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A Burning Velocity Correlation for Premixed Hydrogen/Air/Steam Flames

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In view of safety assessment of containment integrity in nuclear power plants, the structures and burning velocity characteristics of hydrogen/air/steam premixed flames have been analyzed numerically using a detailed chemical mechanism with 19 elementary steps concerning H_2/O_2 reactions. Time integration and the modified Newton method are applied in solving the governing equations and an adaptive grid method is employed to resolve the stiffness.

Burning velocities are obtained as a function of hydrogen mole fraction, steam mole fraction, and initial temperature. The effect of carbon monoxide addition on burning velocities are also considered. The calculated burning velocities are generally lower than the existing experimental values. However, they show good qualitative agreement irrespective of the reaction mechanisms used in the computation. Steam is found to have both cooling effect and chemical effect affecting chain-branching reaction and heat release. A correlation on burning velocities is obtained and can be used as an improved relation over a wide range of steam concentration.

Key Words : Burning velocity, Hydrogen/Air/Steam, Premixed Flame

1. Introduction

Under severe accident conditions in power plants, hydrogen and carbon monoxide can be generated from the reactions of zirconium cladding with hot steam and corium with concrete, respectively. An explosive combustion of hydrogen and air premixture can result in thermal and pressure loads to the containment, as demonstrated in TMI-2 accident, and thus could threaten the containment integrity and equipment survivability. In this regard, many researches have simulated and investigated the phenomena of severe accident (Berman, 1986; Sherman, 1988; Wong, 1988).

In order to assess the strength of thermal and pressure loads resulting from the combustion of hydrogen and air, it is important to predict the burning velocity, which is one of the key factors characterizing flame behaviors. As the burning velocity is high, more heat and stronger mechanical stresses are imposed on the containment or equipment during a unit time.

There are many theoretical and experimental studies on burning velocities (Wu, 1984; Egolfopolous, 1990; Smooke 1983; Warnatz, 1981; Mauss, 1991; Williams, 1985). However, there is significant scattering in the values of burning velocities obtained from experiments (Egolfopolous, 1990) due to the effects of flame stretch and preferential diffusion, especially in hydrogen/air flame. Furthermore, there are only a few burning velocity data for mixtures that include steam (Liu, 1983; Koroll et al., 1993), although a significant amount of steam can be mixed with hydrogen/air in various practical situations. A previous numerical study (Kang et al., 1994) does not reflect the chemical effect of steam appropriately due to the adoption of one-step chemistry. There are available correlations for the burning velocities of hydrogen/air/steam premixture.

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However, there is much discrepancy among experimental results (Liu, 1983 ; Koroll et al., 1993), which the correlations are based on. Thus, a more reliable correlation is required.

Although steam has a significant role in combustion processes (Dryer, 1976), the effect of steam addition has not been fully clarified. Steam has been regarded only as a diluent since it lowers the flame temperature due to its high heat capacity, and leads to a decreased burning velocity. However, degree of reduction in burning velocity with steam addition is not simply proportional to the change in heat capacity of the mixtures (Koroll et al., 1986), which implies that the effect of chemical kinetics is significant. Therefore, this chemical effect will be extensively studied in this paper.

As mentioned above, determination of the burning velocity still has much difficulties and a limited range of validity in experimental side. Motivated by this, the present study investigates the burning velocities over a wide range of hydrogen and steam contents, numerically employing a detailed chemistry model. The effect of carbon monoxide addition is also investigated.

2. Governing Equations and Solution Method

A laminar one dimensional planar flame is adopted as a model. Since burning velocity is in the order of 1 m/s, viscous dissipation can be neglected and isobaric process can be assumed. Radiative heat loss, body force and Dufour effect are neglected.

