Development of Indirect Visualization Technic of Propagating Flame by Densely Installed Ion-Probes

Tomoaki Yatsufusa, Kan Lu, and Koji Ishibashi

***Abstract*—A new technic to measure the propagating flame precisely by using densely installed ion-probes has been developed. Densely installed ion-probes as grid shape are able to capture the propagating flame two-dimensionally along the confinement chamber wall. In the present paper, the characteristics of ion-current in propagating flame were investigated as a first step of the development. Secondary, characteristic features of this measurement technic were investigated. The series of basic tests for measuring the different types of propagating flame shows that the measurement technic has an ability to capture the fluctuation of propagating velocity in microscopic scale both in deflagration propagating at a few meters per second and in detonation propagating at supersonic speed.**

***Index Terms*—Ion-current, signal amplification, flame propagation, detonation, micro explosion.**

I. Introduction

Combustion is the major method to convert the chemical energy stored for example in fossil fuel into the thermal energy used by furnaces, boilers, engines and so on. However, burning the fossil fuel causes serious issues, such as regional air prolusion, global warming, and depletion of fossil fuel resources. To moderate the affect from these issues, it is important to reduce the usage of fossil fuel by burning it much effectively.

Effective combustion of fossil fuel mainly relies on the design of burning environment, including type of fuel, air-fuel mixing, flow condition of air-fuel mixture, shape of combustion chamber, and so on. In other words, such many parameters affect the combustion. To design the effective combustion, degree of influence of each parameter should be investigated. Because the investigation would be parametric and large numbers of trial, measurement technic of combustion should be effective, detailed and robust.

For example in automotive engines, combustion results high-temperature of 1500-2000K and high-pressure of 5-10MPa. And the combustion phenomena in the engine are all done in several mili-seconds [1]. Such extreme environment limits the way of combustion measurement. Ion-probe technic, which detects the existence of flame using the electrical conductivity of the chemically reacting region in flame, is physically strong and relatively low cost. However, ion-probe is usually installed on the surface of the combustion chamber wall, therefore ion-probe can only detect the flame neighboring to the wall. And the ion-probe informs that probe contacts flame or does not.

Although such a limited information, increasing the number of ion-probe itself brings the other advantage. For example, in case of automotive engine, installing a grid of ion-probes in the surface of the combustion chamber reviles the point of outbreaks of knocking that often destroys automotive engine [2], [3]. In other words, two-dimensional flame image propagating along the confinement chamber wall can be observed by the grid of ion-probes. On the other hand, the technic for visualizing the inside of the automotive piston engine (or model combustion chamber) using transparent optical window [4], [5], which is often used at engine development in laboratories [6]-[9] and auto manufacturers [10], [11], cannot be applied such a condition resulting high-pressure.

In the present paper, the first part notes the relation between flame condition and electrical conductivity. Second part notes the selection of appropriate amplifying circuit. Last part notes some experimental result using the densely installed ion-probes.

II. Electrical Conductivity of Flame

A. Experimental Apparatus and Conditions

Fig. 1 shows the experimental apparatus. Combustion occurs in confined stainless tube. Bore and length of the tube were 57.3 mm and 1,070 mm respectively. Two igniters were installed at both closed end of the tube.

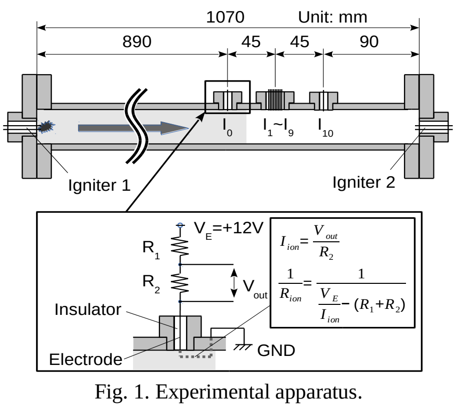

Fig. 1. Experimental apparatus.

Because ion-probe measurement section was deflected to one end, measurement distance from igniter was able to change by selecting the igniter. No obstacles, which enhance the deflagration to detonation transition, were installed in the tube.

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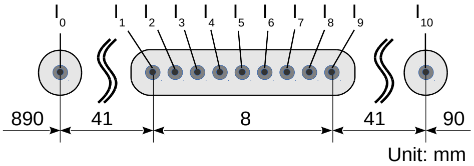

Fig. 2. Installation of ion-probes.

