Applicability Range of Detonation Resonator

Shiro TAKI[1], Toshi FUJIWARA[2] and Yoshito UMEDA[3]

[1] Department of Mechanical Systems Engineering, Hiroshima University, Kagami-yama 1-4-1, Higashi-Hiroshima 739-8527, Japan. Email: taki@mec.hiroshima-u.ac.jp

[2] ATES Corporation, Tanaka-Cho 1-118-3, Toyota 471-0845, Japan. Email: fujiwara-t@ates-net.co.jp

[3] Fundamental Research Department, Toho Gas Company Ltd, Shinpo-Machi 507-2, Tokai-City 476-8501, Japan. Email: umeda@tohogas.co.jp

Corresponding Author: Toshi Fujiwara, ATES Corporation.

Extended Abstract

A numerical analysis is given to the resonant detonation phenomenon that occurs in a small cavity containing a fictitious gas mixture constantly supplied from a high-pressure reservoir. The acquired resonant frequency for cyclic and continuous detonation generation is found to be about 4-5 kHz, which is much lower than the value 25 kHz experimentally observed by Levin et al [1, 2].

A high-frequency detonation resonator has been experimentally studied by Levin and his Russian group for several years [1-4], followed by a GE group in recent years [5, 7], in view of its scientifically interesting characters and possibility of finding out some fields of application like PDE. Although the original experiments are interesting, there are several features to be clarified for more extensive studies. Two-stage combustion is utilized to generate continuous resonant detonations with an extremely high frequency 25 kHz in a 70mm-diameter hemispherical cavity. The advantages of the detonation resonator over the conventional PDE can be considered as (1) valveless, (2) continuous fuel supply, and (3) virtually no DDT processes leading to short detonation tube or cavity.

In view of great potential applicability of detonation resonator, it seems to be necessary, first of all, to explore and understand what is going on in the phenomenon of resonant detonation in a small cavity. In order to perform this, the best method is to simulate the phenomenon using a numerical analysis. However, it would not be very easy to let a realistic gas mixture perform highly-repeating detonation resonance, because the resonant detonation occurred or existed only as the second-stage combustion in the experiment done by Levin et al. In the future application, moreover, it would be much more helpful to run the resonant detonation in a fresh mixture as first-stage combustion. From such fundamental needs, we came to the conclusion to utilize a fictitious gas mixture representing as much as possible some kind of hydrocarbon-air. The readers can see the physico-chemical properties of the present mixture.

A high resonant frequency like 5-25 kHz essentially needs very fast purging of the burnt gas from the previous cycle, naturally to prepare for the next cycle detonation ignition and propagation. This aspect needs clarification by observing the detailed evolution of steady one cycle [7].

Although we wanted to observe resonant detonation in a larger cavity (larger than the experimental resonator diameter D = 70mm), we had no time to simulate the resonant detonation in larger cavities. We only tested the analysis for a smaller cavity D = 50mm.

Governing equations are the axi-symmertric (x, r, t) Euler equations with no transport phenomena, where the gas mixture is treated both thermally and calorically perfect under no influence of chemical reaction; the specific heat, the specific heat ratio and the molecular weight are assumed constant. Thus, the wall surfaces including the reservoir wall are considered slip, adiabatic and non-catalytic.

The initial conditions: The cavity and surrounding open space are filled with the standard air, whereas the reservoir with a high-pressure gas mixture at 20atm, as shown in Fig.1 and Table 1.

The geometry of detonation resonator: As shown in Fig.1, the resonating cavity is an axi-symmetric hemi-sphere having a thin 1-mm slit nozzle on its periphery, through which a combustible mixture is injected from a high-pressure reservoir.

Due to adoption of a fictitious gas mixture, a two-step chemical reaction model initially proposed by Korobeinikov and Levin is utilized, where the chemical reaction is described by the two progress variables α (induction reaction) and β (recombination reaction).