The governing equations for a steady, isobaric, one-dimensional flame propagation are as follows (Kee, 1990):

$$\dot{m} = puA \tag{1}$$

$$\dot{m}\frac{dT}{dx} = \frac{1}{C_p}\frac{d}{dx}\left(\lambda A\frac{dT}{dx}\right) - \frac{A}{C_p}\sum_{k=1}^{K}\rho Y_k V_k \times C_{pk}\frac{dT}{dx} - \frac{A}{C_p}\sum_{k=1}^{K}\dot{\omega}_k h_k W_k \tag{2}$$

$$\dot{m}\frac{dY_k}{dx} = -\frac{d}{dx}(\rho A Y_k V_k) + \dot{\omega} A W_k, \quad k=1, \cdots, K \tag{3}$$

$$\rho = p\overline{W}/RT \tag{4}$$

where x is the coordinate normal to flame, $\dot{m}$ the mass flow rate, A the cross-sectional area, T the temperature, Y_k the mass fraction of the k^{th} species, p the pressure, u the velocity, ρ the density, $\overline{W}$ the average molecular weight of mixture, R the universal gas constant, λ the thermal conductivity, C_p the specific heat of mixture, and W_k, C_{pk}, $\dot{\omega}_k$, h_k, and V_k are the molecular weight, the heat capacity, the reaction rate, the specific enthalpy, and the diffusion velocity of the k^{th} species (Kee, 1983), respectively. Thermodynamic properties and reaction rates are determined from CHEMKIN-II (Kee, 1989) and transport properties are from TRANSPORT PACKAGE (Kee, 1983). The boundary conditions are

$$x \rightarrow -\infty;\ T(-\infty) = T_u,\ Y_k(-\infty) = Y_{ku},\quad k=1,\cdots,K \tag{5}$$

$$x \rightarrow \infty;\ dT/dx = 0,\ dY_k/dx = 0,\quad k=1,\cdots,K \tag{6}$$

where the subscript u denotes an unburned state.

The mass flow rate $\dot{m}$ is the eigenvalue of the above governing equations. Detailed method for solving this eigenvalue problem is described elsewhere (Smooke, 1983; Kee, 1990). Time integration and the modified Newton method are applied in solving the discretized equations and an adaptive grid method is used to resolve the stiffness (Smooke, 1983; Sohn et al., 1995). A 19-step chemical reaction mechanism (Warnatz, 1992), as listed in Table 1, is mainly employed. Other mechanisms (Egolfopolous, 1990; Warnatz, 1981) are also used for the comparison of the burning velocity dependence on reaction mechanisms.

3. Results and Discussions

Numerical calculations are conducted for H_2/air/steam premixtures. First, the effect of reaction mechanisms on burning velocity, S_L^0, is shown in Fig. 1 as a function of steam mole fraction for the composition ratio $X'_{H_2} = X_{H_2}/(X_{H_2} + X_{air}) = 0.42$, at which point the burning velocity is maximum for $X_{H20} = 0$, $T_u = 373\text{K}$, and $p = 1\text{atm}$. Even though there are some scattering dependent on the mechanisms, the qualitative effect of steam is

Table 1 Gas-phase mechanism of hydrogen oxidation (Warnatz, 1992).

			B_i(cm, mol, s)	b_i	E_i(kJ/mol)
1. H_2-O_2 Chain Reaction					
R1	$H+O_2$	$=OH+O$	2.00E14	0.00	70.3
R2	H_2+O	$=OH+H$	5.06E04	2.67	26.3
R3	H_2+OH	$=H_2O+H$	1.00E08	1.60	13.8
R4	$OH+OH$	$=H_2O+O$	1.50E09	1.14	0.4
2. Dissosiation/Recombination Reactions					
R5	$H+H+M$	$=H_2+M$	9.70E16	-0.60	0.0
R6	$H+OH+M$	$=H_2O+M$	2.26E22	-2.00	0.0
R7	$O+O+M$	$=O_2+M$	2.90E17	-1.00	0.0
3. HO_2Formation/Consumption					
R8	$H+O_2+M$	$=HO_2+M$	2.30E18	-0.80	0.0
R9	$H+HO_2$	$=OH+OH$	1.70E14	0.00	3.7
R10	$H+HO_2$	$=H_2+O_2$	4.30E13	0.00	5.9
R11	$H+HO_2$	$=H_2O+O$	3.00E13	0.00	7.2
R12	$O+HO_2$	$=OH+O_2$	3.20E13	0.00	0.0
R13	$OH+HO_2$	$=H_2O+O_2$	6.00E13	0.00	0.0
4. H_2O_2Formation/Consumption					
R14	HO_2+HO_2	$\rightarrow H_2O_2+O_2$	1.00E12	0.00	0.0
R15	$OH+OH+M$	$=H_2O_2+M$	3.25E22	-2.00	0.0
R16	H_2O_2+H	$=HO_2+H_2$	1.70E12	0.00	15.7
R17	H_2O_2+O	$=H_2O+OH$	1.00E13	0.00	15.0
R18	H_2O_2+O	$=HO_2+OH$	6.80E11	0.00	16.6
R19	H_2O_2+OH	$=H_2O+HO_2$	1.80E12	0.00	1.4

