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An experimental investigation of the ignition properties of hydrogen and carbon monoxide mixtures for syngas turbine applications

S.M. Walton ^{*}, X. He, B.T. Zigler, M.S. Wooldridge*Department of Mechanical Engineering, University of Michigan, 2350 Hayward St., Ann Arbor, MI 48109-2125, USA*

Abstract

Ignition studies of simulated syngas mixtures of hydrogen (H₂), carbon monoxide (CO), oxygen (O₂), nitrogen (N₂), and carbon dioxide (CO₂) were performed using a rapid compression facility. Experiments were conducted using pressure time-histories and high-speed imaging to measure ignition delay times (τ_{ign}), over a broad range of conditions relevant to current and proposed gas-turbine technologies, and which included fuel compositions consistent with typical gasification facilities. Specifically, the τ_{ign} data spanned pressures from $P = 7.1$ to 26.4 atm, temperatures from $T = 855$ to 1051 K, equivalence ratios from $\phi = 0.1$ to 1.0, oxygen mole fractions from $\chi_{\text{O}_2} = 15\%$ to 20% and H₂:CO ratios from H₂:CO = 0.25 to 4.0 (mole basis). Regression analysis yielded the following best-fit to the composite data set:

$$\tau_{\text{ign}} = 3.7 \times 10^{-6} P^{-0.5} \phi^{-0.4} \chi_{\text{O}_2}^{-5.4} \exp(12,500/R_{[\text{cal/mol/K}]}T)$$

In this expression, τ_{ign} is the ignition delay time [ms], P is pressure [atm], T is temperature [K], ϕ is the equivalence ratio (based on the H₂ and CO to O₂ molar ratio), and χ_{O_2} is the oxygen mole fraction. The uncertainty in the measured values for τ_{ign} is estimated as less than 30%. The experimental data are in good agreement with model predictions based on a recently proposed detailed reaction mechanism for H₂ and CO.

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Keywords: Carbon monoxide; Hydrogen; Syngas; Ignition; Rapid compression facility

1. Introduction

Syngas offers considerable opportunity for clean use of coal in power generation applications with potential for near zero pollutant emissions, including greenhouse gases such as carbon dioxide

(CO₂). In particular, the integrated gasification combined cycle (IGCC) can improve thermal efficiencies, dramatically lower environmental impact compared to traditional coal-fired power plants [1], and deliver electricity or hydrogen for fuel at competitive costs [2,3]. However, improvements in coal gasification power plant efficiencies to competitive levels (greater than 40%) are essential to make IGCC processes attractive alternatives to natural-gas fired, combined cycle power plants. Specifically, the US Department of Energy's

^{*} Corresponding author. Fax: +1 734 647 3170.

E-mail address: smwalton@umich.edu (S.M. Walton).

Fossil Energy Turbines Program has set a target of 60% plant efficiencies for coal-fueled power systems by 2020 [4]. A primary area for IGCC development with high potential for improving plant efficiencies is in the syngas turbine design [5].

The successful operation of gas turbines using syngas (including hydrogen fuel concentrations >90%) has been demonstrated at numerous facilities in the United States and abroad [6–8]; although there are difficulties. The syngas mixtures can vary widely in the relative hydrogen (H_2) and carbon monoxide (CO) concentrations [7], complicating turbine operation and design. The high-temperatures associated with the hydrogen kinetics can lead to high nitrogen oxide (NO_x) emissions, and existing dry low- NO_x gas-turbine technologies are not amenable to the high mass flow rates and fuel concentrations (from 15% to 40%) required for syngas mixtures [6,8]. As a result, the current approach is to fire syngas with high levels of dilution (typically using nitrogen (N_2) or steam) [9]. Lean premixed turbine operation can overcome the concerns of low efficiency and high emissions, and design of new syngas turbines focuses on such premixed approaches. For premixed operation, flashback and pre-ignition are safety and turbine performance concerns.

