fluids

Communication

Heat Flux Measurement in Shock Heated Combustible Gases and Clarification of Ignition Delay Time

Mikhail A. Kotov [1,*], Pavel V. Kozlov [2], Gennady Ya. Gerasimov [2], Vladimir Yu. Levashov [2], Andrey N. Shemyakin [1], Nikolay G. Solovyov [1], Mikhail Yu. Yakimov [1], Vladislav N. Glebov [3], Galina A. Dubrova [3] and Andrey M. Malyutin [3]

[1] Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences, Prospekt Vernadskogo, 101-1, 119526 Moscow, Russia
[2] Institute of Mechanics, Lomonosov Moscow State University, Michurinskiy Prospect, 1, 119192 Moscow, Russia
[3] Institute on Laser and Information Technologies of Russian Academy of Sciences—Branch of Federal Scientific Research Center "Crystallography and Photonics" of Russian Academy of Sciences, Svyatoozerskaya Str., 1, Shatura, 140700 Moscow, Russia
* Correspondence: kotov@ipmnet.ru

Abstract: Correct understanding of the ignition and combustion processes in the combustion chambers are critical for modeling advanced schemes of engines of high-speed aircraft and promising spacecraft. Moreover, experimental data on the ignition delay time are a universal basis for the development and testing of combustion kinetic models. Moreover, the higher the temperature of the fuel mixture, the smaller this time value and the more important its correct determination. The use of a thermoelectric detector allows to measure ignition delay times and record heat fluxes with a high time resolution (to tenths of μs) during ignition in propane–air mixtures. Due to the faster response time, the use of it allows refining the ignition delay time of the combustible mixture, and the detector itself can serve as a useful device that allows a more detailed study of the ignition processes.

Keywords: propane; air; ignition delay time; heat flux; fast response; shock tube

check for updates

Citation: Kotov, M.A.; Kozlov, P.V.; Gerasimov, G.Y.; Levashov, V.Y.; Shemyakin, A.N.; Solovyov, N.G.; Yakimov, M.Y.; Glebov, V.N.; Dubrova, G.A.; Malyutin, A.M. Heat Flux Measurement in Shock Heated Combustible Gases and Clarification of Ignition Delay Time. *Fluids* **2022**, *7*, 291. https://doi.org/10.3390/fluids7090291

