On the structure of lean premixed H\textsubscript{2}–air flames in an annular microcombustor

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ABSTRACT

Self–sustainable combustion and narrow stability limits are the most critical issues in microcombustors (length scale ~1mm) as increased heat losses can lead to thermal quenching of flame. Hydrogen is a potential fuel for microcombustion due to its high specific energy and wide flammability limits. Under these circumstances, it is important to study the fundamental structure of premixed hydrogen flames established in microcombustors. This work focuses on the lean premixed hydrogen–air flames stabilized in a newly developed annular microcombustor. Detailed axisymmetric numerical calculations involving multiple kinetics, multicomponent mass–heat transport, conjugate heat transfer, and thermal radiation in gas and solid media are performed to address the stabilization mechanism, effects of wall heat losses on flame thinness, and reaction kinetics. It has been shown that flame stabilization occurs by preheating even though wall temperatures are higher than the autoignition temperature. Results unravel the importance of H radical reactions in the kinetics of microflames in low and high temperature regions of the microcombustor.

KEYWORDS

lean premixed flame, microcombustion, heat losses, hydrogen, flame structure

INTRODUCTION

A common feature of cylindrical microcombustors is the lack of any flow structures that aid flame stabilization. Understanding of flame stabilization mechanism in the millimeter scale straight tube combustors is a useful starting point for designing practical microcombustors as the transport processes including flow regime and heat transfer are likely to be similar. Zamashchikov has conducted a series of experimental studies involving methane, propane, and hydrogen premixed flames in narrow tubes [1–5]. Stoichiometric methane–air flame could be stabilized in a warm steel tube of diameter less than the characteristic quenching diameter and the lifetime of the flame was determined by formation and condensation of water on the tube walls. The tendency of the flame to broaden at high flow rates was also observed in these experiments.

A number of studies in the past have focused on flame structure of lean H\textsubscript{2}–air flame [6–9]. Kaskan [6] showed that OH radical concentration is higher than equilibrium and it decays downstream, similar to rich flames. He and Clavin [7] explored the structure of H\textsubscript{2}–O\textsubscript{2} flame near the lean flammability limits. It was found that apart from a superficial similarity with rich flame, H radical concentration is smaller than OH, O, and HO\textsubscript{2}. Additionally, chain breaking reactions \(\text{OH}+\text{HO}_2 = \text{H}_2\text{O}+\text{O}_2\) and \(\text{O}+\text{HO}_2 = \text{OH}+\text{O}_2\) are important. Work of Seshadri et al. [8] based on asymptotic analyses has underscored the similarities and differences between lean methane–air and hydrogen–air flames. Katta and Roquemore [9] numerically studied the H\textsubscript{2}–air flame structure in the context of premixed jet flame and demonstrated the occurrence of tip opening and intensified tip burning as the mixture composition changed from lean to rich.
Few studies on the structure of flames established in microcombustors have been reported. Leach [10] discussed the effects of flame broadening on reaction kinetics and overall conversion of hydrogen–air flames within the framework of 1–D microcombustion in parallel plate channel. Rates of the five dominant reactions, \( \text{H} + \text{O}_2 = \text{O} + \text{OH}, \text{H}_2 + \text{O} = \text{H} + \text{OH}, \text{H}_2 + \text{OH} = \text{H}_2\text{O} + \text{H}, \text{H} + \text{O}_2 + \text{M} = \text{HO}_2 + \text{M}, \) and \( \text{HO}_2 + \text{H} = \text{OH} + \text{OH}, \) increased as the gap width decreased and broadening of the rate profiles also occurred. The changes were attributed to enhancement in heat recycle at smaller gap width. Understanding of flame stabilization is critical to the development of efficient methods of heat recycle in microcombustors. Although thermal aspects of the flame stabilization process are covered in almost all studies on microcombustion, little attention has been devoted to the understanding of kinetics of stabilization process. This is especially important since most of the flames in millimeter scale ceramic tubes are stabilized thermally via heat recycle from the walls. Moreover, recent studies on hydrogen–air flames [11] have suggested that flame stabilization occurs on the walls of microcombustor.

In the present study, flame structure is studied in an annular microcombustor with the objective of understanding the flame stabilization mechanism in furtherance to the thermal stabilization mechanism as established using single step kinetics model [11, 12]. The detailed flame structure for lean hydrogen–air flame is studied to determine dominant heat releasing reactions and understand the influence of dimensionality on the flame structure. Effects of heat losses on the flame structure are investigated in detail.