The utilized numerical technique is an explicit MacCormack-FCT method, where a solution-adaptive multi-level grid refinement method is used to significantly reduce the number of grids for the entire domain of calculation [x = 450mm, r = 200mm encompassing the hemi-spherical cavity of D = 70mm]. Using the 3-fold multi-grid system where a factor 1/3 smaller size for each one-level higher grid size, the allover downsizing of grid is $(1/3)^2 = 1/9$. Here, however, we must confess that starting from the coarse grid size 1mm, the finest size becomes 1/9mm; this value is definitely insufficient to describe the length of induction reaction L_{ind}= 0.3062micron = 0.3062 x 10^{-3}mm for C-J detonation given in Table 3. Due to the coarseness of the grid, we tend to introduce strong dissipation caused by artificial viscosity, which can play the role of large turbulent viscosity, and as a result the ignition characteristics of the present fictitious gas mixture would be on the safety side (more difficult to observe detonation resonance) of calculation.

In the present numerical analysis, a fresh combustible mixture is injected through a narrow nozzle into a hemispherical cavity having the geometry [Fig.1] almost identical to the original experiment by Levin et al [1-4]. Note here that the injection nozzle slit in axi-symmetric geometry can be interpreted as numerous small nozzles distributed along the cavity periphery. The physico-chemical properties of combustible mixture are chosen to give a low combustion initiation temperature range 471-573K (the results of calculation), for Cases B-0 through B-3. The C-J detonation properties of this gas are given in Table 2, giving the CJ detonation velocity 1732.71m/sec for Case B-1. The initial conditions in the reservoir and cavity for Case B-1 are respectively [constantly maintained at 350K, 20atm] and [293.15K, 1atm], as shown in Table 3. Fig.3 indicates that a high-pressure combustible mixture is nearly continuously injected from the reservoir into the low-pressure/-temperature cavity. Thereafter, the entire phenomena including spontaneous ignition are automatically controlled by naturally-cyclic (1) shock-focusing (2) ignition, (3) detonation, (4) purging of burnt gas, (5) fuel-supply, and (6) shock-focusing processes. Fig.3 for Case B-0 gives one cycle time Δt = (1.50 – 1.28) msec = 220microsec, giving the rough resonant frequency 1/0.22msec = 4.55kHz, as shown in Table 1. The velocity of detonation propagation is given by observing the pressure distribution, which is the detailed behaviors of wave propagation during t = 1.420 – 1.440msec. After ignition at t = 1.422msec, the detonation reaches the cavity wall at t = 1.440msec, which gives the propagation velocity D = 35mm/18microsec = 1944m/sec. Roughly speaking, this value is quite close to the Chapman-Jouguet Velocity 1733m/sec given in Table 2. Apparently, therefore, the detonation occurs in a resonant manner, as indicated by the periodic (about 0.2msec) behaviors of thrust and mass flow rate in Figs.2-3. The numerical analysis shows that a limit cycle has been rapidly reached after 0.3msec or 1-2 cycles, since the cyclic behaviors in the physical quantities in Figs.2-3 indicate the establishment of nearly steady oscillation.

Observation of unburned gas mixture during one cycle at t = (1.26-1.50) msec in Fig.4 gives the following evolution of individual processes. (1) Detonation eats up the combustible mixture very quickly during t = (1.42-1.44) msec. (2) Thereafter, due to the penetration of high pressure back into the combustible mixture-supply nozzle/reservoir, the combustible gas practically ceases to be injected into the cavity, which corresponds to the period of low/negative mass flow rate seen in Fig.2. Due to extremely high pressures generated by a detonation inside the cavity, the choking condition between the reservoir and cavity pressures is obviously violated, reducing the combustible supply rate from the constant steady value.
(3) By injecting the combustible gas from the periphery of hemi-sphere cavity, a part of the jet is directed and trailing to the downstream direction, the detonation of which may not too much contribute to the thrust.