Academic Editors: Mehrdad Massoudi and Rajinder Pal

Received: 15 July 2022
Accepted: 31 August 2022
Published: 2 September 2022

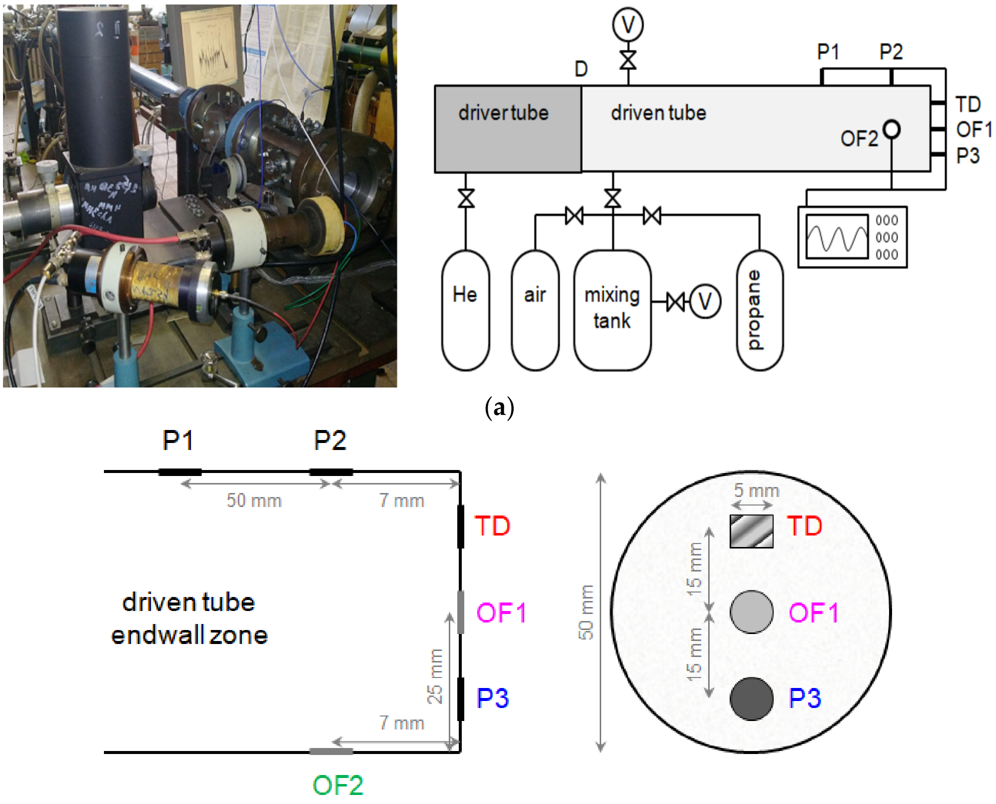
1. Introduction

The correct description of combustible mixtures ignition plays an important role in modeling detonation processes in the combustion chambers of jet engines [1]. This is especially true for the high-temperature region (of the order of 2000 K and above), where the ignition delay time is about a microsecond. Traditional measurement methods (piezoelectric and optical) do not allow accurate recording of such small values of the ignition delay time due to their inertness [2]. In this regard, the search for new, more accurate methods for measuring this quantity is relevant.

Shock tubes are a usable tool for studying various high-temperature gas dynamic processes [3]. A large number of shock tubes are involved for measuring the ignition delay time in high-temperature combustible mixtures [4,5]. The purpose of this work is registration of heat fluxes in the process of the combustible mixture ignition behind a reflected shock wave and improving the accuracy of the ignition delay time measurement at very short timescales. The authors failed to find works describing the use of heat flux detectors to study the ignition of hydrocarbon fuels in shock tubes. This is due to the fact that the use of such devices is difficult, since due to high temperatures and pressures, most of these detectors fail and stop to function. In addition, the data obtained in such aggressive conditions are very difficult to interpret due to the fact that the environmental parameters are far from the operating range of the normal functioning of the detectors. Temperature and heat flux values are obtained in such experiments indirectly. Usually, they are calculated using various computer programs. At the same time, the recently developed thermoelectric detector demonstrated good data in experiments with a reflected shock wave of low and high intensities [6,7]. This work is devoted to its application on measuring heat flux and the ignition delay time in combustible mixtures in a shock tube.

2. Experimental Setup

The inner diameter of the shock tube sections is 50 mm; the lengths of the driver and driven tubes are 1.0 and 3.7 m, respectively (Figure 1). A copper diaphragm D with calibrated notches was installed between the chambers. By varying the thickness of the diaphragm, the depth of the notches, and the pressure in the driver and driven tubes, it is possible to achieve the necessary conditions behind the reflected shock wave. The facility is equipped with systems for pumping out and preparing and filling gas mixtures. The preparation system is used to prepare the test mixture consisting of propane and air (21% O_2/79% N_2). The prepared mixture is fed to the driven tube through the filling system. Helium is used as a driver gas. The preliminary pumping out of the shock tube sections was carried out to a residual pressure of 10^{-3} Torr. The leakage of the sections did not exceed 10^{-4} Torr/min.



(**a**)

(**b**)

Figure 1. Photo with schematic of the shock tube (**a**) and endwall zone scheme (**b**): P1–P3 are pressure sensors; OF1 and OF2 are optical fibers; TD is thermoelectric detector.

