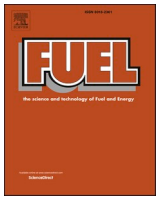
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Short communication

Development of a novel high-pressure well-stirred turbulent combustor for kinetic studies at gas turbine conditions

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ABSTRACT

A novel autoignition-assisted, high-temperature High-Pressure Well-Stirred Turbulent Combustor (HP-WSTC) has been developed for detailed kinetic studies of fuels under gas-turbine conditions that were difficult to obtain with conventional reactors and flame chemistry facilities. It is designed for operations at 1–20 atm, 1200–2200 K, and residence times of 1–100 ms, enabling treatment as a zero-dimensional premixed-combustion system. Methane combustion experiments at 1–10 atm were compared with 0D simulations, showing good agreement for major species across a wide equivalence-ratio range, demonstrating the reliability of the HP-WSTC. Although methane combustion kinetics are well established, NO predictions still show large discrepancies, even at atmospheric pressure. Sensitivity analyses identify CH-pool reactions, including $CH_2 + O_2 = CH_2O + O$ and $CH + CO_2 = HCO + CO$, as key uncertain reactions. The developed HP-WSTC provides a new platform for fuel kinetic investigations and bridges the gap between reactor and flame facilities for high-temperature kinetic studies under gas-turbine conditions.

1. Introduction

Combustion has long been a primary source of energy for power generation and industrial processes worldwide. However, there is a growing need to improve combustion technologies in order to reduce greenhouse-gas and NO_x emissions [1].

Gas turbine combustors feature high-temperature (up to 2200 K), high-pressure (around 20 atm), and short flow residence time of a few milliseconds [2]. To understand combustion and emission kinetics at gas turbine conditions, chemical and flame reactors such as Jet-Stirred Reactors (JSRs) [3,4], plug flow reactors (PFRs) [5], laminar flames [6], rapid compression machines (RCMs) [7], and turbulent jet flames [8] have been widely used to obtain fuel kinetic data and validate combustion models. However, existing JSRs and PFRs have a limited temperature range (usually below 1500 K) and long residence times (0.1–10 s). Laminar flames have difficulty achieving the pressures and residence times required under gas turbine conditions to obtain speciation data. On the other hand, RCMs are limited to ignition kinetics, and turbulent jet flames have large non-uniformity of mixing, composition, and temperature, making it difficult to directly study the fuel kinetics under gas turbine conditions.

Therefore, to study fuel kinetics under extreme gas turbine conditions, a novel high-pressure well-stirred turbulent combustor (HP-WSTC) concept, which can be modeled as a 0D reactor, was proposed [9]. In this work, the HP-WSTC was developed and validated as a 0D reactor for kinetic studies using methane, an extensively studied fuel. Combustion experiments were performed up to 10 atm at flow residence times of a few milliseconds. The experimental data were compared with predictions from 0D simulations to validate the reliability of the HP-WSTC. The measured NO concentrations were compared with several kinetic models, and the key reactions governing NO formation were examined. The HP-WSTC can provide speciation data for both gaseous and liquid fuels over a wide range of conditions, including pressures of 1–20 atm, temperatures of 1200–2200 K, and residence times of 1–100

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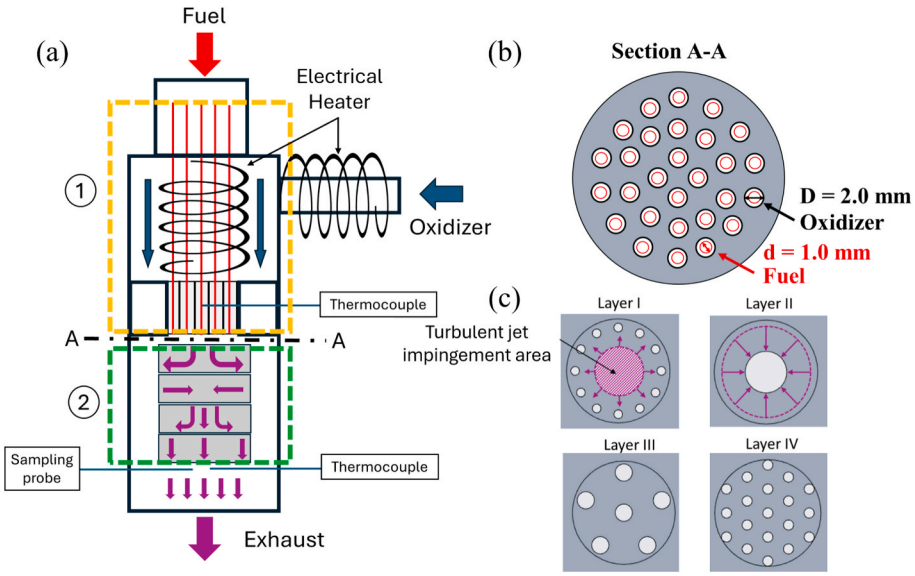