Voltage was applied between ground and ion-probe made by cupper wire with the diameter of 0.2mm. Small electric current flows when flame front contacts the tip of the ion-probe wire. Amperage of the ion current was calculated by measuring the voltage drop at R_2. Not to affect the flame propagation, tip of the ion-probe wire was not projected but made it flat to the tube wall. Two single ion-probes and one bundle of nine ion-probes were installed as shown in Fig. 2.

TABLE I: EXPERIMENTAL CONDITIONS

NMF*		0.76	0.38	0
Mixing ratio	LPG		1	
	O_2		5	
	N_2	19	3.8	0
Initial temerature (K)			293	
Initial pressure (MPa)			0.101	
C-J detonation velocity (m/s)		1785	2142	2363

*NMF: Nitrogen mole fraction

Combustion tube was filled with combustible mixture of LPG, O_2 and N_2 as shown in the table 1. Three types of mixture were investigated. All types of the mixture were same mixing ratio as stoichiometry in LPG and O_2, and diluted by different amount of N_2. Notation of "NMF" means nitrogen mole fraction, which shows the degree of nitrogen dilution. NMF=0 indicate that mixture was not diluted, and NMF=0.76 was same as the mixture of LPG and air.

In general, there are two stable modes of flame propagation. A stable propagation mode with low propagation velocity is "deflagration", which propagates at 0.5-3 m/s. Higher stable propagation velocity mode is "detonation", which propagates at 1.5-3 km/s of supersonic speed [12], [13]. C-J detonation velocity in Table I shows the theoretical propagation velocity of detonation calculated as mixture with propane, which is major component of LPG. NMF=0.76 often resulted deflagration, and NMF=0 resulted detonation in any trial.

Variation of NMF brings wide range of flame propagation velocity. For comparison, flame propagation in candle is about 0.5 m/s, and that in automotive engine knocking is larger than 1.0 km/s. The experimental conditions conducted in the present study covers completely these combustion phenomena.

B. *Experimental Result*

Fig. 3 shows flame propagating velocity under different NMF conditions. Flame velocity was measured by time difference of flame arrival times detected by two ion-probes of I_0 and I_{10} as shown in Fig. 2 separately installed with a distance of 90 mm. Ion-current was amplified by instrumentation amplifier circuit denoted in Fig. 8. Low operation frequency does not affect much to the calculation of the flame propagation velocity because of the longer distance between two measuring ion-probes. Flame velocity at 0.135m was tested by ignited from right side end in Fig. 1, and the velocity at 0.935 was ignited from left side end.

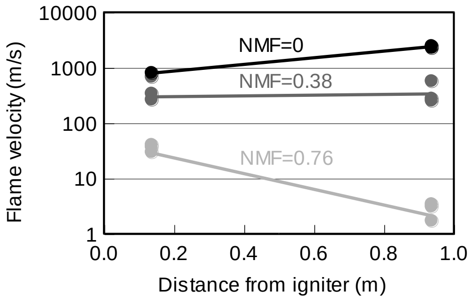

Fig. 3. Flame propagation velocities in different NMF conditions.

In case of NMF=0, velocity at 0.135m is 600-1000m/s. At 0.935m, flame accelerates and results 2300-2600m/s, which is slightly higher than C-J detonation velocity. Observed flame is overdriven detonation. At the acceleration process in general, the velocity is once overshooting, and then converges into the stable detonation. Therefore, observed flame propagation is considered to be still pre-developed detonation.

In case of NMF=0.38, variation of velocities between 0.135m and 0.935m are not so different. Although observed propagation velocities are supersonic speed, they are still pre-developed detonation. In this condition, it requires longer distance to be stable detonation.

In case of NMF=0.76, flame propagation velocity at 0.935m is lower than that at 0.135m. Propagating flame at subsonic speed like this condition produces forward flow ahead of the flame front. Flame is usually accelerated by riding on the flow if the tube is long enough. However in this case, closed end of the tube dams the flow ahead of the flame, and flame is decelerated.

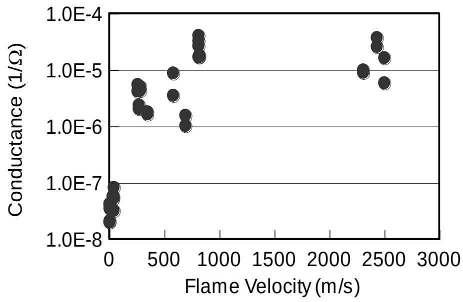

Fig. 4. Effects of flame propagation velocity on electrical conductivity in flame.