**PROBLEM FORMULATION**

In the proposed annular microcombustor design depicted in Fig. 1a, thermally isolated region is created by maintaining walls at high temperature. For this, a hollow inner tube filled with an inert nitrogen gas is used instead of the solid rod used in earlier design [13], as in Fig. 1a.

**Fig. 1.** (a) Annular microcombustor depicting the design concept and (b) corresponding axisymmetric computational domain showing boundary conditions of the mathematical model.

**Table 1.** Typical component dimensions of annular microcombustor.

<table>
<thead>
<tr>
<th>component</th>
<th>( d ) (m)</th>
<th>( t ) (m)</th>
<th>( l ) (m)</th>
</tr>
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<td>inner tube (i)</td>
<td>5e-03</td>
<td>1e-03</td>
<td>2e-02</td>
</tr>
<tr>
<td>outer tube (o)</td>
<td>1.1e-02</td>
<td>1e-03</td>
<td>2e-02</td>
</tr>
<tr>
<td>annular zone (a)</td>
<td>8e-03⁣</td>
<td>1e-03</td>
<td>2e-02</td>
</tr>
<tr>
<td>gas core (c)</td>
<td>5e-03</td>
<td>—</td>
<td>2e-02</td>
</tr>
</tbody>
</table>

⁣ hydraulic diameter

Comparison of thermal properties of gases and typical solid materials [14] shows that gas volumetric heat capacity and thermal inertia is smaller than solids, and gases would reach thermal
equilibrium faster. Such an arrangement would store the heat released in combustion during the flame development stage that would otherwise be lost, and assist in the formation of stable flame structure. Combustion would occur in the annular cavity formed by two concentric tubes (Fig. 1).

Typical dimensions of these structural features utilized in this work are summarized in Table 1. With these specifications, the annular zone between the outer and inner concentric tubes is one mm wide in radial direction. The overall combustor volume is 1.9e-6 m$^3$ and surface area per unit volume based on outermost wall surface area is 364 m$^{-1}$.

**MATHEMATICAL MODEL**

The mathematical formulation is based on transport equations for mass (continuity), momentum, energy, and species presented below in vectorial notation. Only the axisymmetric forms are considered.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \tag{1}
\]

\[
\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot \left( \rho \vec{V} \vec{V} \right) = -\nabla P + \nabla \cdot \vec{\tau} \tag{2}
\]

Where, \( \vec{\tau} = \mu \left( \nabla \vec{V} + \nabla \vec{V}^T \right) - \frac{2}{3} \left( \nabla \cdot \vec{V} \right) \) is the viscous stress tensor.

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot \left[ \rho \vec{V} (\rho E + P) \right] = \nabla \cdot \left[ k \vec{V} T - \sum_{i=1}^{n} h_i \vec{J}_i + \left( \vec{\tau} \cdot \vec{V} \right) \right] + S_t + S_{rad} \tag{3}
\]

Where, total energy \( E = h - \frac{P}{\rho} + \frac{V^2}{2} \)

\[
h = \sum_{i=1}^{n} Y_i h_i \text{ with } h_i = \int_{T_{15}}^{T} C_{P,i} dT
\]

\[
S_t = -\sum_{i=1}^{n} \frac{h^0_i}{MW_i} \cdot r_i
\]

\[
\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot \left( \rho \vec{V} Y_i \right) = -\nabla \cdot \vec{J}_i + r_i \quad (i = 1.....n-1) \tag{4}
\]

Where, \( \vec{J}_i = -\rho D_{i,m} \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \)

Equation (4) is written for \( n-1 \) species of the mixture and mass fraction of \( n^{th} \) specie is obtained from the summation rule, \( Y_n = 1 - \sum_{i=1}^{n-1} Y_i \). Carrier gas (N$_2$) is always set as the \( n^{th} \) specie to accurately predict mass fractions of radicals and trace species. Computation of diffusion flux takes into account diffusion due to concentration and temperature (Soret effect). Mass diffusivity computations are done using kinetic theory and trace diffusion method. Kinetic theory is used to
compute diffusivity of individual species and trace diffusion [15] is used to obtain effective diffusivity of a species in the mixture. Reaction rate term \( r_i \) is computed from the kinetic submodel. In the general case of \( m \)–step reaction mechanism of \( n \) species, following generalized equation accounts for all reversible reactions among all species.

\[
\sum_{i=1}^{n} v_{i,r} A_i = \sum_{i=1}^{n} v_{i,r}' A_i
\]