There are some key experimental investigations of H_2 and CO mixtures [10–13, and references therein] and more recent studies on developing revised H_2 and CO reaction mechanisms [14–16]. However, the reaction kinetics of syngas mixtures remains largely unexplored at conditions relevant to gas turbine applications, with few data at elevated pressures and temperatures and using non-dilute fuel/air mixtures. Experimental studies which can provide an improved understanding of the reaction kinetics and other fundamental combustion characteristics of syngas mixtures are vital to advancing syngas turbine design, and the future of IGCC applications. Specifically, the objective of the current work is to create the first experimental database of combustion kinetic benchmarks at conditions and compositions relevant to syngas combustors, to develop a quantitative understanding of the ignition behavior of simulated syngas mixtures as a function of key state and compositional conditions, and to quantify the performance of an updated H_2/CO chemical reaction mechanism at accurately reproducing the experimental benchmarks.

2. Experimental

In order to meet the stated objectives and isolate the chemical kinetics relevant to syngas combustor operation, ignition experiments were conducted using the University of Michigan (UM) rapid compression facility (RCF). The UM-RCF is an innovative and unique experimen-

tal apparatus that can be used to create uniform high-temperature ($T = 500\text{--}3000\text{ K}$) and high-pressure ($P = 0.5\text{--}60\text{ atm}$) conditions [17] that are directly applicable to many combustion devices, including gas turbines. In ignition studies, the ignition delay time (τ_{ign}) is an important chemical kinetic characteristic of the combustion mixture. In RCF experiments, τ_{ign} is controlled by the chemistry of the reactant mixture and the temperature and pressure conditions of the experiment. Experimental data for τ_{ign} are invaluable as an indication of the magnitude of the reaction kinetics and as targets for benchmarking detailed, skeletal, and reduced reaction mechanisms [14,16,18].

A detailed description of the UM-RCF, the operating procedure, and the results of studies characterizing the performance can be found in [17–20]. Briefly, the UM-RCF consists of five major components: the driver section, the driven section, the test manifold, the sabot (i.e. the free piston), and the hydraulic control valve assembly. For each experiment, the driven section is evacuated with a diffusion pump; the driver section is filled with high-pressure air and the sabot is located at the upstream end of the driven section. The driver and driven sections are separated by the hydraulic control valve assembly and a scored sheet of polyester film (0.05 mm thick, Mylar®). After filling the driven section with the prepared test gas mixture, a globe valve is opened (using the hydraulic control valve assembly), permitting the high-pressure driver gas to break the polyester film, enter the driven section, and rapidly accelerate the sabot. The test gas mixture in the driven section is compressed in front of the sabot and sealed within the test manifold when the sabot nose cone seats by an annular fit with the test manifold walls. The compression process can be considered isentropic, and uniform high-temperature and high-pressure conditions are created in the test section as a result of the compression process.

The test manifold is equipped with two optical ports, a pressure transducer port, and two additional instrumentation ports. The end wall seals the test manifold and allows optical access to the test volume. For the current study, the test section was instrumented with a piezoelectric transducer (Kistler 6041AX4) and charge amplifier (Kistler 5010B) for pressure measurements, and a polycarbonate end wall was used to provide optical access to the test manifold.

Digital imaging, using a high-speed color digital video camera (Vision Research, Phantom V7.1, maximum acquisition of 160,000 frames per second (fps), maximum resolution of 800×600 pixels, SR-CMOS 48 bit color array), and pressure time-histories were used to characterize the ignition for each experiment. A fast 50 mm lens ($f/0.95$ Navitar TV Lens) and c-mount extension tubes were used with the camera.

The high-speed digital camera was used to acquire full-frame video sequences of the ignition experiments at speeds of 26,000 fps, with the spatial resolution maintained at the maximum allowable setting of 256×256 pixels. These settings result in each frame corresponding to $38 \mu\text{s}$, and each pixel in the CMOS array imaging focused light from a volume with a height \times width \times depth of approximately $198 \mu\text{m} \times 198 \mu\text{m} \times 2 \text{mm}$. All test gas mixtures were made using a dedicated mixing tank, and the mixture composition was determined by measurement of the relative partial pressures of the reactants.