reaction-rate constant $k=B \cdot T^{\beta} \cdot \exp(-E/RT)$

third-body efficiencies : $H_2/1.0/$, $H_2O/6.5/$, $O_2/0.35/$, $N_2/0.04/$

$[M]=[H_2]+6.5[H_2O]+0.35[O_2]+0.40[N_2]$

nearly similar.

The modified-Yetter mechanism (Egolfopolous et al., 1990) results in the lowest prediction in S_L^0, and also the new mechanism of Warnatz (1992) somewhat underpredicts than the old mechanism of Warnatz (1981). Even though the Warnatz (1981) mechanism agrees well with experimental results (Koroll et al., 1986), it does not guarantee the accuracy in the burning velocity data due to the inherent difficulties associated with various effects including flame stretch and preferential diffusion in hydrogen flame experiments. The new mechanism of Warnatz has been updated and emphasized for the third body effect of steam. Since over-prediction in burning velocity is desirable in terms of safety assessment, the new mechanism of Warnatz is used in the following unless otherwise specified.

3.1 Effect of steam on burning velocity

The effect of steam addition is investigated by comparing flame structures with steam and that replaced with nitrogen, whose major effect is to reduce flame temperature as a diluent. While steam has a larger heat capacity than nitrogen, thus lowering flame temperature, thereby reactivity, it has a higher third-body chaperon efficiency, α, in view of chemical kinetics -0.4 for nitrogen and 6.5 for steam as listed in Table 1.

For stoichiometric H_2/O_2 premixed flames, flame structures for the following different cases are calculated; (a) the addition of 25% N_2, (b)

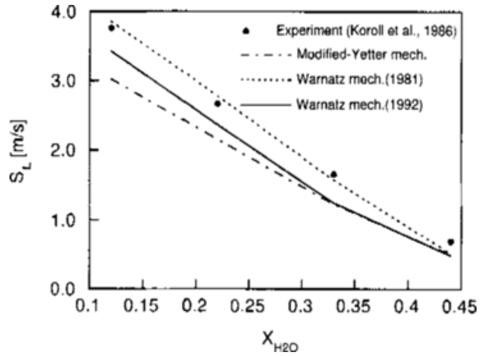

Fig. 1 Comparison of calculated and measured burning velocity as a function of X_{H_2O} near $X'_{H_2}=0.42$ at $T=373$ K, $p=1$ atm; symbols-experiment (Koroll, 1986); lines calculation using various chemical kinetic mechanisms (Egolfopolous, 1990; Warnatz, 1981; Warnatz, 1992).

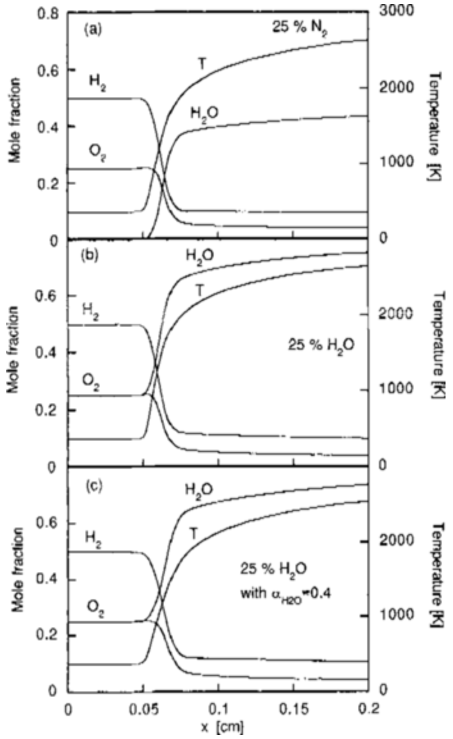

Fig. 2 Mole fraction and temperature profile for 2:1 H_2/O_2 mixtures at $T=373$ K, $p=1$ atm (a) containing 25% N_2 diluent, (b) containing 25% H_2O diluent, and (c) containing 25% H_2O diluent and third-body coefficient of $H_2O=0.4$ for (R8).