Fig. 4 shows the relation between flame propagation velocity and electric conductivity of flame. Electric conductivity was calculated by the peak ion current. All data shown in the figure are consistent with Fig. 3.

There are no data found between 1000-2000m/s. The flame propagating at this velocity is generally unstable and transits lower or upper velocity in a relatively short time. As shown in Fig. 4, electric conductivity increases exponentially as flame propagation velocity increases up to 1000m/s. On the other hand, the difference of the electric conductivity between around 1000m/s and above 2000m/s is small.

The difference of electric conductivity between minimum and maximum value observed is about a thousand times. Therefore, ion-current measuring system should cover this range.

III. Optimization of Amplifier Circuit

A. Target Performance of Amplifier Circuit

Density of the installation of ion-probes should be large enough to resolve target phenomena. However, there exists a limitation of manufacturing for denser installation. Accordingly, we chose the installation interval of 1mm and manufactured the ion-probe bundle, in which nine ion-probes were installed inline, as shown in Fig. 5. In the measuring system being developed, maximum target flame propagation velocity is 3km/s. The flame with this velocity travels 1mm, which is ion-probe installation interval, in 3.3×10^{-7}sec. Minimum sampling rate required is 3MHz that is inverse of 3.3×10^{-7}sec. To set an acceptable measuring error as 10% for our target, sampling rate should be 30MHz. Therefore, operating frequency of the amplifier circuit defines 30MHz as a target.

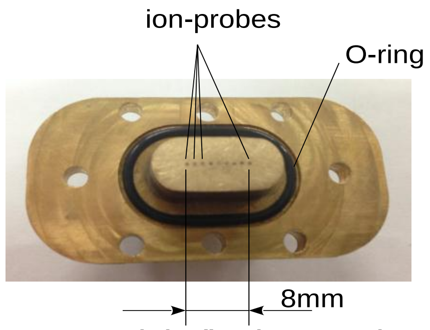

Fig. 5. Ion-probe bundle with nine ion-probes.

Number of installed ion-probes in measuring system is the larger, the better for resolving the phenomenon. Consequently, effective wiring is required. Input to amplifier circuit is ion-current, and output from the circuit to the data acquisition system is voltage. Generally, amplifier circuit requires four wires including two input wires and two output wires. However, if one of two input wires and one of two output wires are grounding and common, total number of wire can be almost half. Therefore, wire design of the amplifier circuit is to have three IOs, including input, output and ground.

B. Tests of Amplifier Circuits

Transistor circuit: Fig. 6 shows circuit diagram using single transistor. Installed transistor is PNP bipolar type. Maximum operation frequency of the transistor is 150MHz. Test result is shown in Fig. 7. Measured four ion-probes were I_1, I_2, I_3 and I_9 illustrated in Fig. 2. Tested gas mixture was NMF=0, which results maximum flame propagation velocity.

Initial rise of output voltage in each channel is steep and distinct. It is favorable if only a timing of flame arrival is detected from the amplified signal. Calculated propagation velocity at I_1-I_2 is 2817m/s, and that at I_2-I_3 is 2307m/s. Average velocity at I_1-I_3 is 2537m/s, and the velocity at I_3-I_9 is 2526m/s. As shown in the local velocity like I_1-I_2 and I_2-I_3, velocity is slightly fluctuated. This is conceivable that the microscopic inconstant propagation of detonation, which is caused by multiple tiny explosions [8], [9], results the velocity fluctuation observed.

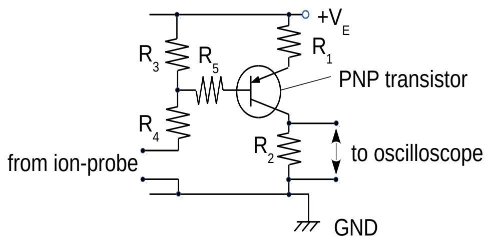

Fig. 6. Amplifier circuit with PNP transistor.

