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NUMERICAL ANALYSIS ON DEFLAGRATION-TO-DETONATION TRANSITION OF A HYDROGEN-OXYGEN MIXTURE IN A SMOOTH TUBE

September 2005

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Numerical Analysis on Deflagration-to-detonation Transition of a Hydrogen-oxygen Mixture in a Smooth Tube

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The Flow and Combustion Engineering Division at the Forschungszentrum Karlsruhe (FZK) carried out the explosion experiments of hydrogen-oxygen mixtures in a smooth tube made of stainless steel after two radiolysis gas ($2H_2+O_2$) explosion accidents occurred in Japanese and German BWRs. In these experiments, stoichiometric hydrogen-oxygen mixtures with different initial pressures were used. The pressure in the tube and the strain of the tube were measured, and then the structural response during the detonation and the Deflagration-to-Detonation Transition (DDT) process were investigated.

In the present study, a numerical analysis was performed to simulate one of the experiments by the use of the 3-dimensional turbulent combustion analysis code COM3D, which has been developed in FZK, and a DDT process was calculated. The COM3D code contains a reaction rate constant, which must be obtained empirically from experimental results. It is necessary to improve the reaction rate constant for the simulation of the DDT process. In the present calculation, the reaction rate constant was assumed to be an exponential function. As a result, it was found that the COM3D code can simulate the DDT process.

Keywords : DDT, Numerical Analysis, COM3D, Smooth Tube, Hydrogen, Oxygen, Radiolysis Gas, Detonation, Deflagration, Run-up-distance

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* Forschungszentrum Karlsruhe GmbH

平滑円管内における水素ー酸素混合気の爆燃から爆ごうへの遷移に関する数値解析

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(2005年8月11日受理)

Forschungszentrum Karlsruhe の Flow and Combustion Engineering Division では、日本とドイツの BWR で起きた放射線分解ガス($2H_2+O_2$)の爆発事故を契機として、ステンレススチール製平滑円管内における水素の爆発実験を行った。この実験では、化学量論比濃度の水素ー酸素混合気が用いられた。初期圧力をパラメータとして、管内の圧力や管の歪みが測定され、爆ごう時の構造応答や平滑管における爆燃から爆ごうへの遷移(DDT)過程が調べられた。

本報告書では、この実験の1つを模擬した数値解析について述べた。数値解析には、Flow and Combustion Engineering Division で開発された乱流燃焼解析コード COM3D を用いた。COM3D の燃焼モデルは、実験データに基づいた燃焼率の相関式を用いており、実験を正確に模擬するためには、この燃焼率の修正が必要である。著者らは、燃焼率が指数関数状に増加すると仮定して、計算を行った。その結果、計算においても DDT を再現することができた。

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1. Introduction

Two radiolysis gas explosion accidents occurred in the Japanese BWR (Hamaoka-1 at November 7, 2001) [1] and the German BWR (Brunsbuettel KKB at December 14, 2001). The investigation of these two accidents showed that an extraordinary large pressure rise due to the high-speed combustion of the radiolysis gas inside the pipes caused ductile material failure.

A tube is heavily damaged if a detonation occurs in the tube, and the system suffers a great loss. Therefore, it is important for safety engineering to investigate the process of the formation of the detonation. The initiation of detonation can be divided into two methods: (a) the indirect initiation of detonation by flame acceleration and Deflagration-to-Detonation Transition (DDT), and (b) the direct initiation of detonation by a strong source. An important parameter for the indirect initiation of the detonation in a smooth tube and unconfined volume is the run-up-distance, which is the distance from an ignition position to a DDT occurrence point. There are only few experimental investigations into the effects of tube diameter, initial pressure and temperature on the run-up-distance in smooth tubes [2] [3] [4] [5]. Combustion waves are classified into subsonic deflagration waves and supersonic detonation waves in the premixed gas of fuel and oxidant. The deflagration waves develop into the detonation waves by flame acceleration via a DDT process. One of the general causes of the transition to detonation of a flame is the turbulence generated by the tube wall. The effect of the boundary layer becomes important in the tube because of the effective turbulent generation inside turbulent boundary layer. The interaction between the wall and the flow behind the leading shock wave generates turbulence in the whole flow field, starting at the wall and propagating toward the centerline of the tube. Correspondingly, the leading point of the turbulent flame is in the vicinity of the wall and this determines the flame velocity. The important effect of the turbulent boundary layer on DDT was shown experimentally [6]. The effect of the boundary layer on flame acceleration and DDT was studied numerically [7] [8]. However, numerical approach of DDT is very difficult because the scales of the phenomena are so different between deflagration, DDT and detonation.

The Flow and Combustion Engineering Division at the Forschungszentrum Karlsruhe (FZK) carried out radiolysis gas ($2H_2+O_2$) explosion experiments in a smooth tube [9] after the two radiolysis gas explosion accidents. Radiolysis gas is generated due to the enhanced water dissociation in a radiation field, which takes place mainly in the cores of operating BWRs. The hydrogen to oxygen ratio for radiolysis gas is usually close to the stoichiometric value. The objectives of the experiments are as follows: (1) Investigation of the effect of radiolysis gas detonation pressures on the structural response of a U-shape stainless steel tube, (2) Combined pressure and strain measurements during the detonation of a stoichiometric hydrogen-oxygen mixture at different initial pressures up to 70 bar, (3) Investigation of the DDT process in a smooth tube for a stoichiometric hydrogen-oxygen mixture at elevated initial pressures from 1 to 70 bar and ambient temperatures from 290 to 300 K.

In the present study, aiming at the third objective of the experiments, a numerical analysis is

performed to simulate one of the experiments described above by the use of the 3-dimensional turbulent combustion analysis code COM3D, which has been developed in FZK. In order to simulate a DDT process, an improvement is added to the reaction rate constant of the COM3D code, and then the DDT process is calculated and the numerical result is compared with the experimental result.

2. Outline of Radiolysis Gas Explosion Experiments [9]

This chapter describes the outline of the radiolysis gas explosion experiments.

The details of the transient combustion behavior of radiolysis gas under the typical conditions of BWRs are uncertain. In the experiments, run-up-distances, DDT processes and detonation characteristics in radiolysis gas explosions at various initial pressures were investigated.

The experiments on the radiolysis gas ($2H_2+O_2$) explosion were carried out using a smooth DN-15 stainless steel tube of 6 m in length with standard U-shape geometry. The tube is 21.3 mm in outer diameter and 2.9 mm in thickness. The schematic drawing of the tube used in the experiments are shown in Fig. 1. The actual dimensions of the tube and its U-shape configuration were chosen in such a way as to be representative of tubes available in BWR plants. DN-15 tubes are installed frequently in German BWRs for instrumentation purposes. The tube was equipped with five ports for pressure measurements located on the cylindrical tube surface (P1–P5), one port for the ignition plug at the tube cover and one port for the gas mixture inlet and the combustion products outlet at the cylindrical surface.

The conditions for the DDT in stoichiometric hydrogen-oxygen mixtures were studied experimentally in the DN-15 tube for a wide range of initial pressures from 0.5 to 70 bar (0.05 to 7 MPa) at an ambient temperature of about 300 K. The stoichiometric hydrogen-oxygen mixtures are the most energetic gas composition.

As a result of the experiments, a strong effect of the initial radiolysis gas pressure on the DDT process was observed, and it was found that the run-up-distance from the ignition position to the DDT occurrence point is inversely proportional to the initial pressure to the power of two thirds. The run-up-distance was evaluated from the experimental results as follows:

$$r_D = 0.42 p_0^{-0.66} \quad (1)$$

where r_D is the run-up-distance (m) and p_0 is the initial pressure of the gas mixture (bar).