The thrust is defined and calculated by integrating the pressure difference over the surface of cavity. The temporal evolution of the thrust T(t) for Case B-0 is shown in Fig.2, indicating that (1) a higher injected combustible temperature like 350K gives a lower thrust/specific impulse due to lower mass density, even if the resonant frequency increases up to f = 4.70kHz, (2) the significant increase of heat of reaction Q from 2.10 to 2.80 MJ/kg increases the resonant frequency to f = 4.43kHz, but contributes to the decrease of Isp (from 1450 to 1310sec), (3) when the rate constant of induction reaction k_a was halved (Case B-3), interestingly, both the resonant frequency f and specific impulse Isp increased.

As a result of the present numerical analysis, we have discovered certain aspects of detonation resonator, even though we must admit that our numerical study still needs a lot of improvements. We can conclude: (1) Nearly every 2nd shock focusing generates detonation. (2) A limit cycle is rapidly reached, where the detonation resonant frequency about 5kHz is one half of the non-reactive gas resonant frequency 10kHz. (3) The resonant frequency seems to depend not much on the induction reaction rate, but more on the temperature of cavity gas. (4) We should further study the generation of resonant detonation on the wider range of parameters; geometry, realistic combustible mixtures, ambient conditions etc.

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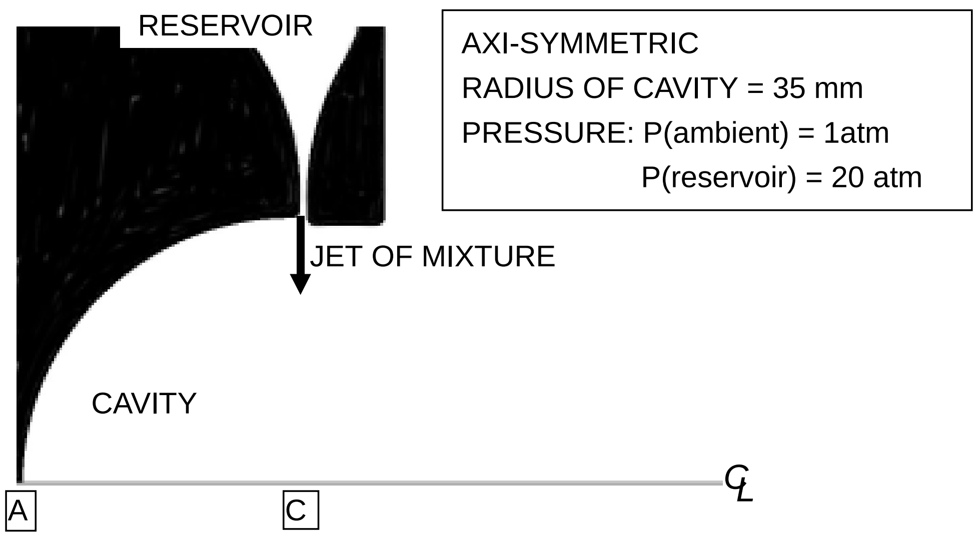

Fig.1 Geometry of Detonation Resonator: Oscillations of Physical Quantities are Monitored at Two Axial Locations A and C.