Above expression leads to the following equation for molar rate of reaction, \( R_{i,r} \) of \( i \)th species undergoing \( r \)th reaction.

\[
R_{i,r} = \left( v_{i,r}' - v_{i,r} \right) \left( \sum_{j=1}^{n} \gamma_{j,r} C_j \right) \left[ k_{f,r} \prod_{j=1}^{n} (C_{j,i})^{\eta_{j,r}} - k_{b,r} \prod_{j=1}^{n} (C_{j,i})^{v_{j,r}' - v_{j,i,r}} \right]
\]

The term in the second bracket on RHS indicates combined effects of third body efficiencies on the reaction rate. Since Eq. (4) is written in terms of mass fractions, and \( r_i \) is the net source term from chemical reactions, it is recovered from the above equation by using \( r_i = MW_i \sum_{r=1}^{n_R} R_{i,r} \). Forward reaction rate constant is obtained from the Arrhenius model, while backward reaction rate constant is obtained from chemical equilibrium constant as given below.

\[
k_{f,r} = k_{0,r} T^{b_r} \exp \left( - \frac{E_r}{R_u T} \right)
\]

\[
k_{b,r} = k_{f,r} / K_r
\]

\[
K_r = \exp \left[ \frac{\Delta S_r^0}{R_u} - \frac{\Delta H_r^0}{R_u T} \right] \left( \frac{P_{atm}}{R_u T} \right)^{\sum_{i=1}^{n} (v_{i,r}' - v_{i,r})}
\]

\[
\Delta S_r^0 = \sum_{i=1}^{n} \left( v_{i,r}' - v_{i,r} \right) s_i^0 / R_u \quad \text{and} \quad \Delta H_r^0 / R_u = \sum_{i=1}^{n} \left( v_{i,r}' - v_{i,r} \right) h_i^0 / R_u
\]

A variant of DOM [16, 17] is used for radiation in gas and solid media, which solves Eq. (5) for total radiation intensity, \( I \) uncoupled from Eq. (3).

\[
\nabla \cdot \left( I(\hat{r}, \hat{s}) \hat{s} \right) = -(a + \sigma_s) I(\hat{r}, \hat{s}) + an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4 \pi} \int I(\hat{r}, \hat{s}') d\Omega'
\]

First term on RHS is attenuation of intensity through absorption and out–scattering and the second term is augmentation due to emission and in–scattering. A transport equation is solved for each direction and four octants are used in 2–D, leading to \( 4N_\theta N_\phi \) equations for the radiation model [18], in which \( N \) denotes angular discretization in \( \theta \) and \( \phi \) directions. Kinetics of the flame is modeled with the updated mechanism of Konnov [19] consisting of eight participating species H, H\(_2\), O, O\(_2\), H\(_2\)O, OH, HO\(_2\), H\(_2\)O\(_2\) (N\(_2\) as inert) and 21 reversible reactions. Limited validation of this kinetic model was performed by reproducing the predictions of ignition delay times against the experimental data and results reported in Ref. [19].
Boundary conditions used to close the model are depicted in Fig. 1b. The model equations are adopted to an axisymmetric computational domain considering the symmetry of the annular microcombustor. However, it is recognized that above simplification does not preclude the existence of asymmetric flames as the whole reaction zone is modeled.

Equations (1)–(5), subject to the boundary conditions described above, are discretized by finite volume method and solved using the density–based coupled implicit solver [18, 20] with second order accurate spatial and temporal differencing. The grid size was 25 µm in both the directions. Detailed numerical uncertainty estimations by Roache’s grid convergence index method [21] are reported elsewhere [11, 12, 14]. In the absence of experimental data on the proposed annular microcombustor, a similar microcombustor configuration for which experimental data are available is chosen for validation of mathematical model. Li et al. [22] conducted experimental investigations of premixed hydrogen–air flame in a dump (backward step) cylindrical microcombustor made of SS316. Results of validation studies are summarized in Fig. 2 for above test cases.