The walls of the driven tube (side and end) are made of stainless steel. P1, P2, and P3 are PCB 113B24 pressure sensors; OF1 and OF2 are optical waveguides, which were tuned to certain radiation wavelengths for recording of OH* emission; TD is thermoelectric detector. When the diaphragm separating the shock tube sections breaks, an incident shock wave is formed in the test gas, the velocity of which is determined directly in front of the endwall. For these purposes, P1 and P2 are used that located at a distance of 50 mm from each other. P1, P2, and OF2 were located on the side cylindrical wall of the shock tube, P3, OF1, and TD were located on the endwall (Figure 1b). All device surfaces were flush mounted. During the experiment, the Agilent 54624A oscilloscope recorded the DT, H2, F2, and F1 data in the range of 10–100 MHz per channel.

TD is based on anisotropic film radiation detectors made of high-temperature materials, which are obtained using vacuum technology at an inclined condensation angle. The design of the device is a heat-conducting substrate made of high-resistance silicon, on which contact pads are applied for thermo-emf receiving. A thermosensitive anisotropic film based on Cr (thickness ~0.3 μm) is formed on top. Such films make it possible to obtain a sufficiently high sensitivity to instantaneous thermal action. The sensors were calibrated using lamp calibration, laser heating, and reflected shock tube experiments. A lamp calibration was performed to evaluate the overall sensitivity of the fabricated sensor without obtaining a calibration factor. Laser heating of the sensor was carried out using a laser diode at a power in the range of 5–30 W at 970 nm and made it possible to determine the calibration dependence. Shock tube experiments allowed to refine the obtained coefficient under conditions close to real laboratory ones. The discrepancy between the characteristics of the sensor obtained with different procedures was no more than 5% in absolute scale. The sensitivity obtained for TD used was 2.4×10^{-8} V·m^2/W. More information about experimental setup, calibration procedures, and uncertainty analysis can be found in [6–8].

The parameters of the experiments are presented in Table 1. ϕ is the equivalence ratio of mixture, P_0 is the driven tube initial pressure in the driven section, V_{SW} (incident shock wave velocity). P_5 and T_5 (pressure and temperature behind the reflected shock) were calculated using the GASEQ program [9].

Table 1. Experimental parameters.

# Exp.	Composition	ϕ	P_0, kPa	V_{SW}, m/s	P_5, MPa	T_5, K
1	2.1% C_3H_8/20.56% O_2/77.34% N_2	0.5	20.02	1289	2.12	1644
2	4.2% C_3H_8/20.12% O_2/75.68% N_2	1	17	1302	1.85	1670

3. Results and Discussion

Figures 2 and 3 show heat flux data from the thermoelectric detector along with the P3 pressure and OH* emission from OF1 and OF2. The conversion of TD sensor readings from mV to MW/m^2 was carried out according to the linear factor defined in previous section. Pressure coefficient from manual was applied for P3 data conversion to atm. Under the considered parameters, the thermoelectric detector records well the history of heat flux changes.

TD heat flux readings have sharper edges. Thus, the rise of the primary disturbance is 0.1–0.5 μs, depending on the amplitude. The first response time of P3 is 1 μs or more. Moreover, the nature of TD data indicates low inertia of the sensor. On the scale of fractions of a microsecond, a thermoelectric detector is capable of registering abrupt changes in the thermal gradient. It should be noted that with such short time scales large heat flux values are available for registration—more than 4 MW/m^2. In addition, the signal-to-noise ratio is at a high level, which makes it possible to recognize all the features that occur when the mixture is ignited and after. Taking into account the inertia of the sensors, the nature of pressure and heat flux in Figures 2 and 3 coincide quite well.

Chemiluminescence emission from excited particles such as OH* or CH*, as well as pressure, are convenient and effective diagnostic tools for monitoring the ignition delay time in mixtures heated by reflected shock. However, at short times (few microseconds), the precise determination of such delay can be difficult due to the insufficiently low inertia of the pressure sensor and the limited numerical aperture of the optical fiber. More details about this can be found in [5]. Data received allow clarifying the ignition delay time. They also show that ignition starts behind the reflected shock near the endwall (before the reflected shock passes OF2). At the time, as the reflected shock with ignited mixture behind passes OF2, it also shows OH* emission after 8 μs. Table 2 demonstrates comparison of beginning of rises from sensor histories.