3. Results

Mixtures and conditions for study were selected based on existing and expected syngas turbine operation. Specifically, syngas compositions including H_2 :CO ratios from 0.25 to 4.0, stoichi-

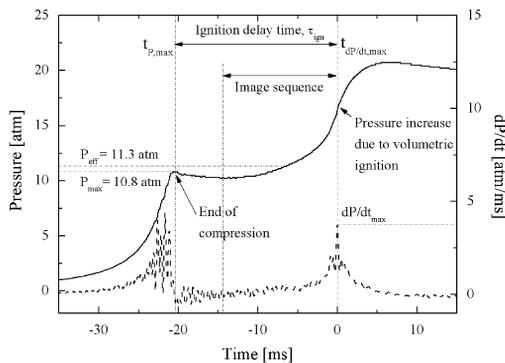


Fig. 1. Typical experimental results for pressure and pressure derivative time-histories for experimental conditions of $T_{\text{eff}} = 1004 \text{ K}$, $P_{\text{eff}} = 11.3 \text{ atm}$, $\phi = 0.4$, inert: O_2 ratio = 3.76, syngas fuel = 20% H_2 , 80% CO.

ometric and lean conditions, elevated pressures, and dilution with N_2 are of interest for modern gas-turbine design. In the current study, the ignition behavior of simulated syngas mixtures of H_2 and CO was investigated in terms of equivalence ratio, H_2 :CO ratio, temperature, pressure, and oxygen concentration. Pure H_2 experiments were conducted for comparison with previous RCF ignition studies [21], as well as pure CO experiments.

Figure 1 presents the pressure and pressure derivative time-histories for a typical H_2 and CO ignition experiment, and Fig. 2 presents the corresponding imaging sequence. The pressure data indicate a smooth compression process, where the end of compression is indicated by the first peak in the pressure profile. After the test gases are sealed in the test section, a period of time exists where the pressure remains relatively constant, followed by a rapid increase in pressure which indicates ignition of the test gas mixture (set as $t = 0 \text{ s}$ in Figs. 1 and 2). Examination of the pressure data near the time of ignition indicates an initial slow increase in pressure followed by a more rapid increase. The change in the rate of pressure rise is associated with the presence of reaction fronts prior to volumetric ignition, which is supported by the imaging data shown in Fig. 2.

Visible emission is observed in the imaging data as early as 14 ms prior to volumetric ignition, corresponding to the start of the gradual increase in pressure in the test volume after the end of compression. As seen in Fig. 2, the emission expands throughout a portion of the test volume, and an increase in pressure is observed in this same time frame (see Fig. 1). Note that Fig. 2 presents a subset of the total imaging data which were acquired throughout compression and ignition. At time $t = 0 \text{ ms}$, a rapid increase in the emission intensity is observed throughout the test volume. The peak in the volumetric emission intensity corresponds with the peak rate of increase in pressure. Consequently, this is designated as the time of ignition,

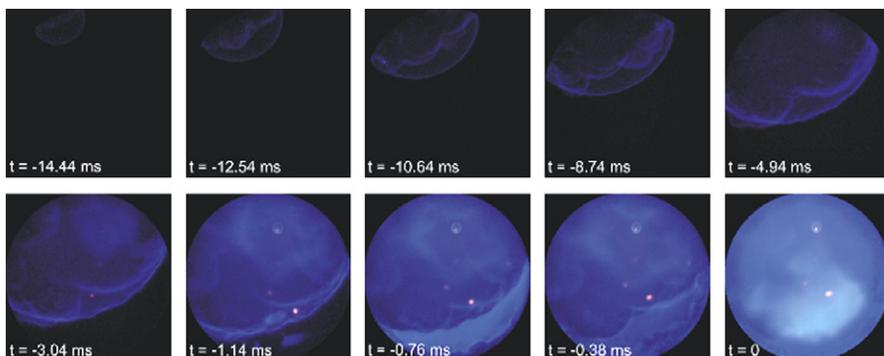


Fig. 2. Imaging sequence corresponding to the conditions and results of Fig. 1. The color in each image has been enhanced (each to the same level) for clarity.

and τ_{ign} is determined from each experiment as the time between P_{max} at the end of compression and the maximum value of dP/dt (see Fig. 1).