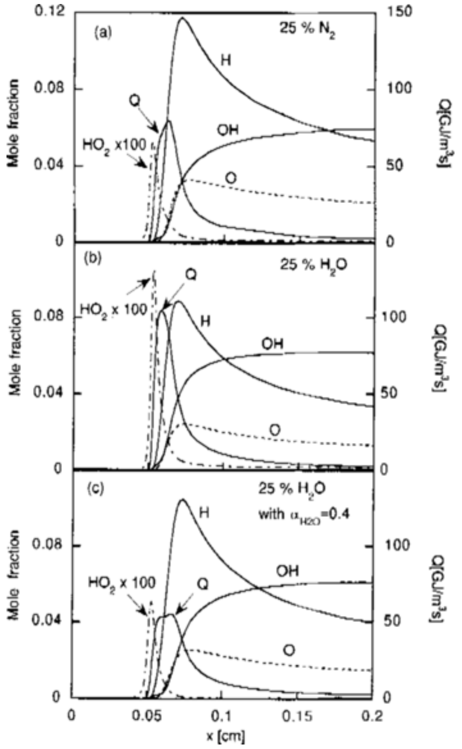

Fig. 3 Minor species mole fraction and heat release rate profile for 2:1 H_2/O_2 mixtures at $T=373$ K, $p=1$ atm; (a) 25% N_2 diluent, (b) containing 25% H_2O diluent, and (c) containing 25% H_2O diluent and third body coefficient of $H_2O=0.4$ for (R8).

25% H_2O, and (c) 25% H_2O with fixed third-body efficiency of 0.4, which is the same as that of N_2. Respective temperature, controlling species, heat release rate, and radical production rate profiles are shown in Figs. 2~4. The burning velocities are found to be 8.75, 9.04 and 7.58 m/s, respectively. Experimentally, the burning velocities are 8.4 and 9.3 m/s for the cases with 25% N_2 and 25% H_2O, respectively (Koroll et al., 1986).

With 25% steam, the mole fraction of HO_2 becomes two times larger than that with 25% nitrogen. Meanwhile, the mole fraction of H decreases and X_{OH} does not vary significantly. Heat release rate increases by 30% and reaction zone moves toward the unburned region. Also, the adiabatic flame temperature T_b decreases to 2796 K, compared with $T_b=2910$ K in the case of nitrogen dilution. Even though the flame temperature decreased with steam, the temperature in the

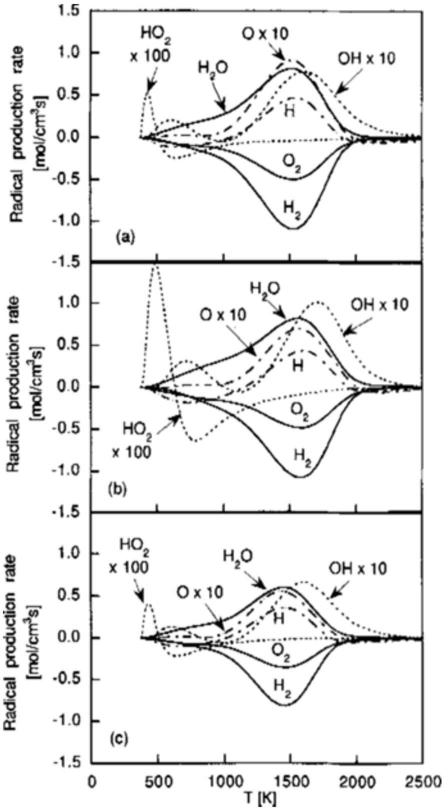

Fig. 4 Radical production rate as a function of temperature for 2:1 H_2/O_2 mixtures at $T=$ 373 K , $p=1$ atm; (a) 25% N_2 diluent, (b) containing 25% H_2O diluent, and (c) containing 25% H_2O diluent and third-body coefficient of $H_2O=0.4$ for (R8).