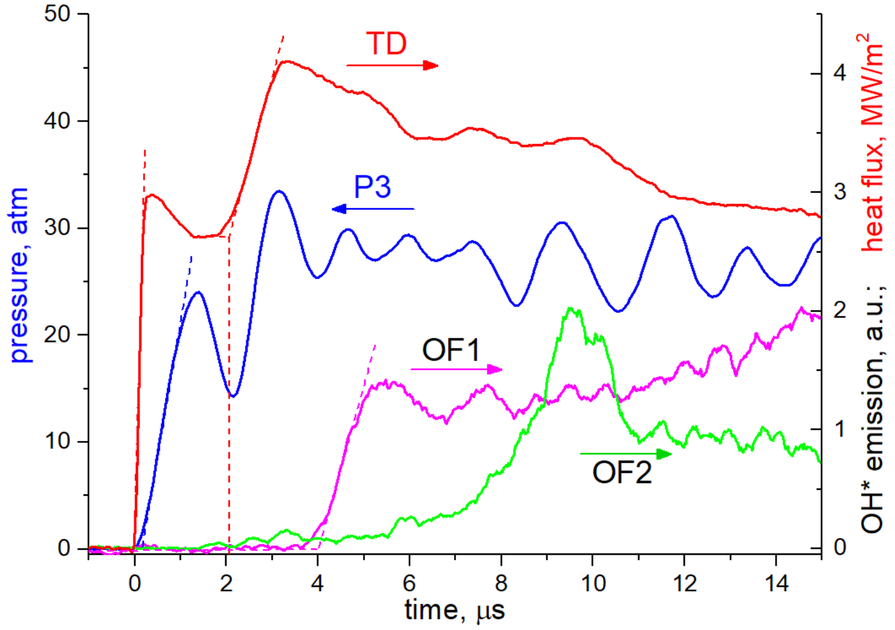


Figure 2. Exp. #1 time histories for P3 [atm], OF1 and OF2 [a.u.], TD [MW/m^2]. Dashed lines are tangents to baselines.

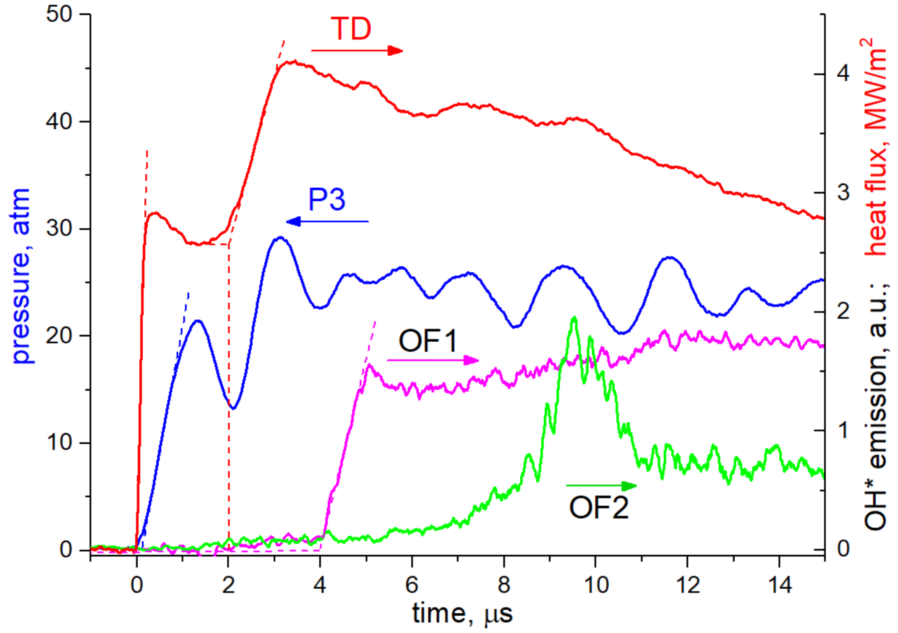


Figure 3. Exp. #2 time histories for P3 [atm], OF1 and OF2 [a.u.], TD [MW/m^2]. Dashed lines are tangents to baselines.