The presence of localized reaction fronts and propagation throughout the test chamber has been observed in previous ignition studies of hydrocarbon and hydrogen fuels using shock tube and rapid compression facilities [22–26]. In studies of the *iso*-octane/air system using the UM-RCF [25,26], volumetric ignition with no reaction front propagation occurred for fuel mole fractions below a critical limit and reaction fronts were consistently observed above the limit. Similarly, volumetric ignition with no reaction front propagation was observed in the current study for a limited number of experiments at very lean conditions. The increased pressure associated with the reaction fronts serves to further compress the unignited gases in the test chamber. Consequently, the pressure and temperature at the time of volumetric ignition are higher than the conditions at the end of compression. In the *iso*-octane studies, the use of time-integrated average pressures were found to yield excellent agreement with ignition data where no reaction fronts were observed [25,26]. The same approach is used here (see Fig. 1), where the effective pressure (P_{eff}) for each experiment is defined as the time-integrated average pressure between the time of maximum pressure due to compression (P_{max}) and the time of maximum rate of pressure rise (dP/dt_{max}).

The effective temperature for each experiment is determined as in previous RCF studies [18] using the P_{eff} and by numerical integration of the isentropic relation

$$\int_{T_o}^{T_{\text{eff}}} \frac{\gamma}{\gamma - 1} d \ln T = \ln \left(\frac{P_{\text{eff}}}{P_o} \right) \quad (1)$$

where P_o is the charge pressure, T_o is the initial temperature (typically 298 K), and γ is the temperature dependent ratio of the specific heats of the unreacted test gas mixture, which is determined using the NASA Thermodynamic Database [27]. The effects of the determination of P_{eff} and T_{eff} on the measured τ_{ign} data are considered in the uncertainty analysis, described below.

Table 1 presents a summary of the mixtures and conditions for the RCF experiments and the resulting ignition data. The complete data set, including mixtures which did not ignite, span $P_{\text{eff}} = 7.1\text{--}26.4$ atm, $T_{\text{eff}} = 752\text{--}1051$ K, $\phi = 0.1\text{--}2.0$, $\text{H}_2\text{:CO} = 0.25\text{--}4.0$ (mole basis) and $\chi_{\text{O}_2} = 1.2\text{--}20.2\%$ (mole basis). The equivalence ratio is based on the molar ratio of the H_2 and CO to O_2 . Note fuel mixtures of 100% H_2 and 100% CO were included in the experimental matrix. As expected, the 100% CO mixture did not ignite within the test times available in the UM-RCF. Due to the high sensitivity of CO to moisture and other impurities, the pure CO exper-

iments serve as an indication that the experimental approach is not affected by uncontrolled impurities. Other experiments which did not ignite indicate the boundaries of conditions that were feasible to study using the UM-RCF. For example, the $T = 752$ K experiment set a lower limit on the temperature conditions.

Figure 3 provides a summary of how the current range of pressures and temperatures compare with previous studies of CO and H_2 ignition. Figure 4 presents a summary of experimental results for the product of τ_{ign} and oxygen concentration as a function of inverse temperature. For comparison, the results of the RCF study of H_2/O_2 ignition delay times by Lee and Hochgreb [21] are included in the figures. The results of the two RCF studies overlap in state conditions examined and agree well on the order of magnitude of the ignition times measured. A more quantitative comparison is complicated by the fact that the study by Lee and Hochgreb considered stoichiometric conditions, used argon as the diluent, and used more dilute O_2 concentrations ($\chi_{\text{O}_2} = 12.5\%$, mole basis) than studied in the current work.