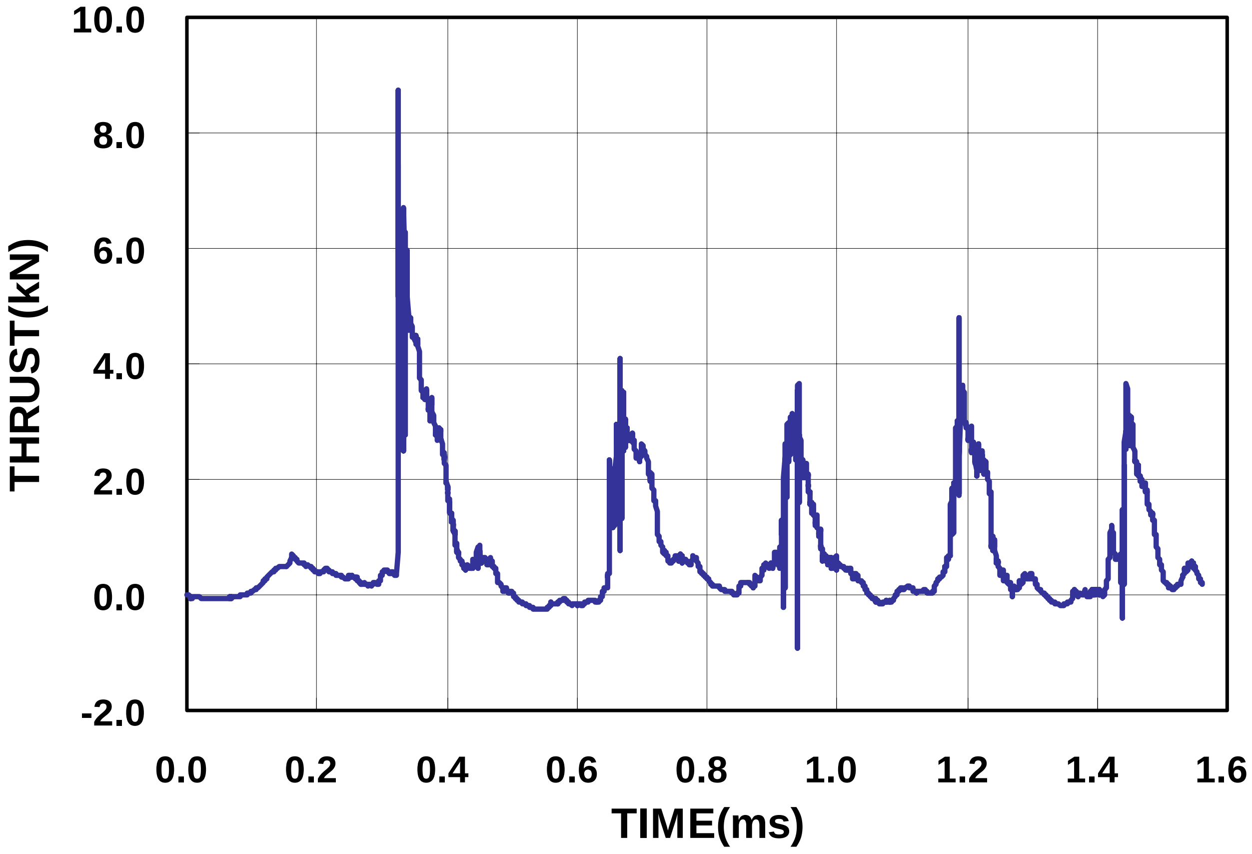

Fig.2 History of Thrust for Case B-0.