![Fig. 2. Results of validation studies based on the experimental data of Li et al. [22]. One case each of extreme dump plane velocities is covered for $\phi = 0.6$ and 0.8. $\phi = 1.0$ case is simulated for three dump plane velocities. The included range of dump plane velocities corresponds to the range 8–16 m/s of inlet velocities.](image)

The ability of the formulated model to predict average wall temperatures is observed in the figure for the stoichiometric case as the predicted values are either within the experimental uncertainty or not far from the error bounds. Apparent deficiency of the model for the fuel–lean cases should be viewed considering the anomalous trends in the experimental data. Average experimental wall temperatures for $\phi = 0.8$ are higher than the stoichiometric case, which hints at unaccounted uncertainties in the experiments. A possible cause for this anomaly could be the lack of steady state when measurements for $\phi = 0.8$ were taken which would explain why the average temperatures were close to each other in the two cases. Validation of mathematical model used in this work has shown that model is capable of predicting experimental data for average wall temperatures for the dump microcombustor.

**FLAME STABILIZATION: KINETIC CONSIDERATIONS**

In earlier studies performed using single step kinetics [11, 12], flame stabilization mechanism in the annular microcombustor was studied from purely thermal considerations (without any regard to reaction kinetics). It was shown that wall temperatures higher than the autoignition point caused flame to anchor directly on the wall. Further, parametric studies [14] revealed that the distance of
anchor point from the combustor inlet is a function of wall thermal conductivity and flame would anchor away from the inlet at low thermal conductivities. Although single step chemical kinetics adequately described the overall thermal stabilization mechanism, further study using multi step kinetics is necessary in order to understand the kinetic aspects of flame stabilization. Specifically, the mode of flame stabilization at the walls and in the bulk flow is analyzed in this section with the help of multi step kinetics data.

Fig. 3. Flame stabilization by autoignition using 1–D computation of fuel–lean case at $T_{in} = 1000$ K. The peaks of radical and minor species mass fractions occur before the peak in OH net production rate. (Case Details: $\phi = 0.5$, $V_{in} = 100$ m/s).

Autoignition and preheating are the two possible modes of flame stabilization within the annular microcombustor. Their existence is surmised since wall temperatures near flame edge are high and by the fact that single step chemistry suggested existence of heat reflux and preheating in the microcombustor. Presence of either of these mechanisms can be demonstrated by following the mass fractions of minor species and radicals as they pass through the flame and comparing the data against canonical cases of one–dimensional autoignition and laminar premixed flame [23]. Figure 3 shows the evolution of species mass fractions in autoignition along with temperature and net rate of OH production/consumption. Corresponding profiles for 1–D premixed flame are shown in Fig. 4. It is observed from Fig. 3 that the radicals and minor species grow prior to build–up of OH (signifies thermal runaway) in case of autoignition. On the other hand, minor species and radical concentrations grow together with OH and their peaks appear near the peak OH production rate in case of preheating. This is the classical premixed flame stabilization mode. These data are now compared with the flame in annular microcombustor. The flame under consideration is a lean flame ($\phi = 0.5$) stabilized within the annular microcombustor with $V_{in} = 7.5$ m/s, $T_{in} = 300$ K, and $k_{wall} = 1.75$ W/m K.
Fig. 4. Flame stabilization by preheating using 1-D computation of fuel–lean case at $T_{in} = 300$ K. The peaks of radical and minor species mass fractions occur near the peak in OH net production rate. (Case Details: $\phi = 0.5$, $V_{in} = 0.5$ m/s).

Similar plots of mass fractions were constructed from data at the inner tube wall as shown in Fig. 5. It is observed that their profiles have similar characteristics as in Fig. 4 which indicates that flame stabilization at the walls is due to preheating of incoming fuel–air mixture by the heat transfer from wall. Further, mass fraction profiles in the centre plane of annular reaction zone (corresponding to $r = 0.004$ m) plotted in Fig. 5 are similar in comparison to the canonical case depicted in Fig. 4.
Fig. 5. Stabilization mode at the inner tube wall and the centre plane of annular reaction zone. Similarity with Fig. 4 indicates that the flame stabilizes by preheating of the incoming mixture. (Case Details: \( V_{in} = 7.5 \text{ m/s}, \ T_{in} = 300 \text{ K}, \) and \( k_{wall} = 1.75 \text{ W/m K} \)).