As seen in Figs. 3 and 4, when mixtures of H_2 and CO are considered, we are unaware of existing data at conditions comparable to those studied here. The shock tube studies of Gardiner et al. [10] and Dean et al. [11] focused on dilute, high-temperature, near-atmospheric conditions. The work by Fotache et al. [12] used a counter-flow diffusion flame apparatus to study ignition of H_2/CO opposed heated air flow.

Regression analysis of the Table 1 data was conducted in order to quantify the effects of the state and mixture conditions on the H_2 and CO ignition properties. Several forms of regression were considered, including the absolute and relative fuel concentrations (as apposed to mole fraction) of H_2 and CO, the concentration of O_2 , and incorporating fuel and oxygen effects via only the equivalence ratio. Ultimately, pressure (P [atm]), temperature (T [K]), equivalence ratio (ϕ), and oxygen mole fraction (χ_{O_2}) were required to determine an expression with the highest correlation coefficient for the complete data set presented in Table 1 (excluding mixtures which did not ignite). The form of the expression is similar to that determined in previous ignition studies [18].

$$\tau_{\text{ign}} = 3.7 \times 10^{-6} P^{-0.5} \phi^{-0.4} \chi_{\text{O}_2}^{-5.4} \times \exp(12,500/\bar{R}_{[\text{cal/mol/K}]}) T \quad (2)$$

In Eq. (2), $\bar{R}_{[\text{cal/mol/K}]}$ is the universal gas constant. Figures 5–7 present a summary of the effects of T , P , and ϕ on τ_{ign} , respectively, where the data have been normalized as necessary using the functional dependence provided in Eq. (2) to isolate each parameter of interest.

Table 1
Summary of experimental conditions and results for ignition delay time

ϕ	Test gas composition ^a				P_{eff} (atm)	T_{eff} (K)	Ignition delay time (ms)		
	H ₂ (%)	CO (%)	O ₂ (%)	N ₂ (%)			τ_{ign}	τ_{reg}	τ_{pred}
0.10	2.4	1.6	20.2	63.9	10.5	916	NI ^b	—	215.0
0.15	3.6	2.4	19.8	74.3	7.1	1011	15.8	11.2	9.9
0.15	3.6	2.4	19.8	74.3	7.6	1028	10.1	9.8	6.2
0.15	3.6	2.4	19.8	74.3	14.9	1033	9.6	6.9	6.2
0.15	3.6	2.4	19.8	74.3	15.9	1051	5.4	6.1	4.0
0.15	3.6	2.4	19.8	74.3	8.1	1046	4.9	8.5	3.8
0.20	4.7	3.1	19.4	60.8	11.1	929	19.2	15.5	81.4
0.30	6.7	4.5	18.6	43.4	19.5	855	23.9	22.0	398.0
0.30	6.7	4.5	18.7	57.9	12.0	944	9.1	13.8	38.6
0.30	6.7	4.5	18.7	57.9	13.0	963	10.5	11.6	22.8
0.40	2.9	11.5	18.0	60.0	11.6	1009	14.0	9.8	4.8
0.40	2.9	11.5	18.0	60.0	11.3	1004	20.5	10.2	5.5
0.40	2.9	11.5	18.0	60.0	11.3	1005	13.1	10.1	5.3
0.40	11.5	2.9	18.0	62.9	17.2	1009	4.7	8.1	6.1
0.40	11.5	2.9	18.0	62.9	10.7	994	7.7	11.1	9.7
0.40	2.9	11.5	18.0	63.5	17.6	1017	9.9	7.6	3.7
0.40	2.9	11.5	18.0	63.5	11.4	1009	11.1	9.9	4.6
0.40	2.4	9.4	14.7	65.2	26.4	1009	22.3	19.7	5.6
0.40	7.2	7.2	18.0	63.2	23.5	1015	7.2	6.7	3.9
0.40	7.2	7.2	18.0	63.2	17.8	1017	6.9	7.6	3.9
0.40	7.2	7.2	18.0	63.2	11.0	999	7.7	10.6	6.4
0.40	5.8	8.6	18.0	55.5	12.5	886	NI ^b	—	144.0
0.70	13.6	9.1	16.2	44.1	15.5	923	15.8	20.7	33.8
1.00	24.0	16.0	20.0	17.6	14.1	881	8.9	8.2	64.8
0.50	10.4	6.9	17.4	10.8	16.5	752	NI ^b	—	NI ^b
0.10	4.0	0.0	20.2	75.8	10.2	1035	8.4	8.8	9.8
0.10	4.0	0.0	20.2	75.8	14.9	1030	8.5	7.6	10.6
0.15	5.9	0.0	19.8	74.3	14.7	1033	5.5	6.9	7.8
2.01	4.7	0.0	1.2	48.5	4.49	938	NI ^b	—	212.0
0.40	0.0	14.3	17.9	41.2	18.6	849	NI ^b	—	NI ^b