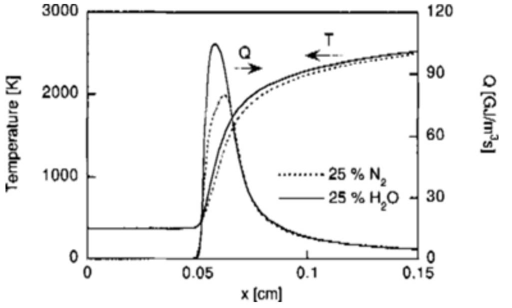

Fig. 5 Temperature and heat release rate at the reaction zone for 2:1 H_2/O_2 mixtures at $T=$ 373 K, $p=1$ atm with 25% N_2 and 25% H_2O.

region where heat is released is higher by 100 K with steam compared to that with nitrogen, as shown in Fig. 5.

In general, the burning velocity depends on adiabatic flame temperature T_b, overall activation energy E, and thermodynamic and transport properties from a phenomenological analysis (Williams, 1985) as shown in Eq. (7);

$$S_L^0 \sim p^{\left(\frac{m}{2}-1\right)}\sqrt{\frac{\lambda}{C_p}}\exp\left(-\frac{E}{2RT_b}\right) \qquad (7)$$

The steam addition will increase heat capacity compared to nitrogen addition, thereby decreasing the adiabatic flame temperature. Thus, with steam addition the burning velocity is expected to decrease compared to that with nitrogen. However, the existing experimental and numerical predictions show that the burning velocity with steam is higher than that with nitrogen.

Such effects of N_2 and steam on burning velocity are mainly caused by the higher third-body efficiency of steam. The increase in the reaction rate of $H+O_2+M=HO_2+M$ (R8) causes the increase in the production of HO_2. This, in turn, increases the heat release, since the reaction step is highly exothermic. Steam enhances the reactions relevant to production or consumption of HO_2 and H_2O_2, and their role is more significant with large amount of steam added. Representative reactions including HO_2 and H_2O_2 are $H+HO_2=OH+OH$ (R9), $HO_2+HO_2 \rightarrow H_2O_2+O_2$ (R14), and $H_2O_2+M \rightarrow 2OH+M$ (R15b), where b denotes the backward reaction.

The step R8 itself terminates the chain reaction, while the reaction initiates the subsequent reactions R9, R14 and R15b, which are all relevant to the chain reaction. Therefore, the step R8 is crucial for both radical-termination and chain-branching paths. It is worthy of note that the large heat release obtained from the step R8 (Glassman, 1987) is the primary cause for the changes in flame structure and burning velocity.

When the third-body efficiency of H_2O is replaced by that of N_2, the flame temperature and burning velocity are reduced significantly since steam has larger heat capacity than N_2 and its third-body effect is underestimated. These results imply that steam has non-negligible chemical effect in addition to the role as a diluent. The third-body effect of H_2O is still emphasized, since

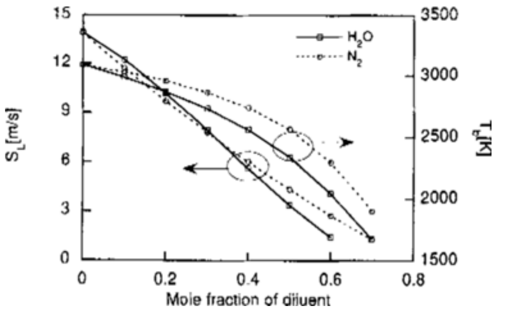

Fig. 6 Burning velocities and adiabatic flame temperature of 2:1 H_2/O_2 mixtures at 373 K with diluents of N_2 and steam.

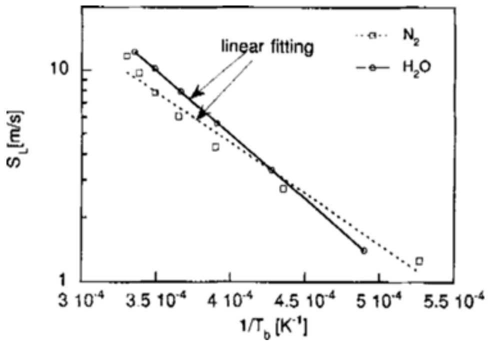

Fig. 7 Linear fitting for burning velocities of 2:1 H_2/O_2 mixtures at 373 K with diluents of N_2 and steam as a function of the reciprocal of adiabatic flame temperature ; symbols-calculated ; lines-fitted.

