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CH* Luminance Distribution Application and a One-Dimensional Model of the Supersonic Combustor Heat Release Quantization

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Abstract: One-dimensional model is an important way to evaluate the performance and flow characteristics of dual-mode scramjet combustor. Current work is based on a modified one-dimensional model assisted by measurements acquired on a direct-connected scramjet facility. CH* images and gas-sampling facility have been employed to quantify heat release for optimizing one-dimensional model. The results show that modified one-dimensional model gives a better evaluation of axis parameters distribution, especially for Mach number, which is the standard parameter to evaluate combustion mode. The ram/scram mode derived by the analytical results has been investigated. Intensive heat release is beneficial to obtain more stable pre-combustion shock and subsonic flow in the recirculation zone.

Keywords: supersonic combustion, one-dimensional modelling, heat release, CH* chemiluminescence

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Introduction

Accurate heat release control is the key factor to realize the dual mode Ramjet engine [1]. The axis distribution of heat release is determined by the combustion organization, engine flow path parameters and engine inlet condition and affects engine states such as ram/scram transition; thus, a reliable heat release model is very important to design and run the engine.

Since scramjets performance researches focus on a global scale, one-dimensional model has been developed to figure out heat release and other parameters. At present, there are two main applications of one-dimensional analysis theory: one is based on the wall pressure and the core flow area estimation; the other is based on the chemical reaction model and the empirical formulas of the combustion heat release law to calculate the other 1-D flow state. William Heiser [2] firstly established combustor model based on gas dynamics differential equations, which made the hypothesis of heat releasing of combustion and core flow reattachment after combustion. Considering the effects of friction, variable area and mass addition, Bussing [3] studied unsteady behaviours of combustor by solving one-dimensional Euler equations and simulating heat release with the assumption of equilibrium. Zhang [4] determined the core area with experimental pressure distribution and improved the one-dimensional model. Birzer [5] calculated axis heat release parameters with mixing controlled combustion model, and brought good match compared with experimental data. Starkey calculated it coupled with the equations of finite-rate chemistry to model high-speed engine flow fields [6].

The shortcoming of the above methods is that the model included a series of hypothesis, which cannot reflect the complicated process of heat release. In current study, the heat release distribution is obtained by CH* chemiluminescence images as a good marker of local release. One-dimensional is able to be more accurate with heat release and pressure distribution.

Modeling and measurements

In the present work, combustor model is studied based on one-dimensional gas dynamics differential equations with assumptions of steady state, the perfect gas and ignoring the mass addition and the wall friction.

Governing equations of combustor

Parameters along the combustor are calculated by ODEs similar to previous works. The following parameters in the left of the equation are calculated by measured static pressure and deduced total temperature.

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Differential Equation of static pressure

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{A}\frac{\gamma M^2}{1-M^2}\frac{dA}{dx} - \frac{\gamma M^2 C_{pt}}{(1-M^2)C_p T}\frac{dT_t}{dx} \tag{1}$$

Differential Equation of density

$$\frac{1}{\rho}\frac{d\rho}{dx} = \frac{1}{A}\frac{M^2}{1-M^2}\frac{dA}{dx} - \frac{C_{pt}}{(1-M^2)C_p T}\frac{dT_t}{dx} \tag{2}$$

Differential Equation of static temperature

$$\frac{1}{T}\frac{dT}{dx} = \frac{1}{A}\frac{(\gamma-1)M^2}{1-M^2}\frac{dA}{dx} - \frac{(\gamma M^2-1)C_{pt}}{(1-M^2)C_p T}\frac{dT_t}{dx} \tag{3}$$

Differential Equation of Ma number

$$\frac{1}{M}\frac{dM}{dx} = -\frac{1}{A}\frac{\left(1+\frac{\gamma-1}{2}M^2\right)}{1-M^2}\frac{dA}{dx} + \frac{(\gamma M^2+1)C_{pt}}{2(1-M^2)C_p T}\frac{dT_t}{dx} \tag{4}$$

Differential Equation of total pressure

$$\frac{1}{p_t}\frac{dp_t}{dx} = -\frac{\gamma M^2 C_{pt}}{(2+\gamma M^2-M^2)C_p T}\frac{dT_t}{dx} \tag{5}$$

Method of quantifying heat release distribution

Measurements of the heat release rate are always a challenge in any combustion environment. The heat release rate can be inferred from the measurement of other flow quantities which are correlated to it. Chemiluminescence is often used as a marker of the heat release rate in flames [7, 8]. The chemiluminescence in hydrocarbon flames comes primarily from OH*, CH*, which may be better markers of the location of heat release for scramjet combustor conditions. Evidence that the heat release rate is proportional to the chemiluminescence first came from Price [7]. Heat release has been proved to be proportional to the luminosity from OH*, CH*, and CO_2* individually in many studies later. However, the luminosity from OH* and CH* can be dependent on the local equivalence ratio and strain rate as well. Therefore it is necessary to interpret images of OH* and CH* carefully where local conditions at the flame surface can vary significantly across the image. D. J. Micka [9] firstly shows axial heat release effect proportioned to CH* in scramjet experiments. However, the correlation between heat release and CH* signal should be used carefully. Various parameters, such as equivalence value and strain rate, make a prominent influence on the correlation. Present model makes an amendment with global combustion efficiency. Meantime, the method could tolerate the shortcut to some extent as a 1-D model.