The mixture composition is provided on a mole basis. Predictions for τ_{pred} were determined using the revised mechanism of Davis *et al.* [15]. τ_{reg} was determined using Eq. (2).

^a Balance CO₂.

^b No ignition within 1 s.

Error analysis was conducted to quantify the uncertainty in the τ_{ign} data. The primary sources of uncertainty in τ_{ign} are due to the presence of

reaction fronts prior to volumetric ignition, uncertainties in the pressure measurement (which are primarily due to the definition of P_{eff}

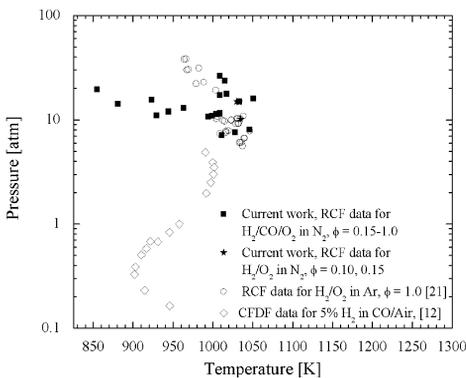


Fig. 3. Previous and current range of conditions of experimental H₂ and CO ignition studies. The CFDF data of [12] are results of a counterflow diffusion flame study.

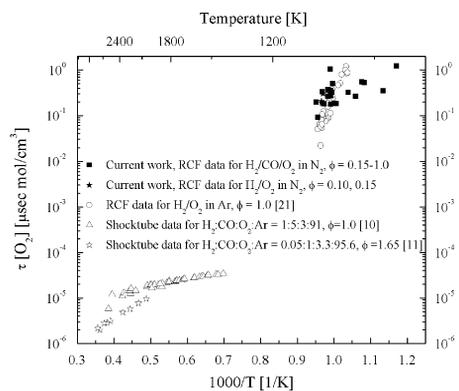


Fig. 4. Summary of previous and current experimental data for ignition of H₂ and CO presented as the product ignition delay time and oxygen concentration.

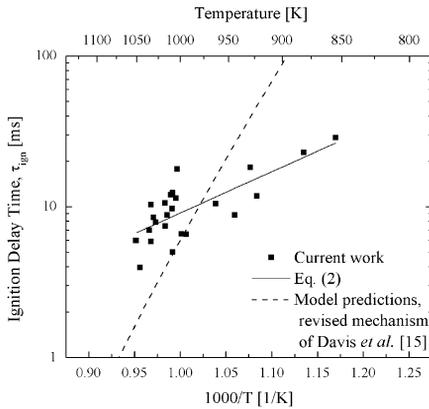


Fig. 5. Comparison of experimentally measured H_2 and CO ignition delay time data with model predictions as a function of inverse temperature. The experimental data have been normalized to $P = 15$ atm, $\phi = 0.4$, $\chi_{\text{O}_2} = 18\%$ using Eq. (2).