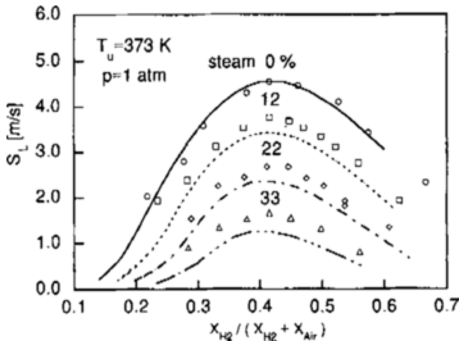

Fig. 8 Comparison of calculated and measured burning velocity at $T=373$ K, $p=1$ atm (Experimental data from Koroll (1986); calculation using Warnatz (1992)'s chemical kinetic mechanism), Symbols-experiment; lines-calculation.

the third-body efficiency increases to 6.5 in the more recent mechanism suggested by Warnatz (1992) compared with 6. 0 in his previous mechanism (Warnatz, 1981).

The effects of N_2 and H_2O dilution on burning velocity and the adiabatic flame temperature T_b are shown in Fig. 6. In contrast to the general prediction that lower T_b causes lower burning velocity, the burning velocity with steam addition is larger than that with nitrogen addition when the diluent mole fraction is less than 0.3 in spite of the lower T_b with steam. This is in a good qualitative agreement with previous experimental results (Koroll, 1986) and supports the fact that, in addition to the flame cooling effect, steam has a significant chemical third-body effect and changes controlling chemical kinetics.

As diluent mole fraction increases beyond, say 0.3, the flame cooling effect of steam becomes dominant than the third-body effect. Therefore, the burning velocity with steam decreases faster than that with nitrogen. The burning velocities with steam and nitrogen addition, are crossing at the diluent mole fraction of 0.3 from numerical analyses, while the crossing mole fraction was reported to be 0.45 experimentally (Koroll et al., 1986). This discrepancy can not be fully explained at this stage whether it is due to the inaccuracies in chemical kinetic mechanism or in experiment. However, the qualitative effects of steam addition can be fully explained.

With the adiabatic flame temperature predetermined, the overall activation energy can be obtained through the fitting using Eq. (7). The results are shown in Fig. 7, where slopes of the fitted lines are the overall activation energies, which reflects the relative difference in chemical kinetic effect. The activation energies with steam and nitrogen are 56.0 kcal/mol and 44.2 kcal/mol, respectively.

3.2 Burning velocity correlation for H_2/Air/steam mixtures

Burning velocities are calculated at various compositions and initial temperatures for H_2/air/steam mixtures. The calculated burning velocities are compared with the measured values (Koroll et al., 1986) in Fig. 8. Without adding steam, the calculated and the measured values are in excel-

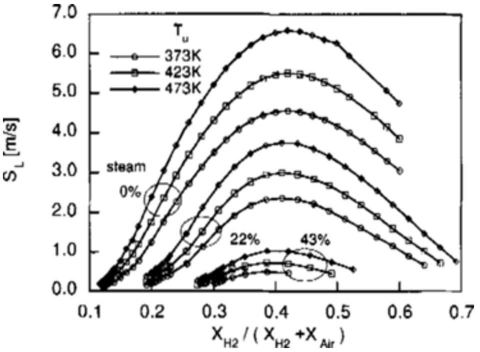

Fig. 9 Effect of temperature on the calculated burning velocity for H_2/air/steam mixtures at $p=1$ atm.

lent agreement, while with steam added, the burning velocities from the numerical calculations are somewhat lower than the experimental values. The errors are estimated about 0.2~0.5 m/s.

Figure 9 shows the calculated burning velocities at initial temperatures of 373K, 423K, and 473K. As the initial temperature increases, the adiabatic flame temperature increases, which, in turn, increases the burning velocities. Liu et al. (1983) expressed the effect of initial temperature on S_L using temperature index n in the form,

$$
\begin{aligned}
&S_L^0(T) \propto T^n \\
&n = C_1 + C_2(0.42 - X'_{H_2}), \\
&C_1 = 1.571,\ C_2 = 0.3839\,(X'_{H_2} \le 0.42), \\
&\qquad -0.2476\,(X'_{H_2} \ge 0.42).
\end{aligned}
\tag{8}
$$

In that experiment, the temperature index was reported ranging from 1.5 to 1.7 depending on mixture composition. In the present calculation without H_2O, the temperature indices are 1.56 at $X'_{H_2}=0.42$, 1.71 at $X'_{H_2}=0.5$, and 1.66 at $X'_{H_2}=0.15$, showing a good agreement with experimental results. With $X_{H_2O}=0.12$, 0.22, 0.33 and 0.43 near $X'_{H_2}=0.42$, temperature indices are 1.73, 1.97, 2.40 and 3.06, respectively. As a result, burning velocity is shown to be more sensitive to the initial temperature as the amount of steam increases. The reason is that steam addition increases activation energy and the flame temperature decreases progressively faster as the amount of steam addition increases (cf. Fig. 6).