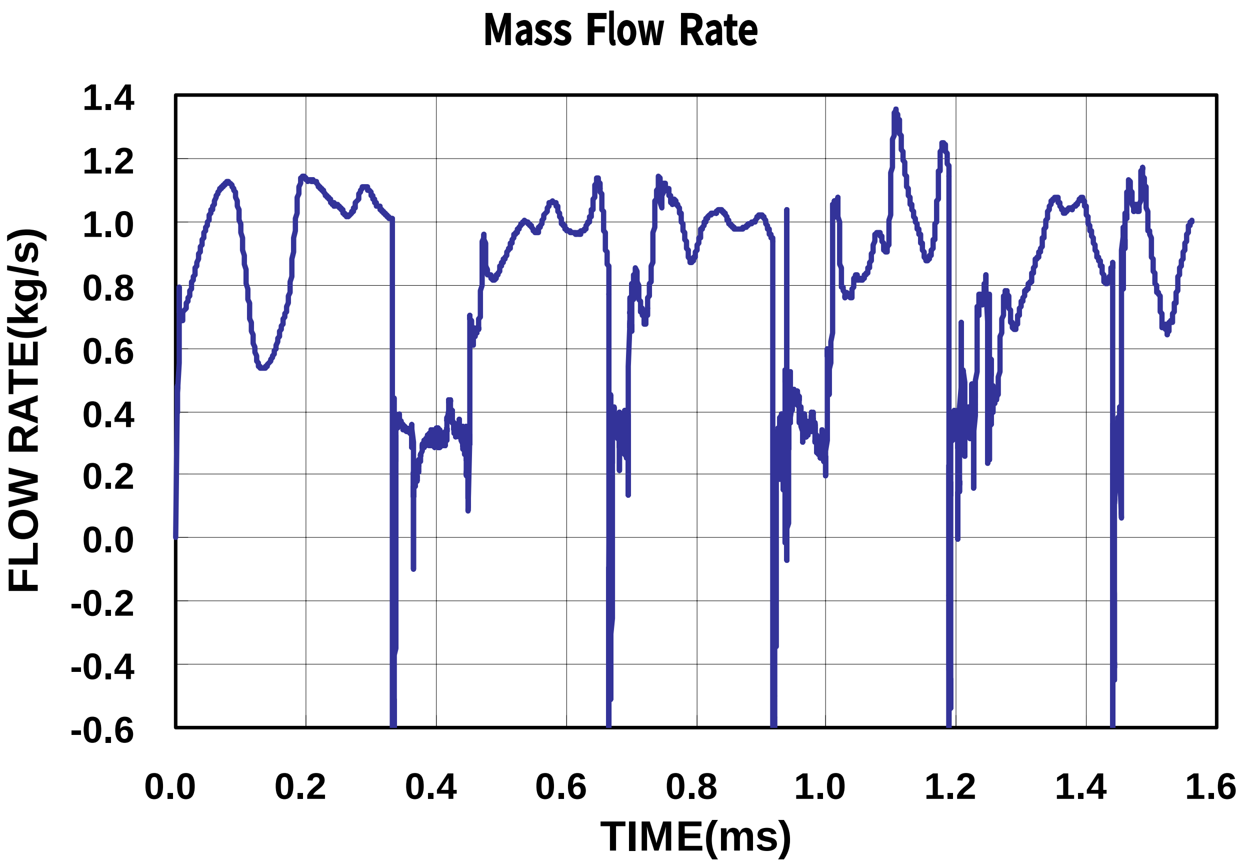

Fig.3 History of Mass flow Rate of Injected Gas Mixture for Case B-0.