Table 2. Rise moments from sensors data.

	Exp. #1 (Figure 2), μs			Exp. #2 (Figure 3), μs		
	P3	**OF1**	**TD**	**P3**	**OF1**	**TD**
first rise	0.2	4	0	0.1	4	0
second rise	N/D	N/D	2.1	N/D	N/D	2

It can be said that despite the relatively low response time of the pressure sensor, the P3 has some kind of second rise (after 2.2 μs). However, the exact definition of its start becomes difficult due to constant fluctuations. However, it speaks for the validity of the TD data. In addition, the beginning of the first rise fronts perfectly coincides with the pressure sensor.

Due to the advantages of the thermoelectric detector, the difference between the data from P3, OF1, and TD exists, and it allows us to determine the values of the ignition delay time more accurately. In exp. #1, it is 2.05 μs vs. 4 μs (OF1). The same goes from data of exp. #2—2 μs vs. 4 μs. That is, the refinement of delay is more than doubled. The results agree with measurements by other authors in this temperature range [8,10,11] and with heat flux calculation studies in shock tubes and detonation engines under similar conditions [12–14].

As described earlier in the previous section, the calibration procedure for the thermoelectric detector for the heat flux behind the reflected shock was carried out in [6] for values less than 1 MW/m^2. In [7], under a similar technique, the sensor recorded values of more than 45 MW/m^2 in high-temperature xenon. However, the calibration characteristic can be nonlinear when going to high values, which were observed in [7] and in this work. When measuring the ignition delay time, the most important thing is the response speed of the sensor; obtaining absolute values does not play a big role. However, we can say that this device allows measuring the heat flux behind the reflected shock in a wide range of values. In addition, TD functions well in such aggressive environments (high pressures and significant heat loads).

4. Conclusions

In the experiments carried out, the thermoelectric detector was used for the first time to register the parameters of the ignition of combustible mixtures in a reflected shock. It was mounted simultaneously on a flange along with pressure transducer and optical fiber for OH* emission recording. The response time to a sharp thermal disturbance caused by the arrival of an incident shock or the ignition start is shorter in comparison to the high-frequency pressure sensor. It also successfully operates at high pressures (more than 20 atm behind the reflected shock). The nature of the device inertia makes it possible to record the history of the heat flux on a scale of hundreds of nanoseconds. The use of TD makes it possible to refine the value of the ignition delay time of the mixture in short time ranges (up to several microseconds). The advantages of the thermoelectric detector make it possible to use it for measuring such periods in various installations (shock tubes, models of various engines, etc.); there is no need to use additional devices, such as pressure sensors or optical recording systems.

Author Contributions: Conceptualization, M.A.K., P.V.K., M.Y.Y. and V.N.G.; investigation, M.A.K., P.V.K., G.Y.G., V.N.G., G.A.D. and A.M.M.; methodology, M.A.K., A.N.S. and V.N.G.; project administration, M.A.K., N.G.S. and V.N.G.; resources, M.A.K., P.V.K., V.N.G., G.A.D. and A.M.M.; supervision, M.A.K., V.Y.L., N.G.S. and V.N.G.; validation, P.V.K., G.Y.G., V.N.G., G.A.D. and A.M.M.; visualization, M.A.K. and P.V.K., writing—original draft, M.A.K., P.V.K., G.Y.G. and M.Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Science and Higher Education within the Russian State Contracts #AAAA-A20-120011690135-5, #AAAA-A19-119012990112-4 and the State assignment FSRC «Crystallography and Photonics» RAS.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful to Vladimir A. Kuznetsov for help in manufacturing the necessary parts and structural elements of the installation.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ϕ	combustible mixture equivalence ratio
P_0	riven tube initial pressure [kPa]
P_5	reflected shock pressure [MPa]
T_5	reflected shock temperature [K]
V_{SW}	shock wave velocity [m/s]
TD	thermoelectric detector
PMT	photomultiplier tube
OF1, OF2	optical fibers
P1–P3	pressure sensors