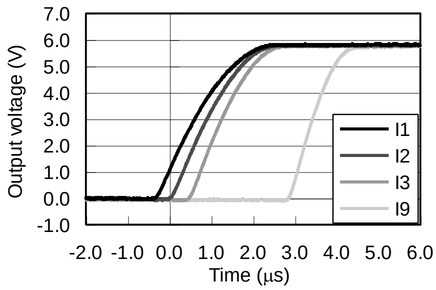

Fig. 7. Amplified signal by amplifier circuit with PNP transistor.

On the other hand, output voltage is saturated just after the initial rise. This feature is disadvantage to acquire the features of original ion-current. Furthermore, temperature drift and individual difference of amplification ratio make it difficult to estimate the original ion-current.

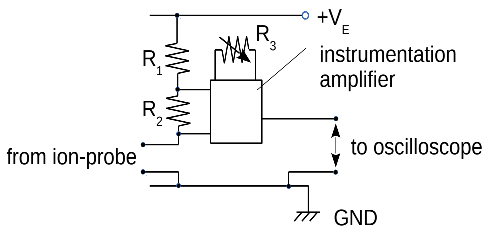

Fig. 8. Amplifier circuit with instrumentation amplifier.

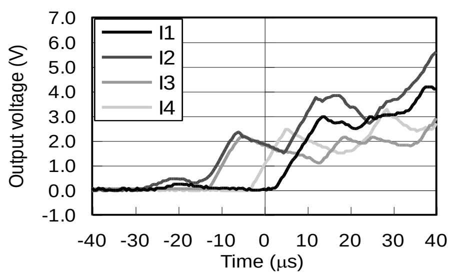

Fig. 9. Amplified signal by amplifier circuit with instrumentation amplifier.

Instrumentation amplifier circuit: Fig. 8 shows circuit diagram using instrumentation amplifier with single power supply. Because input and output channel of this amplifier is insulated, it makes circuit design simple. In addition, amplification ratio can be adjusted by changing the resistance R_3. Test result is shown in Fig. 9. Measured four ion-probes (I_1, I_2, I_3 and I_4) are illustrated in the figure.

Tested gas mixture is NMF=0.

Small initial rise of output voltage is found in all channels. A few micro seconds after this initial rise, significant rise of output voltage is found. However, the order of significant rise in each channel does not match to the order of the ion-probe installation. Although first contact between ion-probe wire and flame front may cause the initial small rise, degree of the rise is so small to determine the rising point of the output voltage precisely. These negative features are conceivable to be caused by low operational frequency of instrumentation amplifier.

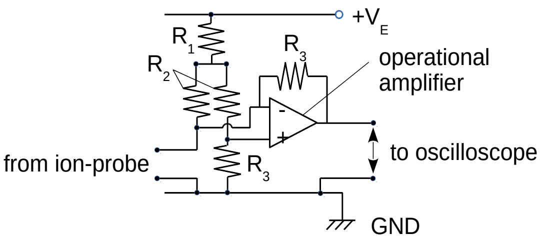

Fig. 10. Differential amplifier circuit with operational amplifier.

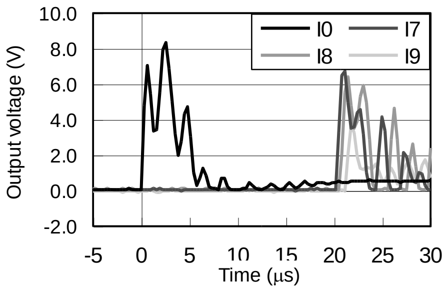

Fig. 11. Amplified signal by differential amplifier circuit with operational amplifier.

Differential amplifier circuit: Fig. 10 shows circuit diagram of differential amplifier circuit using operational amplifier with single power supply. Amplification ratio is adjustable by changing resistance of R_2 or R_3. Test result is shown in Fig. 11. Measured four ion-probes are I_0, I_1, I_2 and I_3 illustrated in Fig. 2. Tested gas mixture is NMF=0.

Initial rise of output voltage in each channel is steep and distinct. The order of initial rise in each channel matches to the order of the ion-probe installation. The calculated velocities at I_2-I_3 and I_3-I_4 are 1897 m/s and 2246 m/s respectively. These values are conceivable as a fluctuation of detonation propagation in small scale.

From the results above, differential amplifier circuit is most favorable for the amplification of ion-current among these three. In the following basic tests, details of flame propagation were measured by ion-probe bundle using differential amplifier circuit.