Fig. 1. (a) Schematic of the HP-WSTC. (b) Schematic of the cross-section at Section A. (c) Top view of the multi-layer burner and the turbulent flow pattern.

ms, thereby offering a valuable new platform for the development and validation of kinetic mechanisms relevant to next-generation high-pressure premixed clean combustion systems.

2. Experimental setup

Figure 1 shows the schematic design of the HP-WSTC, which is characterized by near-homogeneous reactor behavior, a well-defined residence time, and operability at high temperature and pressure. The ratio of turbulent diffusion time to flow residence time was approximately 0.03–0.3, and the Damköhler number based on major products was approximately 0.2–0.6. Details of the reactor design, PLIF/CFD verification of well-mixed behavior, and characteristic time-scale analysis are provided in the Supplemental Material.

To achieve these characteristics, the HP-WSTC comprises four major components: (i) a 2 kW upstream vaporization and preheating system for liquid fuels such as methanol; (ii) a microchannel manifold that separately supplies fuel and oxidizer to the reactor and enables rapid mixing and preheating; (iii) a 6.5 cm^3 multi-compartment, well-stirred turbulent combustion chamber fabricated from silicon carbide, whose surface forms a passivating SiO_2 film to suppress surface reactivity [10–12]. Although surface effects cannot be completely ruled out, they are expected to be secondary under the present high temperature and millisecond residence-time conditions; and (iv) a stainless-steel pressure-resistant chamber that houses the reactor and enables high-pressure operation.

The microchannel manifold for rapid fuel–air mixing is shown in the yellow region of Fig. 1(a), and its cross-sectional view at the exit is shown in Fig. 1(b). The manifold consists of 28 small-orifice fuel injection tubes with an inner diameter of d = 1.0 mm, inserted into the channels of a ceramic honeycomb with a channel diameter of D = 2.0 mm. Methane flows from the top of the burner through the microscale tubes aligned with the honeycomb channels, while air flows through the honeycomb channels around the fuel microtubes. The close proximity of the fuel and air streams promotes rapid mixing, enabling premixed combustion conditions suitable for kinetic studies. The well-stirred turbulent combustor is shown in the green region of Fig. 1(a), and Fig. 1(c) presents a top view of the four parallel multi-hole plates that constitute the multi-stage WSTC. The premixed fuel and oxidizer flow on a stagnation plane located at the center of the first WSTC plate and flow radially outward to further enhance mixing. The radially outward premixed flow is then preheated by the first plate of the WSTC and

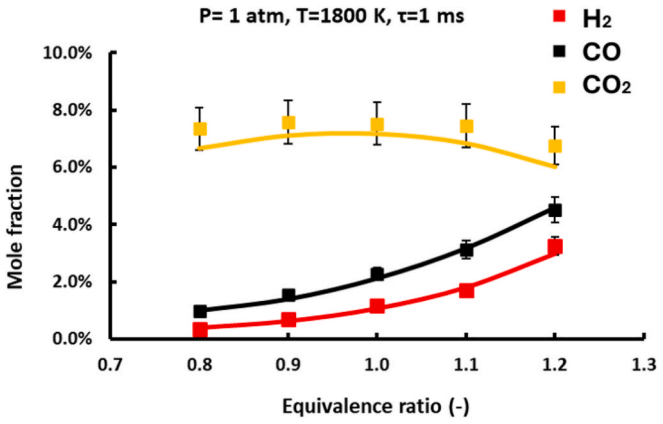


Fig. 2. Experimental and HP-Mech-predicted major species results at a pressure of 1 atm, a temperature of 1800 K, and a residence time of 1.0 ms.

autoignites before passing through the holes near the outer edge of the plate, ensuring an autoignition-assisted combustion regime at elevated Damköhler numbers [13]. The flow then enters the first chamber between the first and second multi-hole plates, where it is redirected toward the center, promoting recirculating turbulent mixing and combustion. This design not only achieves intense mixing but also enables auto-ignition-assisted flame stabilization and heat recirculation, resulting in improved combustion uniformity and stability.