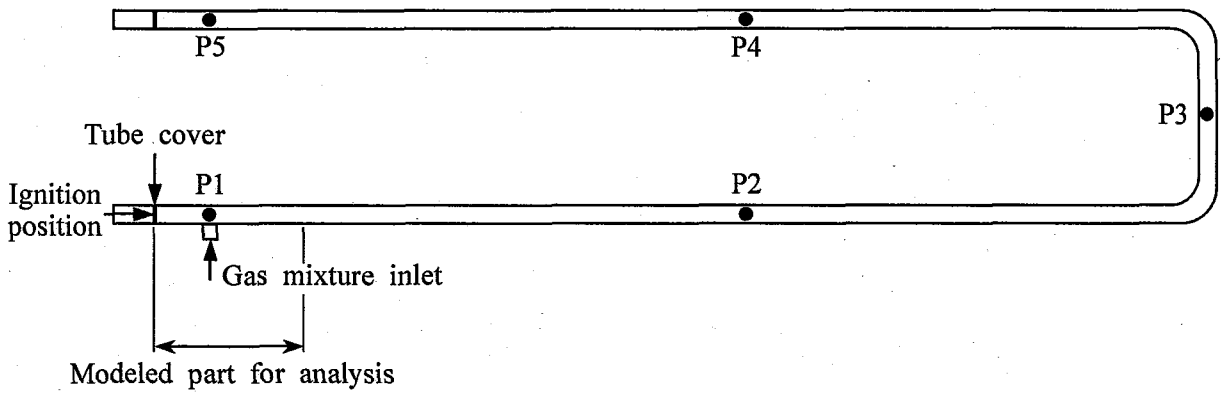

Fig. 1 Schematic drawing of the U-shape DN-15 tube used in the experiments.

3. Outline of COM3D Code

The COM3D code is a 3-dimensional turbulent combustion and explosion analysis code, and the code is applicable for the wide range of hydrogen combustion regimes from slow deflagrations to detonations. The development of the COM3D code has been continued in FZK [10] [11]. This chapter describes the outline of the COM3D code.

3.1 Gas Dynamic Model

The gas dynamic model includes the Favre-averaged conservation laws of total mass, momentum, energy and species mass as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho u_j\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=\rho g_i-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j},\quad i=1,2,3 \tag{3}$$

$$\frac{\partial}{\partial t}\left(\rho e\right)+\frac{\partial}{\partial x_j}\left\{\left(\rho e+p\right)u_j\right\}=\rho g_j u_j+u_i\frac{\partial \tau_{ij}}{\partial x_j}+\frac{\partial}{\partial x_j}\left\{\frac{\mu_{tur}}{C_h}\frac{\partial}{\partial x_j}\left(e-\frac{1}{2}u_i u_i+\frac{p}{\rho}\right)\right\}+B+\rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}\left(\rho f_\alpha\right)+\frac{\partial}{\partial x_j}\left(\rho u_j f_\alpha\right)=\overline{\dot{\omega}}_\alpha+\frac{\partial}{\partial x_j}\left(\frac{\mu_{tur}}{C_{f_\alpha}}\frac{\partial f_\alpha}{\partial x_j}\right) \tag{5}$$

where

$$\tau_{ij}=-\frac{2}{3}\delta_{ij}\left(\rho k+\mu_{tur}\frac{\partial u_k}{\partial x_k}\right)+\mu_{tur}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{6}$$

$$e=\sum_{\alpha=1}^{N}\frac{f_\alpha}{\mu_\alpha}\left(h_\alpha+\Delta h_\alpha^0-RT\right)+\frac{1}{2}u_j u_j \tag{7}$$

$$\mu_{tur}=\mu+C_\mu\rho\frac{k^2}{\varepsilon} \tag{8}$$

$$B=\frac{\mu_{tur}}{C_p}\frac{1}{\rho^2}\frac{\partial \rho}{\partial x_k}\frac{\partial p}{\partial x_k} \tag{9}$$

$$f_\alpha=\frac{\rho_\alpha}{\rho} \tag{10}$$

$$\overline{\dot{\omega}}_\alpha=C_f\times F \tag{11}$$

In the above equations, t is the time, x is the axial coordinate, ρ is the density, u_i is the velocity in coordinate direction i, g is the gravitational acceleration, p is the static pressure, τ_{ij} is the stress tensor given by Eq. (6), e is the total energy given by Eq. (7), μ_{tur} is turbulent viscosity given by Eq. (8), C_h, C_{f_α} and C_μ are the constants, f is the mass fraction, $\overline{\dot{\omega}}_\alpha$ is the mean reaction rate, δ_{ij} is the Kronecker's delta, k is the turbulent kinetic energy, ε is the turbulent kinetic energy dissipation rate, μ is the viscosity, h is the enthalpy, R is the gas constant, T is the temperature, C_p is the specific heat at constant pressure, C_f is the reaction rate constant, F is the reaction rate modeled by the

CREBCOM code [12], and α is the gas component.

3.2 Turbulence Model

The standard k-ε model is available to solve turbulent flow as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho u_j k)=S-\rho\varepsilon+\frac{\partial}{\partial x_j}\left(\frac{\mu_{tur}}{C_k}\frac{\partial k}{\partial x_j}\right) \tag{12}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho u_j \varepsilon)=\frac{\varepsilon}{k}(C_1 S-C_2\rho\varepsilon)+\frac{\partial}{\partial x_j}\left(\frac{\mu_{tur}}{C_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) \tag{13}$$

where

$$S=\frac{\partial u_i}{\partial x_j}\tau_{ij}-B \tag{14}$$

In the above equations, C_1, C_2, C_k and C_ε are the turbulence model constants. In the present numerical simulation, the turbulence model was not used because the CREBCOM code, which is explained in section 3.4, was used as a turbulent combustion model.

3.3 Thermodynamic Model

The thermodynamic model offers the thermophysical properties of four gas components (H_2, O_2, N_2, H_2O). The thermophysical properties of these gases are calculated with polynomial fitting functions dependent on temperature based on the JANAF data.

3.4 Chemistry Model

The CREBCOM code [12] is used as a combustion model. The CREBCOM code can be applied to simulate all possible ranges of hydrogen combustion regimes from slow deflagrations to detonations, and it gives a conservative estimation of loads from hydrogen combustion based on a combination of empirical criteria and correlations. It has already been verified that the code can give reliable estimations of maximum flame speeds and the maximum level of overpressure.

3.5 Numerical Scheme

In order to solve the previous equations, a first-order windward scheme is used instead of a TVD (Total Variation Diminishing) scheme in terms of the stability of DDT and detonation calculations. The TVD scheme is a standard solution method in the COM3D code, and the scheme is adequate for the calculations of deflagrations. The windward scheme is adequate for the calculations of detonations. Comparing the calculation results of the windward scheme and the TVD scheme in the case of the present numerical simulation, the authors confirmed that the windward scheme had a

better accuracy. The equations are solved on a 3-dimensional Eulerian Cartesian grid.

4. Numerical Analysis

A numerical analysis is performed to simulate one of the radiolysis gas explosion experiments by the use of the COM3D code. In this chapter, the analytical model, the results and the discussion of the numerical analysis are described.