Table 2. Results of integral reaction flow analysis for \( \phi = 0.5, k_{wall} = 1.75 \text{ W/m K}, \) and \( V_{in} = 7.5 \text{ m/s hydrogen–lean flame in annular microcombustor. Negative sign under parenthesis indicates contribution for destruction of a species.}

<table>
<thead>
<tr>
<th>R/Species</th>
<th>H</th>
<th>H(_2)</th>
<th>O</th>
<th>O(_2)</th>
<th>H(_2)O</th>
<th>OH</th>
<th>H(_2)O(_2)</th>
<th>HO(_2)</th>
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<td>3</td>
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<td>2.8</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>(-)9.4</td>
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<td>–</td>
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<td>4.1</td>
<td>1.9</td>
<td>(-)36.4</td>
<td>5.1</td>
</tr>
</tbody>
</table>

**Total** | **96.7** | **98.9** | **95.5** | **91** | **94.6** | **99.4** | **84.5** | **91.6**

**REACTION KINETICS**

Leach [10] investigated the effects of fluid–wall thermal interaction on chemical kinetics of hydrogen–air flame and found that heat recirculation tends to broaden the flame and alter relative importance of elementary reactions. In this section, reaction kinetics for different flames is studied to determine the dominant reactions controlling the flame kinetics and effects of heat losses on chemical kinetics. Another objective is to study the importance of low temperature reactions in flame stabilization since low temperature kinetics is of interest in microcombustion and failure of single step kinetics to predict low temperature kinetics is conjectured to be one of the possible reasons affecting its reliability.
In order to determine the dominant reactions of the mechanism under different conditions of heat losses and mixture composition, integral reaction flow analysis (RFA) [24] was performed by volumetric integration of production/consumption rates of each species from all the reactions in which it participates as reactant or product. Magnitudes of percent contributions of each reaction in production and consumption of a given species were arranged in matrix form with rows defining reaction contributions and columns defining individual species. A particular row entry was deemed unimportant if percent contributions for most of the entries in that row were near 1% or less. RFA of the fuel–lean flame is reported in Table 2. Entries shown are for reactions significantly influencing heat release rates as determined by their total contributions in the last row and negative sign in the parenthesis against dominant contributions indicates species destruction.

Fig. 6. Molar rates of dominant reactions. 1–D flame data for the reactions appears in panel (a).

Rates of the dominant reactions are plotted in Fig. 6 at three locations viz. reaction zone centre plane, inner tube wall, and outer tube wall. Left side panel shows data for corresponding 1–D flames. Considering the burning intensity, it is observed that reaction rates increased when compared to the corresponding 1–D flame at the inner tube, as most of the dominant reactions were active at higher temperatures prevailing in the inner tube. In the centre plane of annular reaction zone, the reaction rates decreased and active chemistry is observed in the low temperature zones. Effect of thermal conductivity is observed most clearly in case of outer tube data in panel (d). For the lean flame burning near low thermal conductivity wall (similar to ceramic), chemistry is almost inactivated presumably by lower wall temperatures near the inlet and flame appears to have quenched. Considering the quenching of lean flame near the outer tube wall, an inspection of
reaction rates at the inner tube wall also shows the similarly inactive chemistry in the low
temperature zones. Further, active chemistry is present in the centre plane, panel (c).

These observations indicate that low temperature at the outer tube wall is not the only reason of
flame quenching for low \( k_{\text{wall}} \) material. To find out more about this, consider the canonical cases in
light of the dominant reactions reproduced below.

\[
\begin{align*}
\text{OH} + \text{O}_2 + \text{M} & = \text{HO}_2 + \text{M} \quad \quad \text{(R8)} \\
\text{O} + \text{H}_2 & = \text{OH} + \text{H} \quad \quad \text{(R14)} \\
\text{H} + \text{O}_2 & = \text{OH} + \text{O} \quad \quad \text{(R15)} \\
\text{H}_2 + \text{OH} & = \text{H}_2\text{O} + \text{H} \quad \quad \text{(R16)} \\
\text{H} + \text{HO}_2 & = \text{OH} + \text{OH} \quad \quad \text{(R19)}
\end{align*}
\]

Contribution of R11, a reaction similar to R8, is neglected in comparison to R8. It is observed
that all the five reactions involve H radical either as a reactant or as product species. Destruction of
H radical occurs at low temperatures mainly by R8 and R19 (and by R15 to a lesser extent). R14
and R16 are responsible for production of H at high temperatures. In the lean case, H radical pool is
reduced due to smaller proportion of \( \text{H}_2 \) in the mixture. In the absence of H radical in low
temperature zones, smaller rates of R8, R19, and R15 would lead to a reduced pool of \( \text{OH} \) radical
and thermal runaway would not occur, ultimately resulting in smaller heat release rate or no flame at
all. Although R14 and R16 form H radicals in the high temperature zones, its diffusion into low
temperature zones is impaired due to generally low temperatures near the outer tube wall. Thus,
low temperature levels at the outer tube combined with reduced H radical pool impair thermal
runaway (production of \( \text{OH} \)) and reduce heat release rates. Additional calculations (not shown)
indicate that availability of H radicals increases at higher equivalence ratios and formation of upper
flame branch near the outer tube is possible even though wall temperatures are low (high axial
temperature gradients).