From the numerical results, a burning velocity correlation is constructed based on the following three assumptions.

(i) The functional form of burning velocity considering the effect of initial temperature can be written in the form,

$$S_L^0 \propto T^{[C_1+C_2(0.42-X'_{H_2})](1+C_3X_{H_2O})} \tag{9}$$

where C_1, C_2 and C_3 are constant to be determined and $X'_{H_2}=0.42$ is the hydrogen mole fraction at which S_L^0 is maximum.

(ii) With the initial temperature specified, S_L^0 is nearly parabolic with respect to $X'_{H_2}=0.42$. To account for slight asymmetry with respect to mixture composition, third-order polynomials are constructed at both $X'_{H_2}<0.42$ and $X'_{H_2}>0.42$. And, the two polynomials are matched smoothly at $X_{H_2}=0.42$.

(iii) Effect of steam addition is not straightforward to formulate since it has a chemical effect. Thus, the formulations suggested by Liu et al. (1983) and Koroll et al. (1993) can not be applied in the wide range of steam concentrations. To construct a valid correlation, combination of an exponential function multiplied by a second-order polynomial with respect to X_{H_2O} is constructed. Here, X_{H_2O} is normalized by the mole fraction of H_2O at the flammability limit, $X_{(H_2O)L}$, which is expressed in a second-order polynomial through curve fitting from experimental data by Koroll et al. (1993).

The collective correlation equation constructed based on above principles is as follows;

$$
\begin{aligned}
&S_L^0/S_{L\,ref}^0 = B\,(T_u/T_{ref})^C D \\
&B = A_1 + A_2(0.42 - X'_{H_2}) + A_3(0.42 - X'_{H_2})^2 \\
&\qquad + A_4(0.42 - X'_{H_2})^3 \\
&C = [A_5 + A_6(0.42 - X'_{H_2})] \\
&\qquad \times [1 + A_7(X_{H_2O}/X_{(H_2O)L})] \\
&D = \exp(A_8X_{H_2O})\,[1 + A_9X_{H_2O}/X_{(H_2O)L} \\
&\qquad + A_{10}(X_{H_2O}/X_{(H_2O)L})^2] \\
&X_{(H_2O)L} = [0.59 - 4.7554(0.42 - X'_{H_2})^2]
\end{aligned}
\tag{10}
$$

where the reference temperature and pressure are 300K and 1 atm, respectively, and $S_{L\,ref}^0=3.2$ m/s is a burning velocity at the reference state and $X'_{H_2}=0.42$. The number of calculated S_L^0 data used to construct the correlation is about 400 in the range of X'_{H_2} from 0.14 to 0.60. The coefficients A_i's in the correlation are determined by a

Table 2 Coorelation-equation coefficients for the burning velocity of hydrogen/air/steam mixtures.

	$X'_{H2} \leq 0.42$	$X'_{H2} \geq 0.42$
A_1	1.0038	1.0038
A_2	0.2415	-0.1106
A_3	-25.7666	14.0198
A_4	46.6738	-20.3969
A_5	1.5710	1.5710
A_6	0.3839	-0.2476
A_7	0.7212	0.8861
A_8	1.3060	1.0467
A_9	-2.1830	-2.1655
A_{10}	1.2278	1.2077

linearized least-square-fitting to the calculated S^0_L data. All coefficients are listed in Table 2.

Root-mean-square values for deviation between the correlation and the calculated S^0_L data are 0. 123 m/s when $X'_{H_2}<0.42$ and 0.299 m/s when $X'_{H_2}>0.42$. The comparison of burning velocity from the correlation with S^0_L calculated numerically are demonstrated in Fig. 10, which shows a very good agreement between the correlated and numerical data.