The temperatures at the exit of the microchannel manifold and the reactor were measured using thermocouples. Three electric heaters (BXX06B31-10T, ARI Industries) were used to preheat the inlet gases. The target reactor temperature under different equivalence-ratio conditions was maintained by adjusting the heating power. The maximum measurement uncertainty of the species mole fractions was estimated to be ±10 %, including contributions from gas sampling, GC analysis, calibration, and repeatability. The total inlet flow rate was fixed at 58.1 SLPM while the pressure was varied. The corresponding flow residence times for each experimental condition are summarized in Table S1 in the Supplementary Material. A summary of the uncertainty sources and the propagated uncertainties in equivalence ratio and residence time is provided in Table S2.

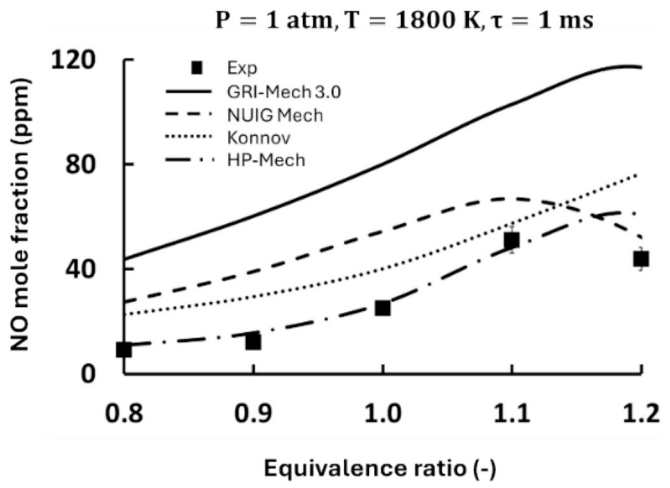


Fig. 3. NO results at a pressure of 1 atm, a temperature of 1800 K, and a residence time of 1.0 ms.

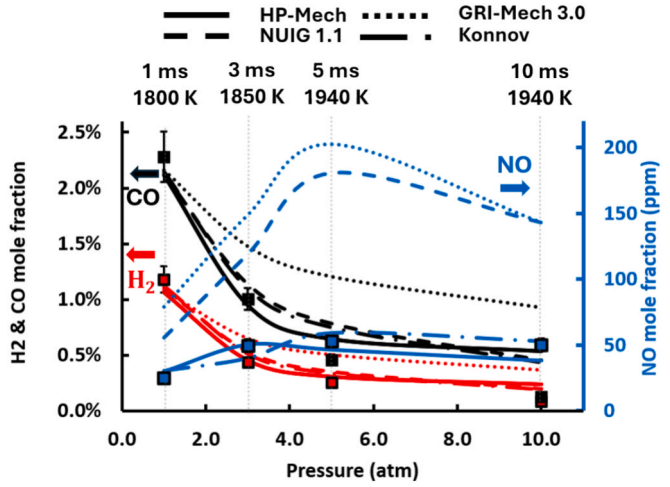


Fig. 4. Comparison of experimental data and simulation results of H_2, CO, and NO at an equivalence ratio of 1.0 at different pressures and corresponding flow residence times.