**Table 3.** Results of integral reaction flow analysis under adiabatic conditions.

<table>
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<th>R/Species</th>
<th>( \text{H} )</th>
<th>( \text{H}_2 )</th>
<th>( \text{O} )</th>
<th>( \text{O}_2 )</th>
<th>( \text{H}_2\text{O} )</th>
<th>( \text{OH} )</th>
<th>( \text{H}_2\text{O}_2 )</th>
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<td>1.6</td>
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<td><strong>96.1</strong></td>
<td><strong>82.5</strong></td>
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**EFFECTS OF HEAT LOSSES**
Percentage contributions of dominant reactions shown in Table 3 remained essentially unchanged between adiabatic and diabatic flame (Table 2) and this is reflected in the local distributions and magnitudes of dominant reactions in the centre plane and inner wall regions shown in Fig. 7. Significant changes however are observed in case of outer tube shown in panel (d) of Fig. 7 and a strong upper branch could form near the outer tube walls as insulated walls prevented heat losses from the flame zone.

This difference is also visualized through the distributions of heat release rates in these cases from Fig. 8. Flame with heat losses is near–quenching and upper branch on the outer tube is entirely absent. Flame without heat losses has formed a short and intense upper branch due to high wall temperatures brought about by insulation.

A key difference from corresponding 1–D cases noted here is in the R16 distribution vis–à–vis R8. If in the 1–D case, R16 became significant only after the low temperature peaks in R8 and R19 (both are necessary to produce OH), in the axisymmetric cases, peaks of R8 and R19 shifted to higher temperature and R16 shows a plateau at the same locations. The spurt in R16 before any significant rates from R8 and R19 is due to low temperature activity of R17: \( \text{OH} + \text{OH} = \text{H}_2\text{O} + \text{O} \) that produces two OH radicals even though its contribution is small in the overall scheme. Other two possible reactions viz. R6 and R31 are active in high temperature zones and play no significant role in the build–up of product \( \text{H}_2\text{O} \) by R16 in the low temperature zones.

**Fig. 7.** Molar rates of dominant reactions for the adiabatic walls case.
It thus appears that O radical is either unusually immobile at low temperatures or minor reactions like R20 which produce both O and H$_2$O along with the diffusion of H radical in the low temperature zone could explain the differences. In other words, the multidimensional effects are at work and the superficial similarity with 1-D case is influenced through these related developments near flame tip/centre plane. These effects are noticed irrespective of mixture composition and most noticeably in the wall regions where low temperature peaks of R8 and R19 are entirely absent even though R16 is actively producing H$_2$O. This observation rules out migration of O and H radicals from the shoulder and edge regions of flame due to funneling action as the possible reason for active R16 in the low temperature zones.

Figure 9 shows that low temperature production of water occurred in the center plane of the reaction zone and also in the outer wall region when heat losses were allowed. While, water production at low temperatures is not likely to contribute flame quenching in conventional scale combustors due to large reaction volume, condensation of water on to the walls of microcombustor has been observed experimentally [2, 4] in case of microcombustion. Thus, low temperature production of H$_2$O through minor reactions could be detrimental to flame stability due to possibility of condensation, which would lead to cooling of the walls and thermal quenching.

CONCLUSIONS

The main conclusions of the analysis of lean premixed hydrogen–air flame established within the annular microcombustor are as below.
• Although wall temperatures are higher than the autoignition temperature of \( \text{H}_2 \)-air system, flame stabilization is controlled by preheating of the incoming fuel–air mixture and not autoignition. Reactions involving H radicals are dominant contributors to steady state heat release.

• Level of heat losses does not change the reaction pathway as well as the percentage contributions of dominant reactions. However, upper flame branch can be established for lean mixture under the conditions of zero heat losses because chemistry is activated at higher temperatures even though H radical pool is inherently small.

• Low temperature kinetics plays a dual role in microcombustion. On one hand, it allows the establishment of flame by activating reactions of H radical but on the other hand, it can also result in production of small quantities of \( \text{H}_2\text{O} \) in the low temperature regions near combustor inlet. Eventual condensation of \( \text{H}_2\text{O} \) on the combustor walls could lead to cooling and flame quenching.

REFERENCES