4.1 Analytical Model

Fig. 2 shows the analytical domain for the present calculation. A short part of the experimental tube shown in Fig. 1 was modeled by a rectangular cylinder composed of rectangular cells. The range of the analytical domain is 15.5 mm (20 cells) in the x-direction, 15.5 mm (20 cells) in the y-direction and 387.5 mm (500 cells) in the z-direction, and so the length of the one cell is 0.775 mm. The geometry model of the numerical analysis uses a three-dimensional Cartesian grid with a total of 0.2 million computational cells to model the domain. The analytical domain is divided into two parts: a gas region and a solid region. Slip boundary conditions are applied to all the boundaries. Fifty-one pressure gauges and light gauges to record pressure and flame propagation velocity are installed on the inner surface of the tube at every 10 cells in the z-direction. The explosion experiment of a stoichiometric hydrogen-oxygen mixture at an initial pressure of 5 bar (0.5 MPa) and an initial temperature of 36°C in the tube is simulated with the COM3D code. A length of 387.5 mm (500 cells) in the z-direction is long enough to reach the DDT point from the ignition position when the length is compared with the run-up-distance 145.2 mm (187.3 cells) evaluated from Eq. (1). For the stoichiometric hydrogen-oxygen mixture with an initial pressure of 5 bar and an initial temperature of ambient temperature, the Chapman-Jouguet pressure (CJ-pressure) is 98.9 bar, the Chapman-Jouguet velocity (CJ-velocity) is 2932 m/s and the Chapman-Jouguet temperature (CJ-temperature) is 4000 K.

4.2 Modeling of C_f Value

The CREBCOM combustion model of the COM3D code contains a reaction rate constant C_f, which must be obtained empirically from experimental results. A large series of calculations for turbulent combustion experiments with different hydrogen concentrations and blockage ratios confirmed a value of $C_f = 6 \pm 1$ for a great variety of deflagration experiments. However, DDT doesn't occur if C_f is a constant value. The COM3D code with the constant value of C_f can not calculate the rapidly flame acceleration in a DDT process. The appropriate modeling of C_f is needed for the simulation of the DDT process.

In the present study, C_f is assumed to be an exponential function, and C_f is changed every time step until C_f reaches $C_{f,\max}$. After reaching $C_{f,\max}$, C_f is a constant value of $C_{f,\max}$. The functional expression of C_f is assumed as follows:

$$C_f = C_{f0}\exp\left\{\frac{\ln(C_{f1}/C_{f0})}{t_{CJ}}t\right\} \quad (C_f = C_{f,\max} \text{ after reaching } C_{f,\max}) \tag{15}$$

where C_{f0} is the value at $t=0$, C_{f1} is a constant value, t_{CJ} is the onset time of DDT, and $C_{f,\max}$ is a maximum value of C_f. t_{CJ} is evaluated from Eq. (1) and the CJ-velocity. C_{f1}, $C_{f,\max}$ and t_{CJ} must be adjusted in accordance with the experimental results. For the calculation of an initial pressure of 5 bar, $C_{f0}=6$, $C_{f1}=200$, $C_{f,\max}=120$ and $t_{CJ}=5\times4.952\times10^{-5}$ were used. The time history diagram of the C_f value expressed by Eq. (14) is shown in Fig. 3.

4.3 Results and Discussion

A numerical simulation was performed with the COM3D code under the same conditions as the experiment previously described above.

Fig. 4 shows the time history diagram of the pressures at thirteen different positions recorded by the pressure gauges along the tube. The peak pressure at each position increases with time as the pressure wave moves to the downstream. After the pressure reaches the maximum at the position of 280 cell (217 mm away from the ignition position), it gradually decreases. The maximum peak pressure is 18.3 MPa, which is 85.4% higher than the theoretical CJ-pressure of 9.89 MPa. It is inferred from the pressure rise that DDT occurs.

The maximum peak pressure observed at a DDT process is higher than the theoretical CJ-pressure since, just after the onset of DDT, the detonation wave propagates in a pre-compressed gas mixture with a pressure much higher than the initial gas pressure [13]. The CJ-pressure is achieved only at the later stage of detonation wave propagation.

Fig. 5 shows the position-time diagram of the pressure waves. This figure shows the calculated pressure-time histories as the function of the position along the tube. It is found in this figure that the DDT occurs at around the position of 200 cell (155 mm away from the ignition position) because the pressure wave moves at a constant velocity after the position of 200 cell. The run-up-distance evaluated from Eq. (1) is 145.2 mm (187.3 cells) from the ignition position. It can be said that the numerical result of the DDT point is in good agreement with the value evaluated from Eq. (1).

Fig. 6 shows the flame propagation velocity distribution in the tube evaluated from the data recorded by the light gauges. The flame propagation velocity is accelerated with the pressure wave until a detonation occurs. After the onset of the detonation, the flame propagates at a constant velocity of about 2908 m/s, which is just a little smaller than the theoretical CJ-velocity of 2932 m/s. It can be said that the numerical result of the CJ-velocity is in good agreement with the theoretical CJ-velocity.

Fig. 7 shows the comparison of numerical and experimental pressure transients at the same pressure recorded point (180 cell and P1). The peak pressure of the calculation is 42.3% higher than the experimental peak pressure. The maximum value of C_f ($C_{f,\max}=120$) may be large. However,

the pressure change shows a similar tendency between the calculation and the experiment.

Figs. 8–12 show the 2-dimensional pressure distributions, temperature distributions, H_2 concentration distributions, schlieren images and z-velocity distributions at each time as the reference of the calculation results. In these figures, the white parts show the highest values, and the black parts show the lowest values. As shown in Figs. 8–12, a high-pressure region exists in front of the reaction zone with a high temperature region and a 0% H_2 concentration region after 2.3480×10^{-4} sec. It is the characteristics of a detonation wave. It can be found from the maximum velocity shown in Fig. 12 that the z-velocity of the shock wave front reaches a constant velocity of about 2500 m/s after the z-velocity rapidly accelerates until 2.3480×10^{-4} sec, and the DDT may occur at around 2.3480×10^{-4} sec.

As shown in these calculation results, the COM3D code with the C_f value of the exponential function can simulate the DDT process.