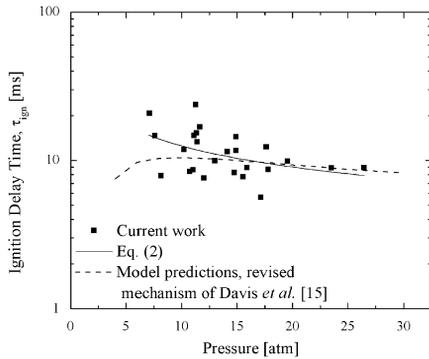


Fig. 6. Comparison of experimentally measured H_2 and CO ignition delay time data with model predictions as a function of pressure. The experimental data have been normalized to $T = 980$ K, $\phi = 0.4$, $\chi_{\text{O}_2} = 18\%$ using Eq. (2).

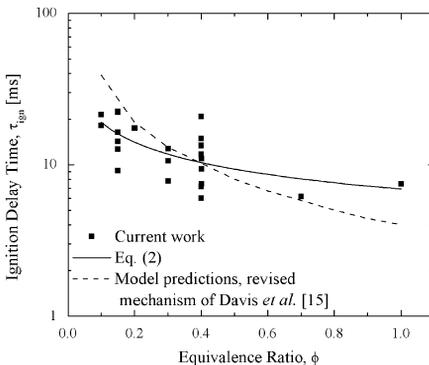


Fig. 7. Comparison of experimentally measured H_2 and CO ignition delay time data with model predictions as a function of equivalence ratio. The experimental data have been normalized to $T = 980$ K, $P = 15$ atm, $\chi_{\text{O}_2} = 18\%$ using Eq. (2).

and the accuracy of the pressure transducer and charge amplifier), corresponding uncertainties in the calculated T_{eff} , and uncertainties in the mixture composition (which yields an uncertainty of 0.4% in the determination of ϕ and 0.2% in χ_{O_2}). Combining the uncertainties as independent sources of error using a square-root-of-the-sum-of-the-squares approach yields an estimated uncertainty in the measured ignition delay time of $\pm 28\%$.

4. Discussion

The experimental data for τ_{ign} were compared with predictions based on the mechanism developed by Wang and co-workers [15,28]. The mechanism was primarily that of Davis et al. [15], which was based on the work by Mueller et al. [14]. Davis et al. revised the mechanism of [14] with updated thermodynamic data and reaction chemistry and optimized the mechanism performance to reproduce experimentally measured H_2 and CO combustion data obtained over a range of conditions. The mechanism was subsequently revised per Wang [28] to include an increase in the rate coefficient for the $\text{CO} + \text{HO}_2 = \text{CO}_2 + \text{OH}$ reaction to $k = 1.35 \times 10^{-3} T^{5.0} \exp(-14,950_{\text{cal/mol}}/\bar{R}_{\text{cal/mol/K}}/T[\text{K}])$.

The revised mechanism of Davis et al. [15] was used with the CHEMKIN 4.0.1 suite of programs [29] to predict ignition delay time using an adiabatic, constant-volume model. The modeling predictions, τ_{pred} , are provided in Table 1 and Figs. 5–8. The model results agree well with the experimental data for most of the range of conditions studied, with particularly good prediction of the quantitative trends of pressure and ϕ . The model predicts higher activation energy than that observed in

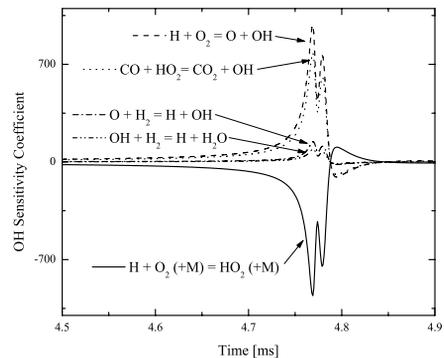


Fig. 8. OH sensitivity analysis based on the revised reaction mechanism by Davis et al. [15], for conditions of $T = 1009$ K, $P = 11.6$ atm, $\phi = 0.4$, $\text{H}_2:\text{CO} = 0.25$.

the current work ($E_{a,model} = 49.5$ kcal/mol versus $E_{a,experimental} = 12.5$ kcal/mol). The difference in the modeling and experimental results may be attributable to the large uncertainty in the $\text{CO} + \text{HO}_2 = \text{CO}_2 + \text{OH}$ reaction, which is discussed further below.