3. Results and discussion

Methane combustion experiments were first conducted at 1 atm and 1800 K with a residence time of 1.0 ms to provide a baseline for mechanism validation. Mole fractions of major species (H_2, CO, and CO_2) and NO are presented in Figs. 2 and 3. For the major species shown in Fig. 2, the comparisons between experiments and simulations show that the measured mole fractions were reproduced within the experimental uncertainty of ± 10 % by the four detailed methane combustion mechanisms: GRI-Mech 3.0, NUIG-Mech 1.1, the Konnov mechanism, and HP-Mech [14–17], with differences among their predictions of only approximately 5 %. Therefore, HP-Mech is shown as a representative mechanism in Fig. 2 to avoid overcrowding the figure. The good agreement between the experimental data and the simulations demonstrates the reliability of the HP-WSTC as a 0D reactor for kinetic studies. In contrast, even atmospheric pressure, NO predictions showed large discrepancies among the mechanisms, with HP-Mech providing the best agreement with the experimental data. The influence of pressure was subsequently investigated between 1 and 10 atm. Fig. 4 shows the measured and simulated H_2 and CO mole fractions from 1 to 10 atm. Although the mechanism predictions are close to each other at 1 atm, the differences among the mechanisms become more pronounced with increasing pressure. HP-Mech shows good agreement with experimental data up to 5 atm, while the decreasing trends toward 10 atm are better captured by the Konnov and NUIG-Mech 1.1 mechanisms. The observed pressure-dependent divergence suggests that the high-pressure discrepancies may arise from differences in pressure-dependent reaction pathways controlling H_2 and CO consumption, including CH_4 (+M) = CH_3 + H (+M), HCO (+M) = CO + H (+M), and CH_3OH (+M) = CH_3O + H (+M). Therefore, further investigation of these pressure-dependent pathways is needed to improve predictions of H_2 and CO mole fractions at elevated pressures.

Sensitivity analyses were performed using the HP-Mech and NUIG mechanisms to compare the key reactions controlling NO formation, as shown in Fig. 5. In both mechanisms, reactions associated with the prompt NO pathway exhibited large sensitivity coefficients, indicating that prompt NO chemistry is important for NO formation under the investigated conditions. However, the dominant non-prompt-NO reactions differed between the two mechanisms. In HP-Mech, CH_2 + H = CH + H_2 and CH + CO_2 = HCO + CO showed relatively high sensitivities, and the reaction pathway CH_2 + OH = CH_2O + H was found to be dominant for CH_2 oxidation by OH. In contrast, NUIG predicted higher sensitivities for fuel radical oxidation reactions including CH_3 + O = CH_2O + H, CH_2 + O = CO + 2H, and CH_2 + O_2 = CH_2O + O, as well as CH + H_2O = H + CH_2O.

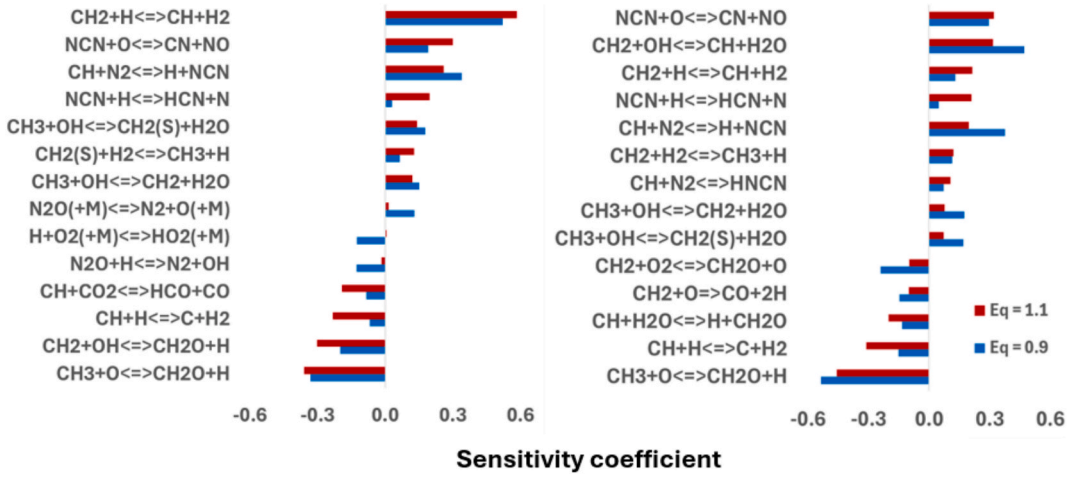


Fig. 5. Sensitivity analysis of NO using NUIG-Mech and HP-Mech at 1 atm and residence time of 1 ms on the fuel-lean and fuel-rich sides.

