (m/s)
X	Mole fraction
Y	Mass fraction
x, y	Co-ordinate directions

Greek symbols

ϕ	General variable
θ	Orientation angle (°)
κ_p	Planck mean absorption coefficient
μ	Dynamic viscosity (Ns/m^2)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ_B	Stefan–Boltzmann constant (W/m^{2}K^4)
σ, τ	Normal and shear stresses (N/m^2)
υ_I	Stoichiometric coefficient of ith species
$\dot{\omega}$	Mole based reaction rate (kmol/m^3 s)

Subscripts

b	Boiling point
$diff$	Diffusion
F	Fuel
I	ith species
L	Length of the wick (m)
m	Gas mixture
o	Oxygen
s	Wick surface
v	Vapour
w	Wall
∞	Ambient conditions

Superscripts

n_1, n_2	Exponents in rate equation

turbulent fire plumes were investigated in gravity assisted configuration. For laminar plumes, an integral analysis was used to predict the mass burning rates and heat flux to the walls, whereas for turbulent plumes, experimental results were provided. An analysis of laminar, free convective burning of a thermally thick, vertical PMMA surface has also been described by Sibulkin et al. [7]. Other notable studies include that of Pagni and Shih [8], Sibulkin and Kim [9], and Sibulkin and Annamalai [10]. Recently, numerical studies were presented by Ali et al. [11] on laminar, quasi-steady burning characteristics of a thin film under atmospheric pressure and normal gravity conditions. The entire orientation range of $-90° \leq \theta \leq +90°$ was considered and the mathematical model accounted for normal as well as cross flow buoyancy components, so as to differentiate between upward and downward burning rates. Later, Ali et al. [12] extended the studies of Ahmad [5] by estimating the variation of heat flux parameter along the fuel and downstream wall surface for orientation angles other than $\theta = 0°$.

All the above mentioned studies considered burning on single wall without confinement. One of the earliest experimental studies on parallel combustible wall fires was presented by Tamanini et al. [13]. Experiments were carried out with walls made of 1 m high wicks, soaked with methanol and toluene-methanol mixtures. The ratio of wall spacing to wall height that provides the maximum burning rate was discussed. A comparison of the mass burning rate with single wall fire case was also presented. Later, Tamanini et al. [13] also extended his earlier single wall fire numerical model to investigate parallel wall fires. This model was applied to predict pyrolysis rate and radiant heat flux from PMMA fires. A detailed numerical model was later described by Wang et al. [14] to predict the burning rate and convection/radiation fluxes in large-scale vertical parallel PMMA wall fires. This model was applied to obtain the characteristics of flame structure as a function of wall spacing/wall height ratio. A similar study was then conducted by Wang et al. [15] where a comparison of flame parameters for parallel walls with single and two side burning was made. Both numerical and experimental results were reported with propane as the fuel.

The current study differs from some of the earlier studies reported in literature for parallel wall burning in that it considers the burning of a thin liquid fuel wick instead of solid or gaseous fuel. The evaporation rate of the fuel surface and its burning is strongly coupled to the heat transfer and convective flow field. The coupled heat and mass transfer problem is modelled by applying appropriate interface boundary conditions at the wick surface; the burning process is quasi-steady in nature. Methanol is chosen as a representative fuel since the present numerical model has been validated earlier using methanol by Raghavan et al. [16,17] and Ali et al. [18]. The main parameters varied are the fuel wick separation distance and air velocity to bring out their effect on flame characteristics, mass burning rates and conditions leading to flame liftoff. Comparison with corresponding single wall burning cases is also presented.

2. Description of the problem

A schematic diagram depicting the diffusion flames established over vertically oriented, parallel, methanol soaked wick surfaces in a forced convective flow field is shown in Fig. 1. Two configurations are shown, in the first [Fig. 1(a)], fuel wicks are placed on two parallel surfaces facing each other, whereas in the second [Fig. 1 (b)], only one of the surfaces contains the fuel wick. In both the configurations, flow of air is from bottom of the domain and