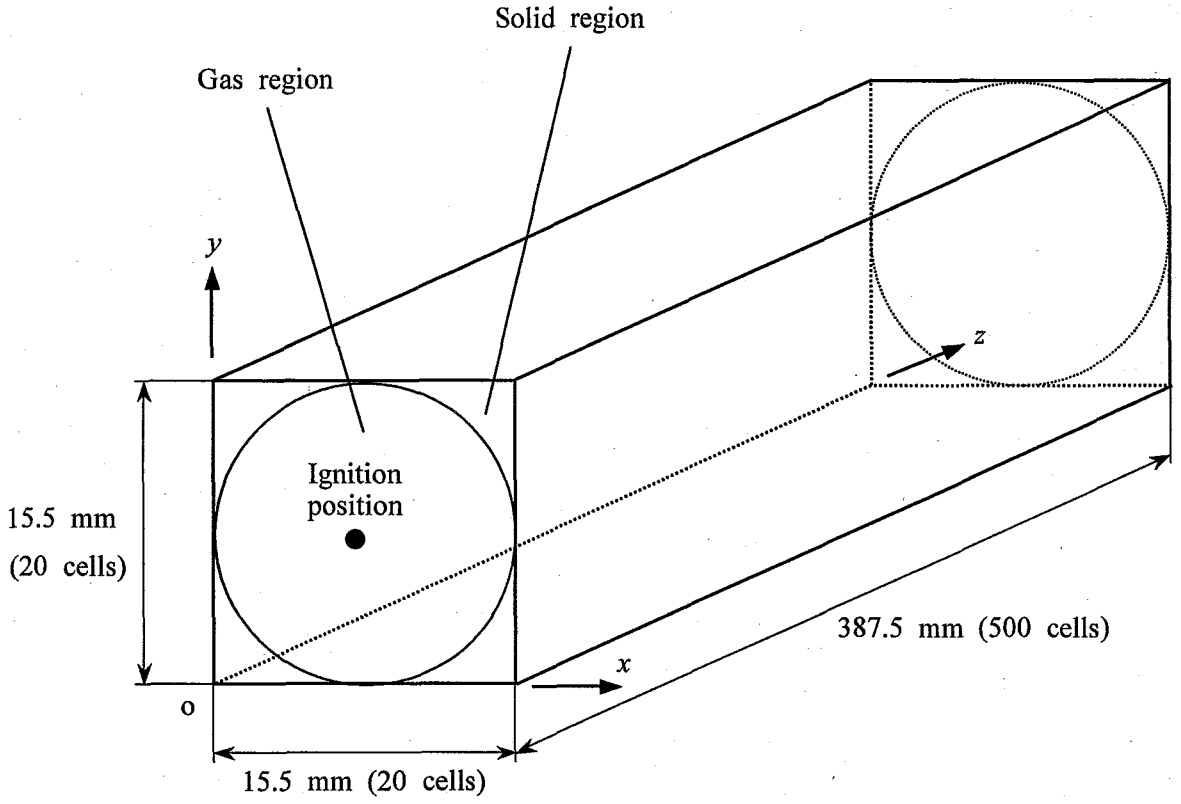

Fig. 2 Schematic drawing of the analytical domain.

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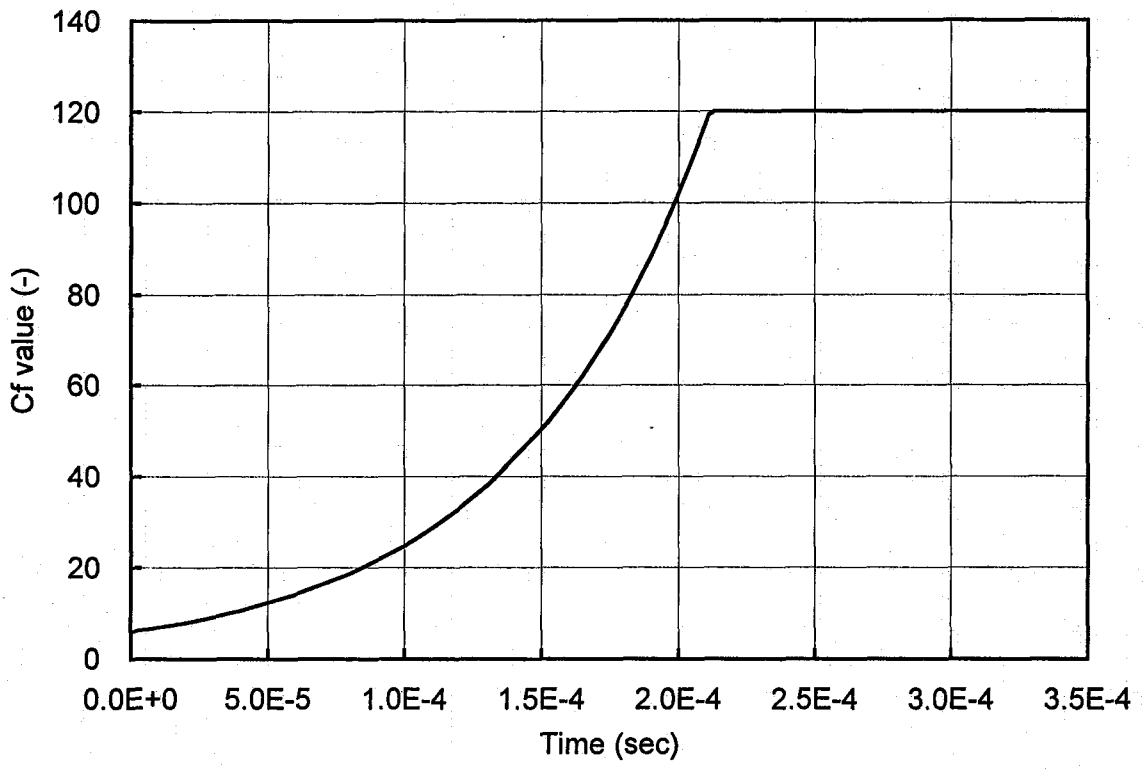

Fig. 3 Time history diagram of the C_f value.

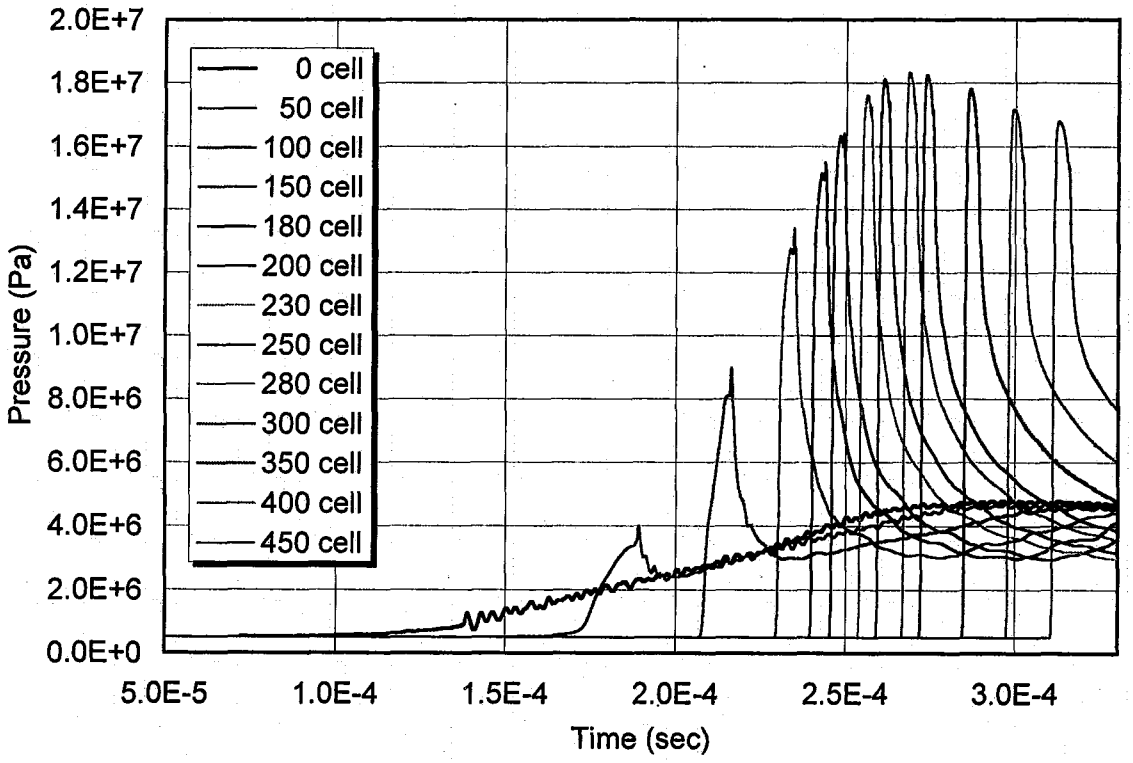

Fig. 4 Time history diagram of the pressures at different positions along the tube.