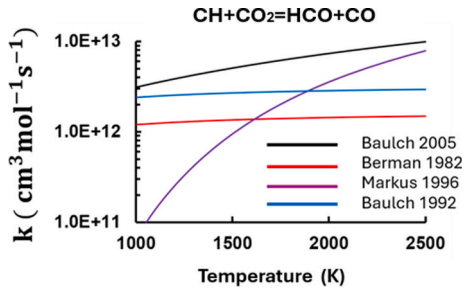


Fig. 6. Plot of the temperature dependence of theoretically calculated and experimentally measured rate constants for CH + CO_2 = HCO + CO. [18–21].

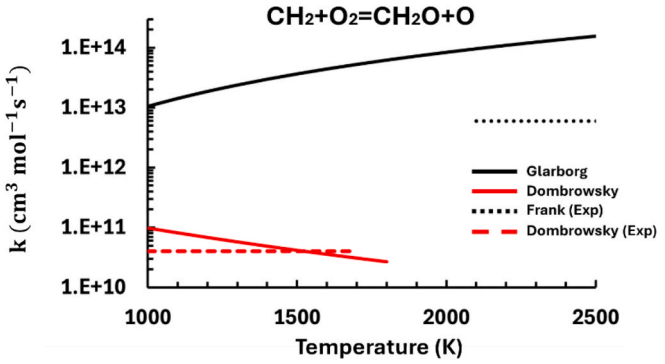


Fig. 7. Plot of the temperature dependence of theoretically calculated and experimentally measured rate constants for CH_2 + O_2 = CH_2O + O. [22–24].

As shown in Figs. 6 and 7, the reactions CH + CO_2 = HCO + CO and CH_2 + O_2 = CH_2O + O exhibit strong sensitivity in HP-Mech and NUIG-Mech but have received comparatively limited scrutiny. Given the substantial discrepancies between the few available experimental data and theoretical predictions, the kinetic uncertainties associated with these reactions may significantly affect the accuracy of NO predictions.

4. Conclusion

A novel High-Pressure Well-Stirred Turbulent Combustor (HP-WSTC) enabling kinetic studies under gas-turbine-relevant conditions has been developed and validated using methane combustion between 1 and 10 atm with residence times of a few milliseconds. The good agreement between the experimental results and zero-dimensional modeling indicates that the HP-WSTC is a robust platform for generating kinetic data to support advanced gas-turbine and clean-fuel combustion design. However, despite the well-established methane kinetics, several kinetic mechanisms show large discrepancies for NO formation, indicating that substantial uncertainty remains in prompt NO chemistry. The developed HP-WSTC provides a new platform for fuel kinetic investigations and bridges the gap between conventional reactor-based and flame-based kinetic studies under high-temperature, gas-turbine-relevant conditions.

CRediT authorship contribution statement

Kaii Ri: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bowen Mei:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization, Investigation. **Andy Thawko:** Writing – review & editing, Methodology, Conceptualization. **Jan M. Cluse:** Methodology. **Liang Ji:** Methodology. **Ziyu Wang:** Methodology. **Masahiro Uchida:** Resources. **Toshiro Fujimori:** Resources. **Kaoru Maruta:** Writing – review & editing. **Yiguang Ju:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2026.141354.

Data availability

Data will be made available on request.