3.3 Burning velocity with carbon monoxide added to hydrogen mixture

Burning velocity can be affected by carbon monoxide generated during a severe accident. To consider the chemical kinetic effect of CO, the following reaction step (Peters, 1991) is added to the present reaction mechanism (Warnatz, 1992).

$$\begin{aligned}&CO+OH=CO_2+H\\&B(\text{cm, mol, s})=4.4E+6,\ \beta=1.5,\\&E(\text{kJ/mol})=-3.10\end{aligned} \tag{11}$$

When CO is included in H_2/air/steam mixture, the shape of burning velocity curve with respect to X'_{H_2} and X_{H_2O}, changes minimally compared with that in H_2/air/steam mixture. It only shifts the burning velocity curve toward a larger X'_{H_2}. This implies that adding CO can be treated as an extra hydrogen is added. The equivalence of CO in terms of hydrogen concentration is expressed by the form (Park, 1991),

$$X_{Eq.H_2}=X_{H_2}+F\times X_{CO}. \tag{12}$$

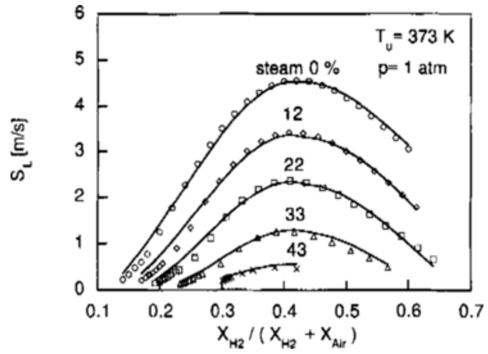

Fig. 10 Comparison of calculated and fitted burning velocities of H_2/air/steam mixtures, symbols-calculated ; lines-fitted.

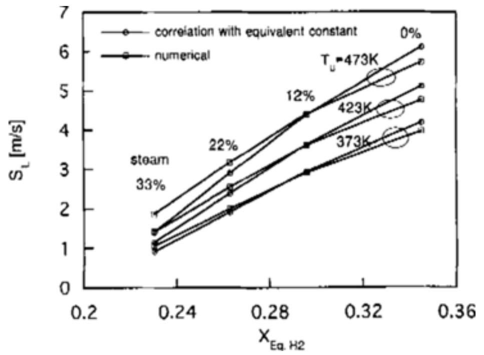

Fig. 11 Comparison of burning velocities of H_2/CO/air/steam mixtures with CO and equivalent $X_{Eq.H_2}$ at $T=373$ K, 423K and 473 K, H_2 : CO=4 : 1 in mole fraction ratio.

From Eqs. (10) and (12), the best-fit equivalent constant F is found to be 0.1095. Burning velocities from the direct numerical calculation and the correlation with transformed CO are shown for comparison in Fig. 11. The equivalent constant underestimates the role of CO in the range of low $X_{Eq.H_2}$ and overestimates in the range of high $X_{Eq.H_2}$.

In view of safety, it is desirable to overestimate burning velocity at the condition where the burning velocity is relatively high. Therefore, the prediction of burning velocity using the equivalent constant is found to be acceptable.

4. Concluding Remarks

Using numerical calculation, the burning velocity for H_2/air/steam is obtained in the present study. It is one of the factors characterizing the thermal and pressure loads imposed on the containment in nuclear power plants.

Reliable correlation has not been available since experimental data over a wide range of hydrogen and steam concentrations are not sufficients and there are much variations in the burning velocity depending on experimental methods used in the measurement. And, the effect of steam on the burning velocity has not been extensively studied. The numerical calculation makes us overcome these limits and treat steam addition with ease. Therefore, the numerical analysis is employed in this study.

The effect of steam addition on burning velocity is investigated in various aspects and chemical effect of steam is emphasized. A correlation equation based on the calculated burning velocities is proposed for the prediction of burning velocity at various conditions. It is more reliable and useful than the existing correlations, because it has no ambiguity from the measurement and is applicable over a wide range of steam concentration, respectively.

With carbon monoxide added to hydrogen mixture, CO is replaced with equivalent amount of hydrogen using a fitted equivalent constant. The correlation equation, considering CO in that way, produces reliable burning velocity in a good agreement with burning velocity data from the direct numerical calculation with the representative reaction step for CO oxidation included.

The proposed burning velocity correlation for H_2/air/steam/CO can be applied for the prediction of burning velocity in severe accident analysis codes such as CONTAIN (Murata, 1989) or MELCOR (SNL, 1989).

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