IV. Measurement of Flame Propagation

Flame propagations in small scale under different mixture conditions were measured by ion-probe bundle. The series of tests were conducted using two configurations of measuring ion-probes shown in Fig. 2. Configure 1 measured the ion-probes of I_0, I_1, I_2, I_3, and Configure 2 was the ion-probes of I_0, I_7, I_8, I_9. Repetition of each experimental condition was three times.

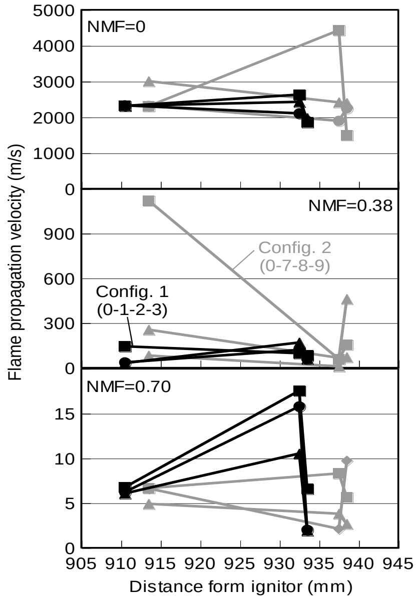

Fig. 12. Flame propagation velocities measured by densely installed ion-probes.

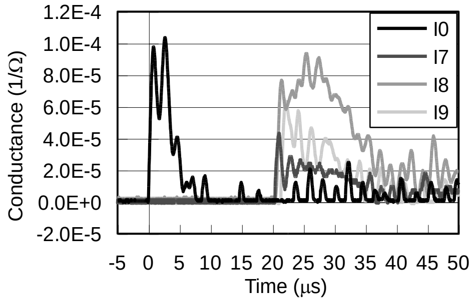

Fig. 13. Change histories of electrical conductance in case of high-velocity flame propagation observed (test case #a).

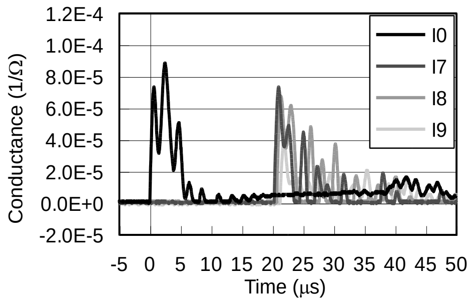

Fig. 14. Change histories of electrical conductance in case of flame propagation velocity on the same level with C-J detonation velocity observed (test case #b).

Fig. 12 shows the profiles of flame propagation in different mixture conditions. In case of NMF=0, most of the observed velocities are between 2000-3000m/s, which is slightly larger than C-J detonation velocity. There is a single data point that has quite large velocity of 4427m/s. Fig. 13 shows raw ion-current profiles of the test case #a in case of flame propagation with high-velocity observed. On the other hand, Fig. 14 shows raw data of the test case #b, in which such a high-velocity was not observed. Both tests were conducted under same experimental conditions. The difference of I_3 ion-current profile between test case #a and test case #b is significant compared to the other ion-current profiles. Although ion-current profiles except I_3 quickly attenuate, I_3 ion-current profile in test case #a keeps high conductance behind the initial steep rise. Ion-probe I_3 in test case #a may capture the micro-explosion in detonation. Therefore, it is conceivable that observed large velocity is not brought by measuring error but actual phenomenon occurred.

Go back to the case of NMF=0.38 shown in Fig. 12. Most of the data points indicate propagating velocity of 10-500 m/s. However, one data point indicates 1119m/s, and it decelerates urgently. The mixture condition of NMF=0.38, it requires longer distance than combustion tube length to transit to detonation. Therefore, observed flame propagation is in the phase of deflagration to detonation transition. In this phase, flame front is quite disturbed, and shape of flame front is strongly bended. Therefore, observed urgent deceleration may be not an actual phenomenon but resulted by strong three dimensionality of flame front.

In case of NMF=0.70 shown in Fig. 12, all of data points at 934mm in configure 1 indicate obviously larger velocity than other data points. It is thought that one of the reasons of this larger velocity is caused by the turbulence [14] initiated by the edge of ion-probe bundle just ahead of I_1 as shown in Fig. 2. This fact tells that densely installed ion-probes can capture the velocity fluctuation of small scale even in low speed propagation flame.