Sensitivity analysis using the revised mechanism by Davis et al. [15] was conducted in the current work to identify the reactions with the largest effects on τ_{ign} for the H_2 and CO mixtures studied. Results for temperature, H, OH, and O were similar and sensitivity data for OH are presented in Fig. 8 for representative experimental conditions. The OH is most sensitive to the chain-branching $\text{H} + \text{O}_2 = \text{O} + \text{OH}$ reaction, the $\text{H} + \text{O}_2$ recombination reaction to form HO_2 , and the $\text{CO} + \text{HO}_2 = \text{CO}_2 + \text{OH}$ reaction. H_2O_2 decomposition appears to play a less significant role in this system compared to the sensitivity data for 100% H_2 ignition presented by Lee and Hochgreb [21] and the sensitivity data for lean *iso*-octane ignition presented by He et al. [20]. This shift from the importance of H_2O_2 to HO_2 is consistent with the reduced H concentrations available in the lean H_2 and CO mixtures studied here. The relatively high uncertainty (a factor of 2 [15]) and the large role of the $\text{CO} + \text{HO}_2 = \text{CO}_2 + \text{OH}$ reaction, may be the primary source of the discrepancies between the model predictions and the experimental data.

5. Conclusions

A significant handicap to syngas turbine design is the severe lack of data on syngas combustion properties such as flammability limits, flame speeds, and ignition characteristics (excluding 100% H_2 studies) at conditions relevant to syngas combustor operation. The results of the current work are the first experimental ignition data of which we are aware for H_2 and CO fuel mixtures at elevated temperatures and pressures greater than 5 atm. The data provide quantitative understanding of the effects of combustion conditions and reactant compositions on the ignition properties of H_2 and CO mixtures over a broad range of conditions with direct relevance to syngas-fired combustors and provide experimental data critical for validation of H_2 and CO reaction mechanisms. The regression results for τ_{ign} isolate the trends of ignition delay time as a function of pressure, temperature, equivalence ratio, and dilution. The relation for τ_{ign} also provides a means to estimate ignition properties and is in a simplified form that facilitates integration into computationally intense combustor design codes, where detailed chemical kinetic models can be costly.

Acknowledgments

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Comments

Simone Hochgreb, Cambridge University, UK. Given that the auto-ignition of these mixtures is not homogeneous, is it justified to model the system as a zero dimensional homogeneous constant volume case?

Reply. We have found that by defining a time-averaged pressure, P_{eff} (and thus T_{eff}), to account for the slow increase in pressure associated with the formation and propagation of the reaction fronts, we achieve good agreement with a single-zone model when either homogeneous or reaction front cases are observed. In other words, the primary effects of the reaction fronts on the unignited reactants are volumetric by means of an increase in pressure. Transport effects, which are localized and are not captured by the single-zone model, do not appear to significantly influence τ_{ign} . For a more detailed discussion see work by Walton et al. [1].

Reference

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Jerry Seitzman, Georgia Institute of Technology, USA. You present an ignition time correlation for the complete H₂/CO composition range. Could you comment on any systematic variations in τ_{ign} at the edges of the composition range, e.g., H₂/CO = 0.1 or 10? For example, could the pressure dependence be similar but perhaps the ϕ or T coefficients might change?

Reply. Within the uncertainty of the data, we did not observe any systematic variations in τ_{ign} as a function of the CO/H₂ concentration.