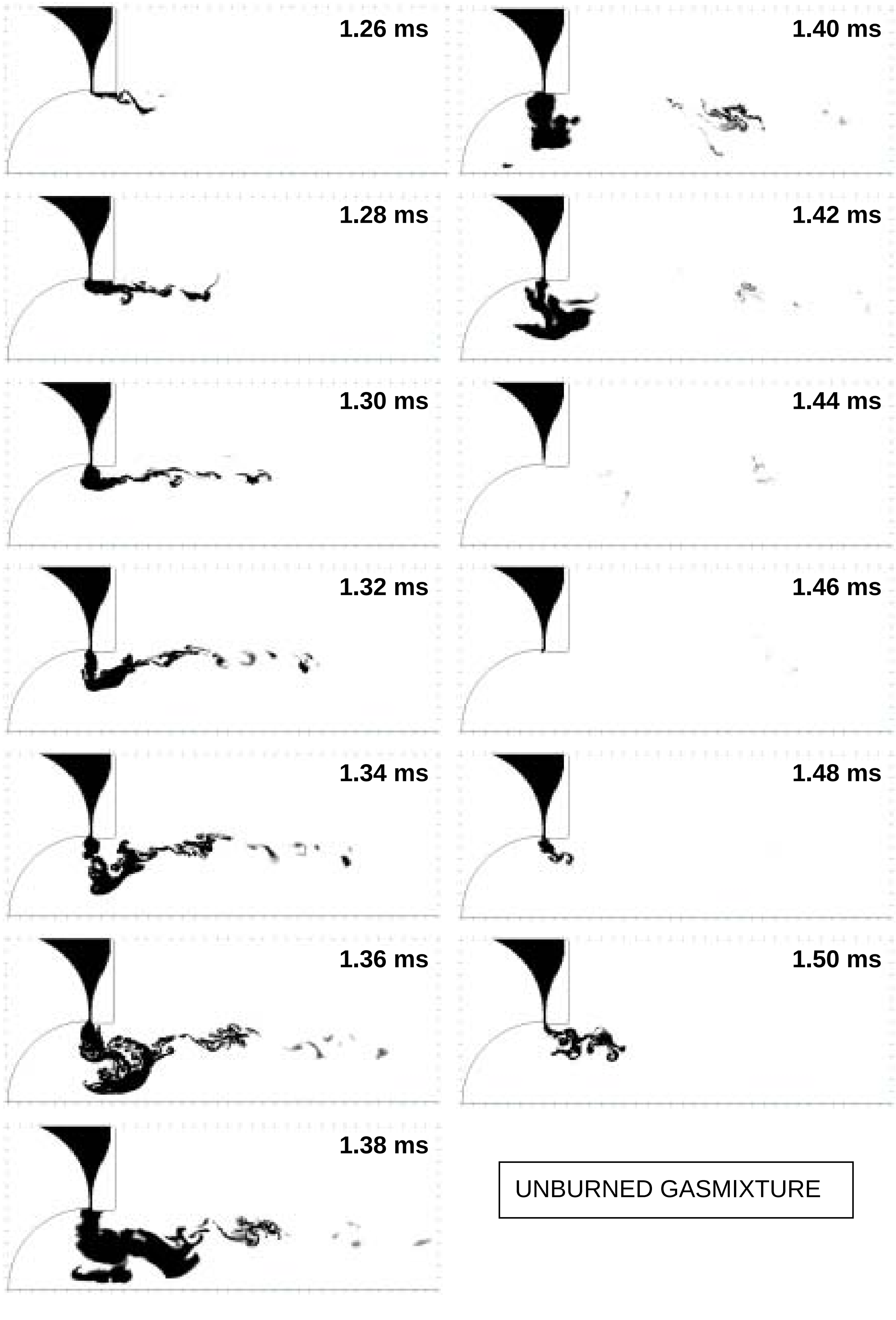

Fig.4 Behavior of Unburned Mixture Contour for Case B-0 during t = 1.26 – 1.50 msec (total 240 microsec).

Table 1 Parameters and Calculated Results for Simulated Cases.

Case	Heat of reaction; Q (MJ/kg)	RateConstant of Induction; k_a(m^3/kg.s)	Injected Gas Temperature; T_{00}(K)	Resonance Frequency; f (kHz)	Specific Impulse; Isp(sec)
B-0	2.10	0.50e+9	293.15	3.96	1,450
B-1	2.10	0.50e+9	350.00	4.70	-
B-2	2.80	0.50e+9	293,15	4.43	1,310
B-3	2.10	0.25e+9	293.15	4.11	1,560

Table 2 Properties of C-J Detonation for Calculated Gas Mixture for Case B-1

C-J Detonation Propagation Velocity D_{CJ} = 1732.71m/s

Mach Number M_{CJ} of C-J Detonation Propagation = 4.7077

Induction Length L_{ind}= 0.3062 micron

CJ Detonation Parameters	Before Shock Front	At von Neumann Spike	C-J State	Cavity Exit	Unit
Density	1.0097	5.3899	1.77008	0.82045	kg/m^3
Velocity	1732.706	324.602	1028.654	1732.706	m/s
Pressure	0.101325	2.5649	1.33312	0.498245	MPa
Temperature	350.000	1659.784	2733.797	2118.125	K
Total Energy	1.7878	1.4123	2.7685	3.2362	MJ/kg

Table 3 Various Physical Properties at Different Locations for Case B-1

Fi	Temperature	Pressure	Density	V(x)	E(total)	α	β
	K	MPa	kg/m^3	m/s	kJ/kg	-	-
F1 Cavity	293.15	0.101325	1.20556	0.00	0.240138	1.0	0.00000
F2 Reservoir	350.00	2.02650	20.1948	0.00	0.286707	1.0	1.00000
F3 CJ Detonation	2733.80	26.6625	34.0170	1028.65	2.76849	-1.0	0.20757
F4 Adiabatic Flame	1988.99	2.02650	3.55366	0.00	1.62931	-1.0	0.13690