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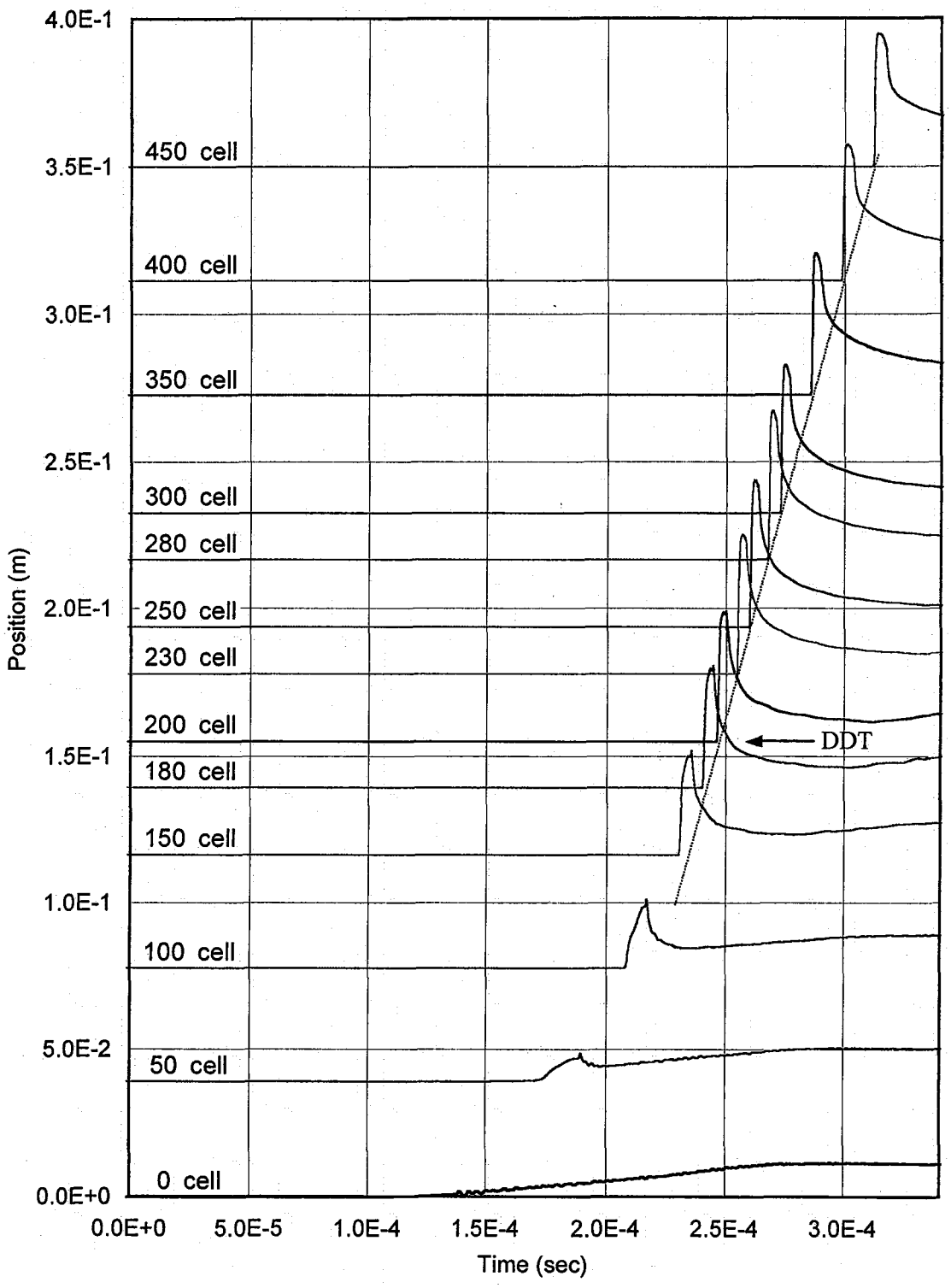

Fig. 5 Position-time diagram of the pressure waves.

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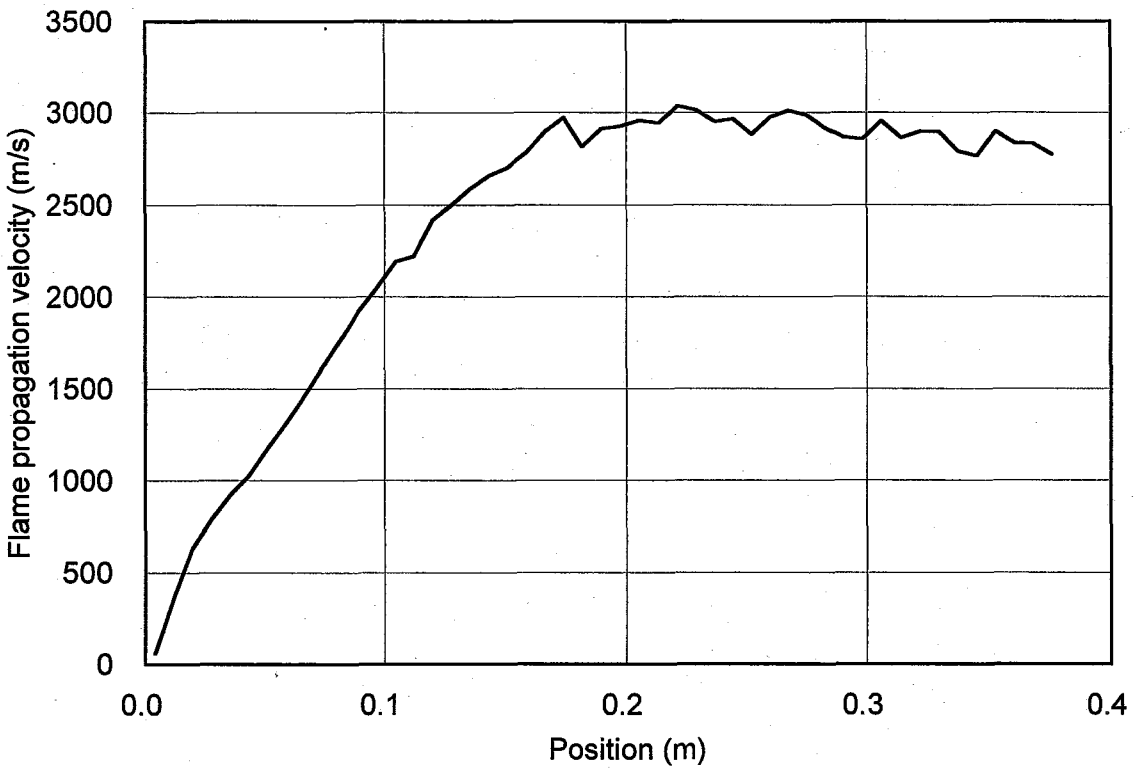

Fig. 6 Flame propagation velocity distribution in the tube.