The results of the series of tests indicate that the measuring technic by densely installed ion-probes is able to capture the fluctuation of propagating velocity in microscopic scale both in deflagration propagating at a few meters per second and in detonation propagating at supersonic speed. This characteristic is suitable for precise measurement of explosion-like combustion in a confined space, such as knocking in spark ignition engine or detonation initiation in gas pipe, which is high-speed and high-pressure phenomenon.

V. CONCLUSION

A new method to measure the flame propagation precisely by using densely installed ion-probes was developed and its characteristic features of measurement were investigated. The following results were obtained.

1) Electrical conductivity of flame increases exponentially as flame propagation velocity increase up to 1000m/s. Above that velocity, electrical conductivity is almost unchanged. The difference electric conductivity between minimum and maximum value observed is about a thousand times.
2) Proper amplifier circuit is required to measure the ion-current in flame. Differential amplifier circuit, which has higher operational frequency and reliable amplification ratio, is most suitable for amplifying the ion-current.
3) Flame propagations in small scale under different mixture conditions were measured by densely installed ion-probes. Densely installed ion-probes were able to resolve the small scale fluctuation of flame propagation velocity both in deflagration propagating at low speed and detonation propagating at supersonic speed.
4) The characteristic of this measurement technique is suitable for precise measurement of explosion-like combustion in a confined space, such as knocking in spark ignition engine or detonation initiation in gas pipe, which is high-speed and high-pressure phenomenon.

REFERENCES

[1] A. Khalid, T. Yatsufusa, T. Miyamoto, J. Kawakami, and Y. Kidoguchi, "Analysis of relation between mixture formation during ignition delay period and burning process in Diesel Combustion," SAE Technical Paper, 2009.
[2] Y. Ohta and H. Takahashi, "Inhibitory action of preflame reactions on flame propagation in end gas," *Prog. Astronaut Aeronaut*, vol. 105, no.1, pp. 69-77, 1986.
[3] T. Hayashi, M. Taki, S. Kojima, and T. Kondo, "Photographic observation of knock with a rapid. compression and expansion machine," SAE Technical Paper, pp. 13-36, 1984.
[4] G. P. Merker, C. Schwarz, and R. Teichmann, *Combustion Engines Development*, Springer, 2011, pp. 91-114.
[5] H. Hiroyasu and H. Miao, *Optical Techniques for Diesel Spray and Combustion*, Springer, 2004, pp. 91-114.
[6] T. Yatsufusa, Y. Kidoguchi, A. Adam, and T. Gomi, "Measurement of particle diameter in diesel spray by long-distance microscopic shadow-graph photography (in Japanese)," *ILASS-Japan*, vol. 18, no. 63, pp. 88-95, 2009.
[7] Y. Aoyagi, E. Kunishima, Y. Asaumi, Y. Aihara, M. Odaka, and Y. Goto, "Diesel combustion and emission using high boost pressure in a single cylinder engine," *JSME International Journal, Series B*, vol. 48, no. 4, pp. 648-655, 2005.
[8] P. Wolanski, Z. Gut, W. Niedziela, and J. Przastek, *et al*., "Study of combustion dynamics in the research engine," SAE Technical Paper, 1997.
[9] C. Espey and J. Dec, "Diesel engine combustion studies in a newly designed optical-access engine using high-speed visualization and 2-d laser imaging," SAE Technical Paper, 1993.
[10] T. Fuyuto, K. Akihama, T. Fujikawa, and K. Nakakita, "In-cylinder measurement technique for diesel by using a multi-directional optically accessible engine (in japanese)," *Transactions of the Japan Society of Mechanical Engineers, Series B*, vol. 74, no. 740, pp. 980-985, 2008.
[11] K. Kuwahara and H. Ando, "Time series spectroscopic analysis of the combustion process in a gasoline direct injection engine," in *Proc. 4th International Symposium For Combustion Diagnostics*, Baden-Baden, May 18–19, 2000, pp. 130–137.
[12] J. H. S. Lee, *The Detonation Phenomenon*, Cambridge University press, 2008, pp. 171-186.
[13] J. H. S. Lee, "Dynamic parameters of gaseous detonations," *Ann. Rev. Fluid Mech.*, vol. 16, pp. 311-336, 1984.
[14] P. Clavin and F. A. Williams, "Theory of premixed-flame propagation in large-scale turbulence," *J. Fluid Mech.*, vol. 90, part 3, pp. 589-604, 1979.

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