References

1. Tunik, Y.V.; Gerasimov, G.Y.; Levashov, V.Y.; Mayorov, V.O. Busemann diffuser for supersonic ramjet on detonation combustion of kerosene vapor. *Acta Astronaut.* **2022**, *198*, 495–501.
2. Hanson, R.K.; Davidson, D.F. Recent advances in laser absorption and shock tube methods for studies of combustion chemistry. *Prog. Energy Combust. Sci.* **2014**, *44*, 103–114.
3. Reyner, P. Survey of high-enthalpy shock facilities in the perspective of radiation and chemical kinetics investigations. *Prog. Aerospace Sci.* **2016**, *85*, 1–32.
4. Han, H.S.; Kim, C.J.; Cho, C.H.; Sohn, C.H.; Han, J. Ignition delay time and sooting propensity of a kerosene aviation jet fuel and its derivative blended with a bio-jet fuel. *Fuel* **2018**, *232*, 724–728. [CrossRef]
5. Petersen, E.L. Interpreting endwall and sidewall measurements in shock-tube ignition studies. *Comb. Sci. Technol.* **2009**, *181*, 1123–1144.
6. Kotov, M.A.; Shemyakin, A.N.; Solovyov, N.G.; Yakimov, M.Y.; Glebov, V.N.; Dubrova, G.A.; Malyutin, A.M.; Popov, P.A.; Poniaev, S.A.; Lapushkina, T.A.; et al. Performance assessment of thermoelectric detector for heat flux measurement behind a reflected shock of low intensity. *Appl. Therm. Eng.* **2021**, *195*, 117143. [CrossRef]
7. MKotov, A.; Shemyakin, A.N.; Solovyov, N.G.; Yakimov, M.Y.; Glebov, V.N.; Dubrova, G.A.; Malyutin, A.M.; Popov, P.A.; Poniaev, S.A.; Lapushkina, T.A.; et al. The analysis of applicability of thermoelectric radiation detectors for heat flux measurements behind a reflected shock wave. *J. Phys. Conf. Ser.* **2021**, *2103*, 012218.
8. Kozlov, P.V.; Zabelinskii, I.E.; Bikova, N.G.; Gerasimov, G.Y.; Levashov, V.Y. Ignition of Propane-Air Mixtures in Shock Tube at Pressure of 30 atm, Physical-Chemical Kinetics in Gas Dynamics. *High Temp.* **2021**, *59*, 240–244. [CrossRef]
9. A Chemical Equilibrium Program for Windows. Available online: http://www.gaseq.co.uk/ (accessed on 9 January 2022).
10. Tang, C.; Man, X.; Wei, L.; Pan, L.; Huang, Z. Further study on the ignition delay times of propane–hydrogen–oxygen–argon mixtures: Effect of equivalence ratio, Combust. *Flame* **2013**, *160*, 2283–2290. [CrossRef]
11. Mathieu, O.; Goulier, J.; Gourmel, F.; Mannan, M.S.; Chaumeix, N.; Petersen, E.L. Experimental study of the effect of CF3I addition on the ignition delay time and laminar flame speed of methane, ethylene, and propane. *Proc. Combust. Inst.* **2015**, *35*, 2731–2740. [CrossRef]
12. Paxon, D.E.; Naples, A.G.; Hoke, J.L.; Schauer, F. Numerical Analysis of a Pulse Detonation Cross Flow Heat Load Experiment. In Proceedings of the 49th AIAA Aerospace Sciences Meeting—AIAA 2011, Orlando, FL, USA, 4–7 January 2011; p. 584.
13. Hoke, J.; Bradley, R.; Schauer, F. Heat Transfer and Thermal Management in a Pulsed Detonation Engine. In Proceedings of the 41st AIAA Aerospace Sciences Meeting and Exhibit—-AIAA 2003, Reno, Nevada, 6–9 January 2003; p. 852.
14. Ragozin, K. Thrust Performance and Heat Load Modelling of Pulse Detonation Engines. Master's Thesis, Luleå University of Technology, Luleå, Sweden, 2020.