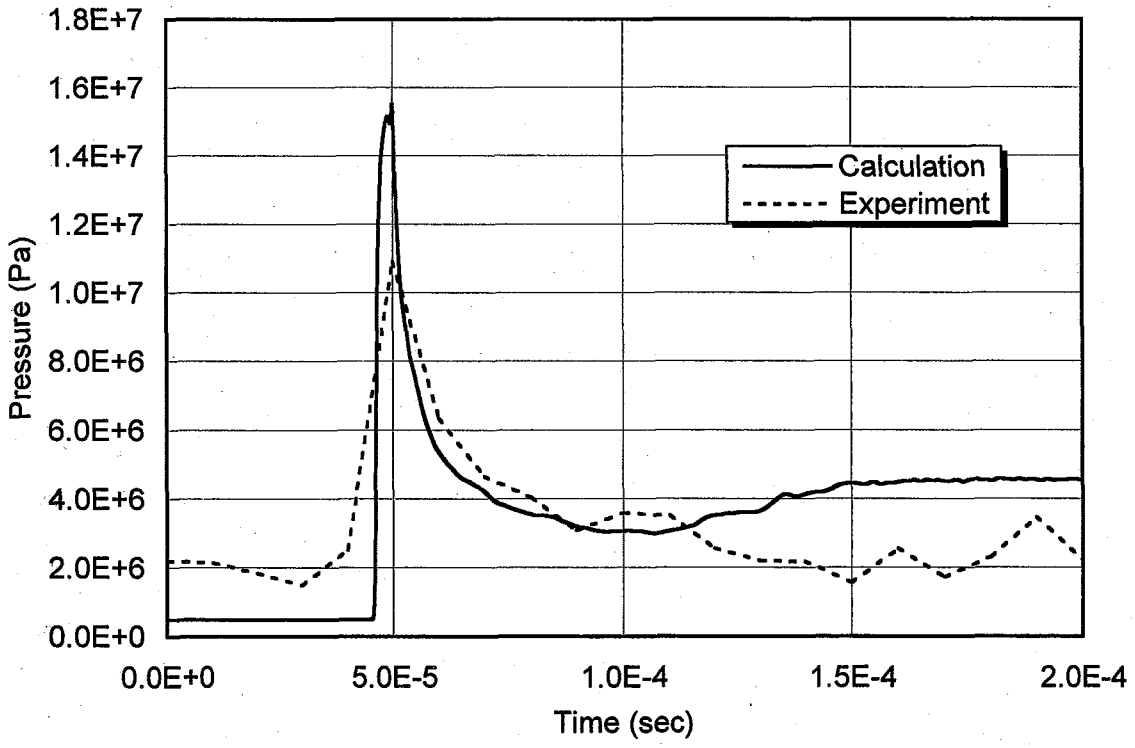

Fig. 7 Comparison of numerical and experimental pressure transients.

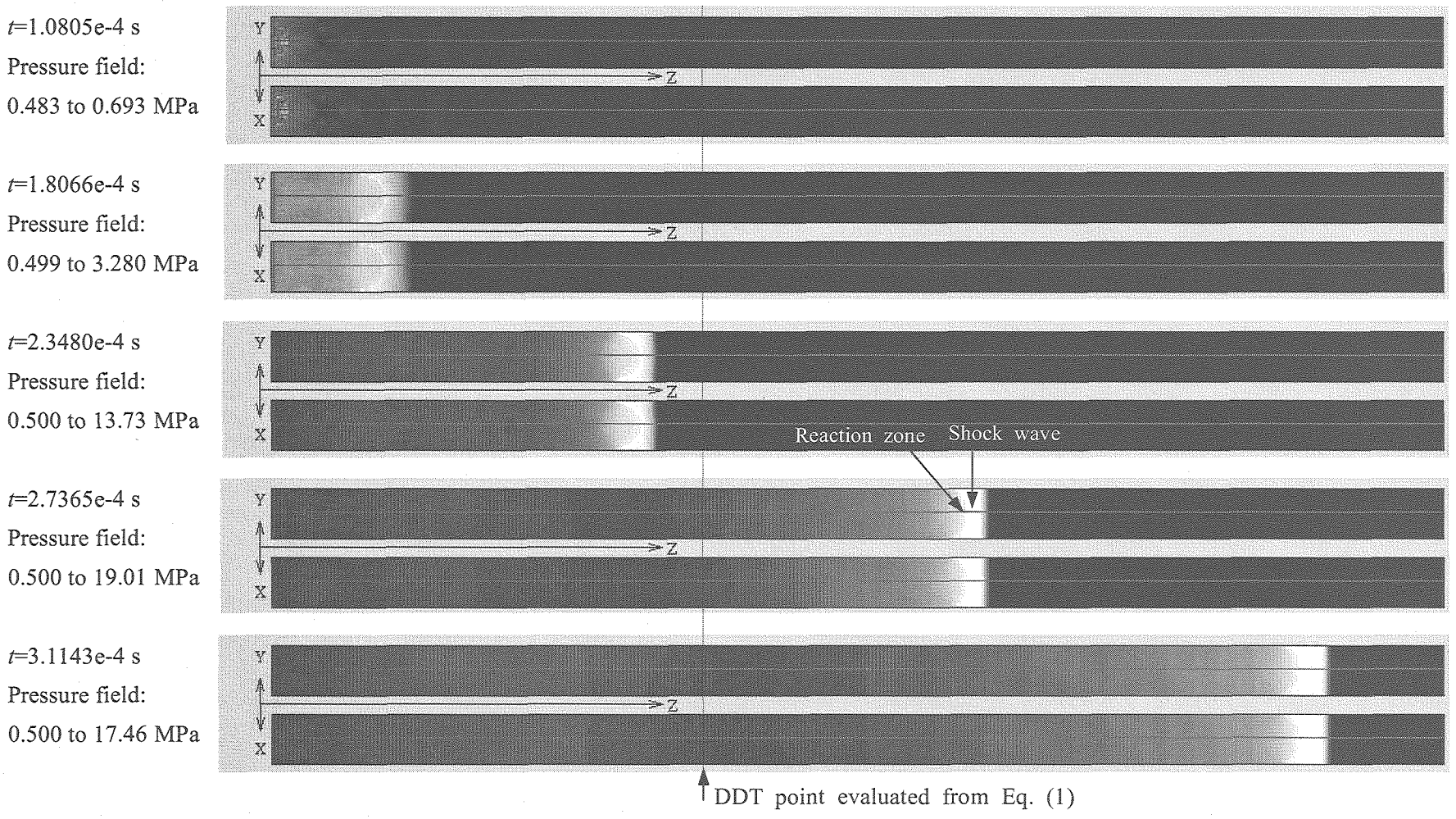

Fig. 8 2-dimensional pressure distributions in the tube at each time.