References

[1] Ju Y, Starikovskiy A. Plasma assisted combustion and chemical processing. 1st ed. CRC Press; 2025.
[2] Correa SM. A review of NOx formation under gas-turbine combustion conditions. Combust Sci Technol 1993;87(1–6):329–62.
[3] Dagaut P, Cathonnet M, Rouan JP, Foulatier R, Quilgars A, Boettner JC, et al. A jet-stirred reactor for kinetic studies of homogeneous gas-phase reactions at pressures up to ten atmospheres (≈1 MPa). J Phys E: Sci Instrum 1986;19(3):207.
[4] Zhao H, Yan C, Zhang T, Ma G, Souza MJ, Zhou C-W, et al. Studies of high-pressure n-butane oxidation with CO2 dilution up to 100 atm using a supercritical-pressure jet-stirred reactor. Proc Combust Inst 2021;38(1):279–87.
[5] Glarborg P, Alzueta MU, Dam-Johansen K, Miller JA. Kinetic modeling of hydrocarbon nitric oxide interactions in a flow reactor. Combust Flame 1998;115(1–2):1–27.
[6] Egolfopoulos FN, Hansen N, Ju Y, Kohse-Höinghaus K, Law CK, Qi F. Advances and challenges in laminar flame experiments and implications for combustion chemistry. Prog Energ Combust Sci 2014;43:36–67.
[7] Sung C-J, Curran HJ. Using rapid compression machines for chemical kinetics studies. Prog Energ Combust Sci 2014;44:1–18.
[8] Barlow RS, Dibble RW, Chen JY, Lucht RP. Effect of Damkohler Number on Superequilibrium Oh Concentration in Turbulent Nonpremixed Jet Flames. Combust Flame 1990;82(3–4):235–51.
[9] Ju Y, Thawko A. A novel high pressure well-stirred turbulent combustor for low NOx and energy-efficient combustion. *Patent.*
[10] Jacobson NS. Corrosion of silicon-based ceramics in combustion environments. J Am Ceram Soc 2005;76(1):3–28.
[11] Harder B, Jacobson N, Myers D, Cinibulk M. Oxidation transitions for SiC Part II. Passive-to-active transitions. J Am Ceram Soc 2012;96(2):606–12.
[12] Wan S, Fan Y, Maruta K, Suzuki Y. Wall chemical effect of metal surfaces on DME/air cool flame in a micro flow reactor. Proceedings of the Combustion Institute 2019;37(4):5655–62.
[13] Zhang T, Ju Y. Structures and propagation speeds of autoignition-assisted premixed n-heptane/air cool and warm flames at elevated temperatures and pressures. Combust Flame 2020;211:8–17.
[14] Gregory P. Smith DMG, Michael Frenklach, Nigel W. Moriarty, Boris Eiteneer, Mikhail Goldenberg, C. Thomas Bowman, Ronald K. Hanson, Soonho Song, William C. Gardiner, Jr., Vitali V. Lissianski, and Zhiwei Qin. GRI-MECH 3.0; 1999. Available from: http://www.me.berkeley.edu/gri_mech/.
[15] Zhang K, Banyon C, Burke U, Kukkadapu G, Wagnon SW, Mehl M, et al. An experimental and kinetic modeling study of the oxidation of hexane isomers: developing consistent reaction rate rules for alkanes. Combust Flame 2019;206:123–37.
[16] Mei B, Wang Z, Xu W, Thawko A, Cao Y, Klippenstein SJ, et al. Study on ammonia and dimethyl ether oxidation and kinetic interaction up to 100 atm. Combust Flame 2025;281:114428.
[17] Konnov AA. Implementation of the NCN pathway of prompt-NO formation in the detailed reaction mechanism. Combust Flame 2009;156(11):2093–105.
[18] Baulch DL, Bowman CT, Cobos CJ, Cox RA, Just T, Kerr JA, et al. Evaluated kinetic data for combustion modeling: Supplement II. J Phys Chem Ref Data 2005;34(3):757–1397.
[19] Baulch DL, Cobos CJ, Cox RA, Esser C, Frank P, Just T, et al. Evaluated kinetic data for combustion modelling. J Phys Chem Ref Data 1992;21(3):411-.
[20] Markus MW, Roth P, Just T. A shock tube study of the reactions of CH with CO2 and O2. International Journal of Chemical Kinetics 1996;28(3):171–9.
[21] Berman MR, Fleming JW, Harvey AB, Lin MC. Temperature dependence of CH radical reactions with O2, NO. CO and CO2. Symp (Int) Combust 1982;19(1):73–9.

[22] Glarborg P, Miller JA, Ruscic B, Klippenstein SJ. Modeling nitrogen chemistry in combustion. Prog Energy Combust Sci 2018;67:31–68.
[23] Dombrowsky C, Hwang SM, Röhrig M, Gg. Wagner H. The formation of O and H atoms in the reaction of CH2 with O2 at high temperatures. Berichte der Bunsengesellschaft für physikalische Chemie 1992;96(2):194–8.
[24] Frank P. A high temperature shock tube study on fast reactions of methylene and methyl radicals. Proc Int Symp Rarefied Gas Dyn 1986;2:422–6.