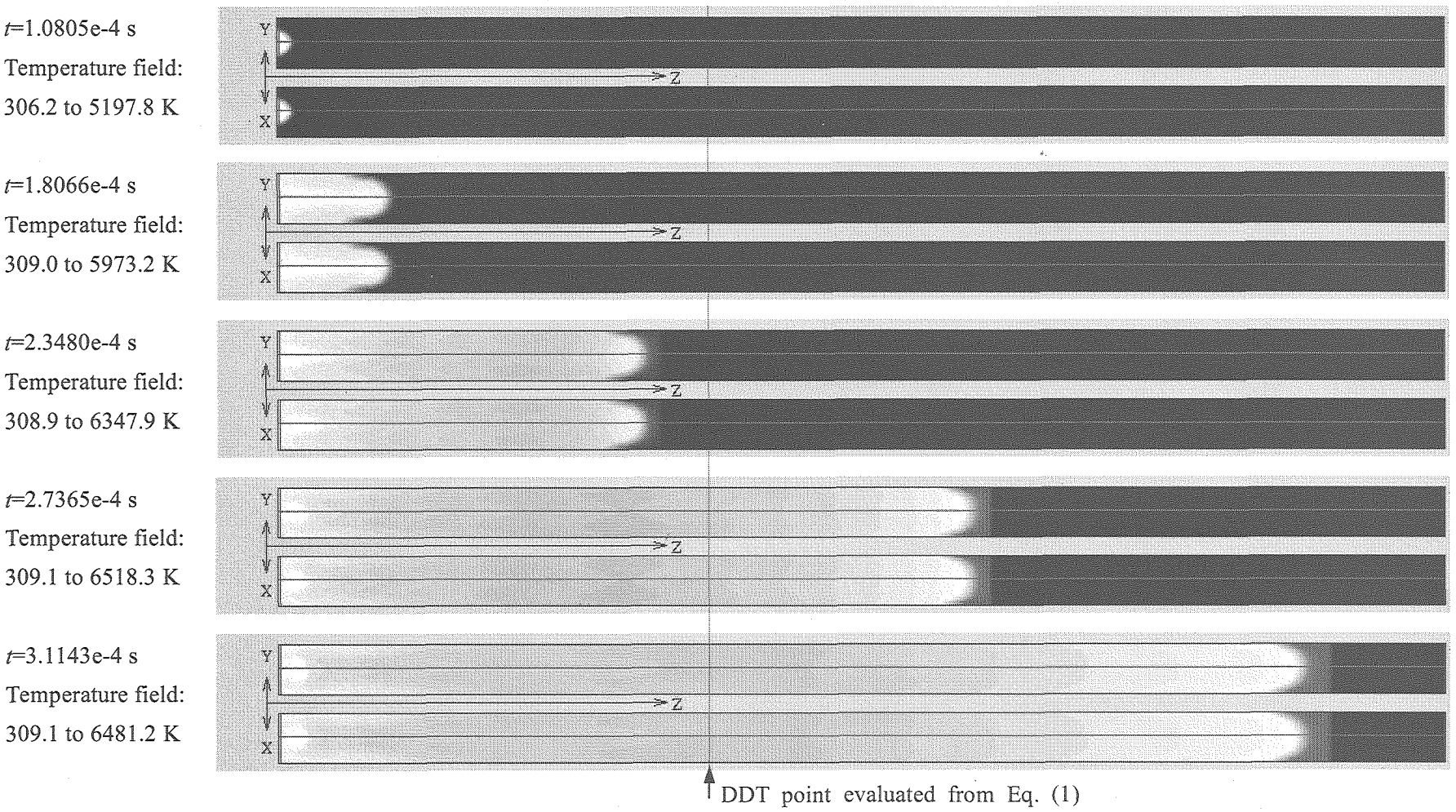

Fig. 9 2-dimensional temperature distributions in the tube at each time.

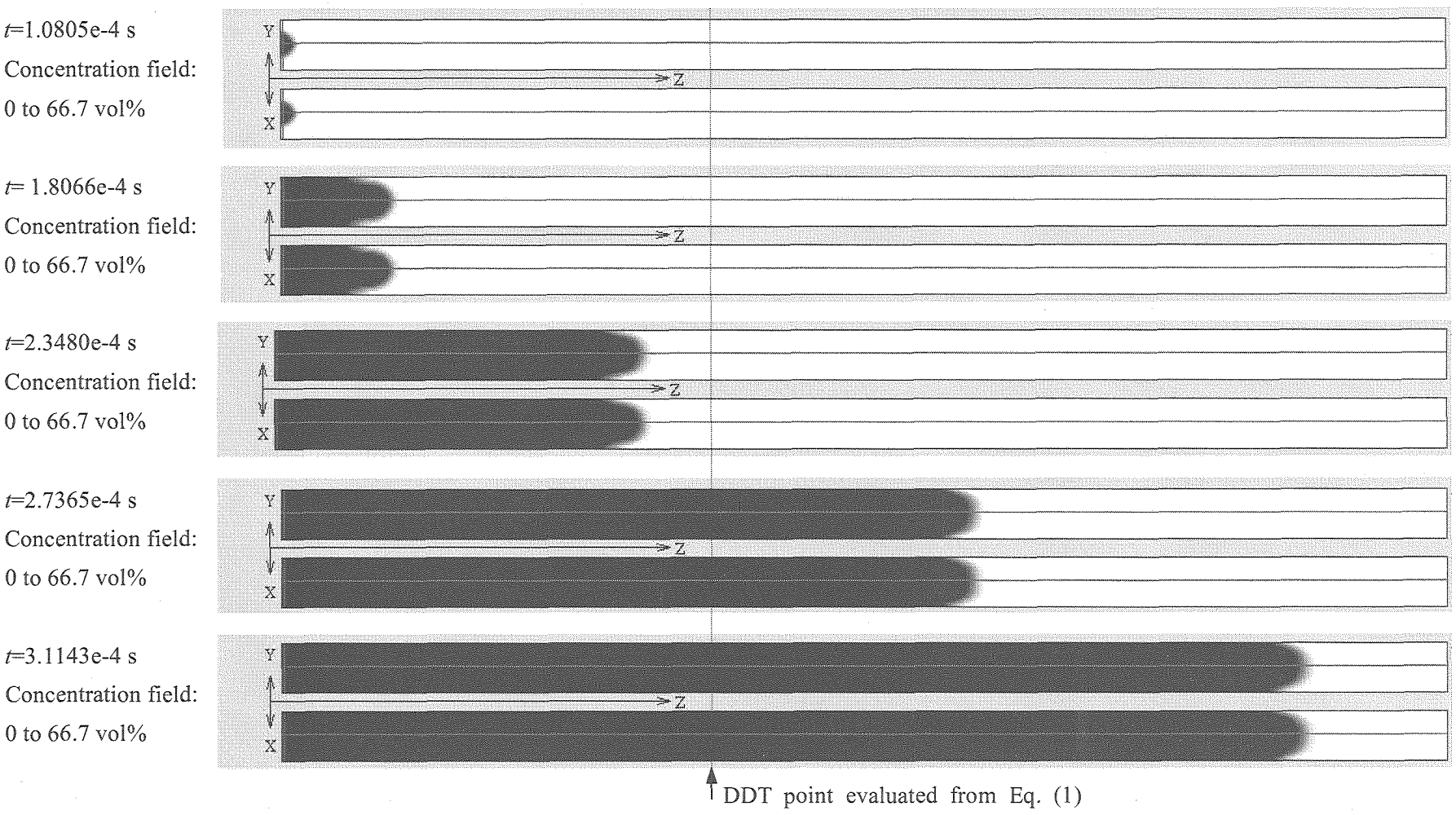

Fig. 10 2-dimensional H_2 concentration distributions in the tube at each time.

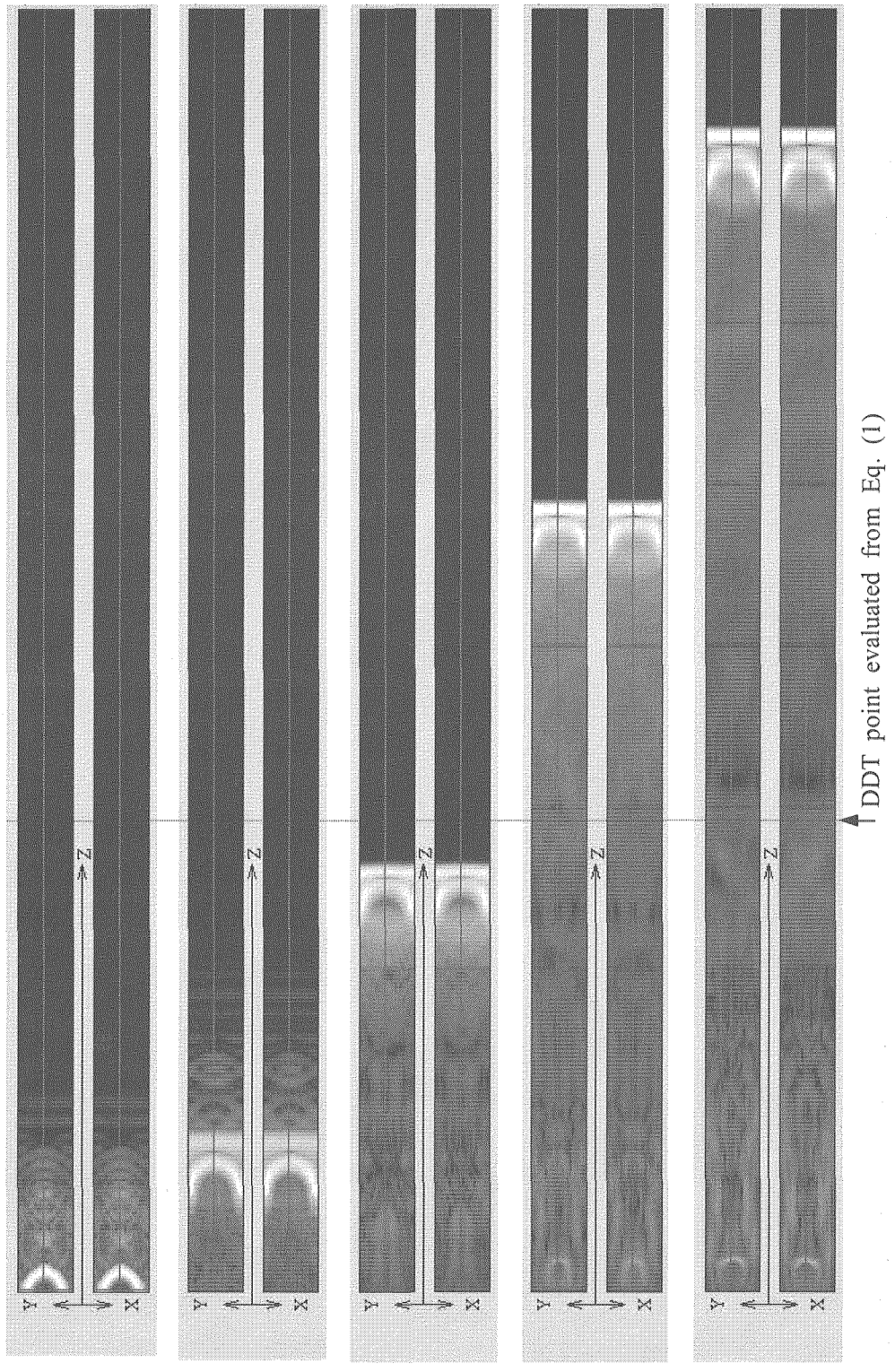

Fig. 11　2-dimensional schlieren images in the tube at each time.

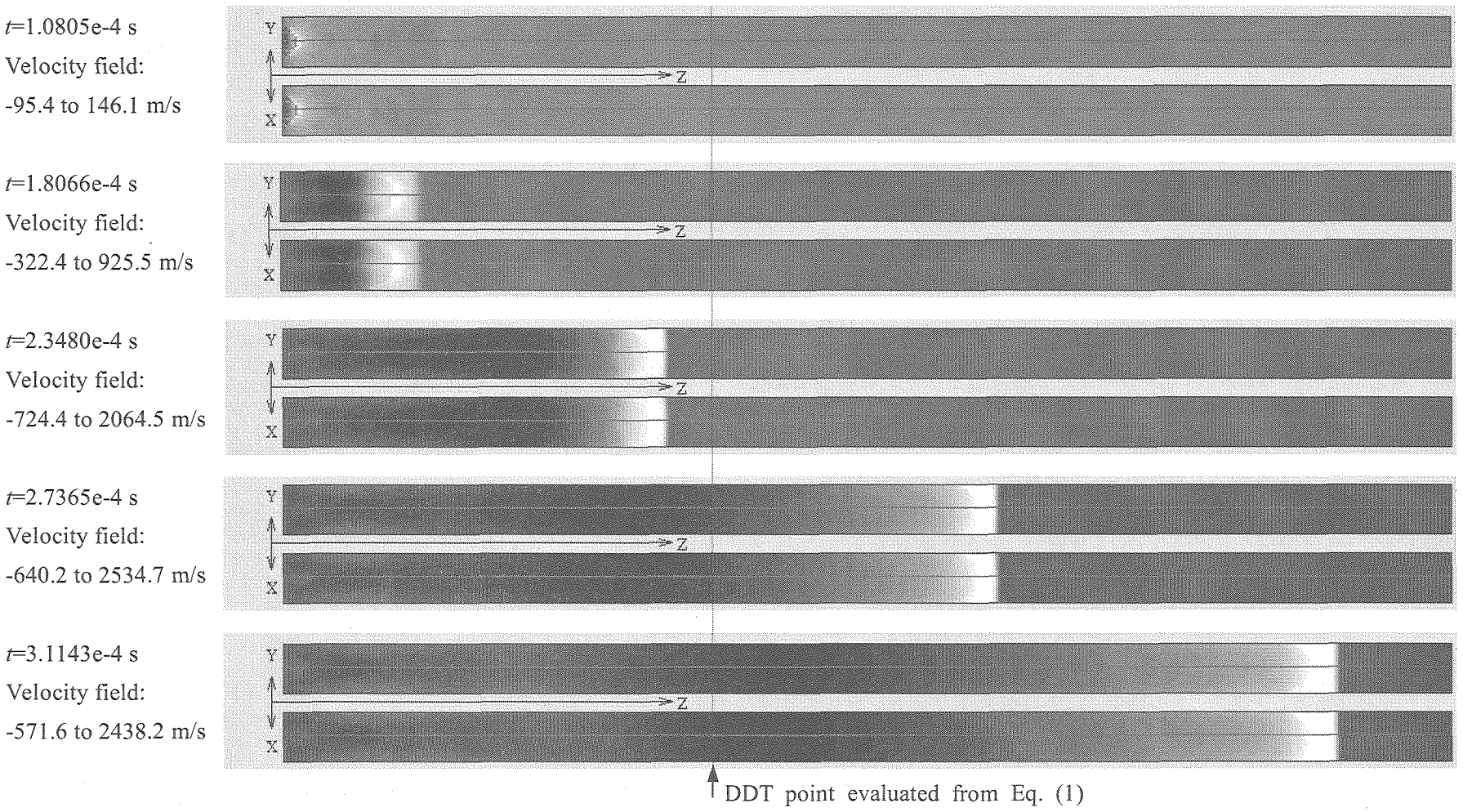

Fig. 12 2-dimensional z-velocity distributions in the tube at each time.

5. Concluding Summary

In the present study, the numerical analysis, which simulated one of the radiolysis gas explosion experiments using a smooth tube, was performed with the COM3D code, and the DDT process was calculated. The calculated DDT point was in good agreement with the experimental one, and the flame propagation velocity in detonation was in good agreement with the theoretical CJ-velocity.

As a result, it was shown that the COM3D code with the appropriate model of C_f value can simulate the DDT process in the tube.

As a future task, it is necessary to compare numerical results with the other experimental results in order to derive the more general form of the C_f value.

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国際単位系 (SI) と換算表

表 1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J

1 u=1.66054×10^{-27} kg

表 3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1 nm=10^{-10}m

1 b=100 fm^2=10^{-28} m^2

1 bar=0.1 MPa=10^5Pa

1 Gal=1 cm/s^2=10^{-2} m/s^2

1 Ci=3.7×10^{10}Bq

1 R=2.58×10^{-4}C/kg

1 rad=1 cGy=10^{-2}Gy

1 rem=1 cSv=10^{-2}Sv

表 5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s=10^4St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）

= 4.184 J　（熱化学）

= 4.1855 J （15 °C）

= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）

= 75 kgf·m/s

= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

Numerical Analysis on Deflagration-to-Detonation Transition of a Hydrogen-Oxygen Mixture in a Smooth Tube