One-step reaction mechanism is considered to calculate total combustion heat release. Then eqs (6)–(8) give the local heat release. M. L. Fotia [10] found different combustion conditions with heated wall and explained that wall heat transfer is a critical factor in scramjet experiments. A conjugate gradient method for measurements of wall heat flux of Cheng [11] is also applied to refine the results.

$$C_2H_4 + 3O_2 \rightharpoonup 2CO_2 + 2H_2O \tag{6}$$

$$\delta q = \frac{m_{total}}{2M_{average}}(X_{H2O,\ out} - X_{H2O,\ in})q_{C2H4}L_{CH,\ local} / \int L_{CH}dx \tag{7}$$

$$dh_t = \delta q - \delta q_w = C_{pt}(T_t)dT_t \tag{8}$$

Facilities and measurements

The experiments were performed in a dual-mode combustor on the direct-connected facility. The facility using the method of burning hydrogen and adding oxygen provides vitiated air with Mach number of 2.5. The test section scheme is sketched in Figure 1. The constant-area isolator with the cross section of 85 mm by 40 mm is followed by with two diverging ducts with angles of 1.5° and 2.0°, respectively.

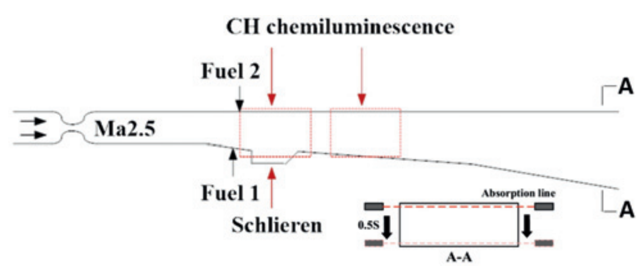


Figure 1: Scheme of dual-mode combustor model.

Axial pressure and wall temperature was measured during steady combustion time. To better analysis the heat release distribution along the duct, CH* imaging were arranged at two quartz windows covered over 300 mm shown in Figure 1 in order to capture all the heat release zone. CH* luminosity images were taken at from two windows using a high speed camera (10,000 p/s) with a 430 ± 10 nm bandpass interference filter. The CH* results are averaged by 1 s. Combustion efficiency was measured by TDLAS systems at the exit [12]. The absorption line scanned the cross-section of exit in 1 s (a steady combustion range).

Results and discussion

Experiment results

The investigations of the current study are mainly focused on the analysis of combustion mode. In the experiments air was heated to stagnation temperature 1,550 K, and the corresponding stagnation pressure was 1.5 MPa. Two opposite removable wall injections are available in the dual-mode combustor. C_2H_4 was injected sonically through parallel $7\times\Phi2$ mm multi-ports at the bottom wall and $7\times\Phi1.5$ mm multi-ports at the upper wall with room temperature. The combustion efficiency is given in Table 1.

Comparison of different model of case A1

Firstly, to evaluate the improvement of the model, the comparison among three models of case A1 is addressed in present case. Model 1 utilizes fitting method from the pressure distribution for separated flow area [4]. With CH* images and TDLAS system, Model 2 replaces core flow concept with total temperature data. Model 3 considers wall heat flux based on model 2 (introduced in Sections "Governing equations of combustor" and "Method of quantifying heat release distribution"). The scheme of three 1-D models is described by Figure 2.

Processed with the combustion efficiency and CH* distribution results, total temperature and measured pressure data are showed in Figure 3, which act as the input of 1-D model (model 3). The curve of total temperature appears to decrease due to wall heat transfer obviously. Figure 4 compares the static temperature results of three models. Model 1 makes an underestimate of combustion heat, although model 3 has a similar trend along the duct. And in this case of relatively intensive heat release condition the influence of wall heat flux is about 11 percent. The static temperature of model 3 is also low in the centralized heat release area, which provides an approximate result with TDLAS system.

Figure 5 depicts Mach number axis distribution of three models. The comparison of velocity plays an important role of determining supersonic or subsonic mode. The

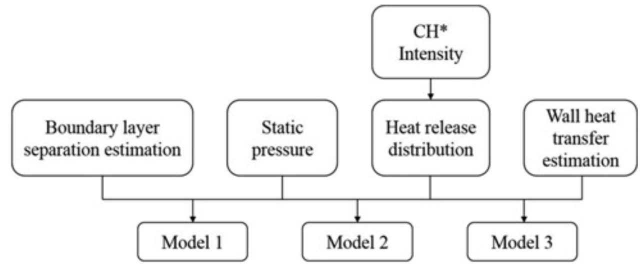


Figure 2: Scheme of three 1-D analyses model.

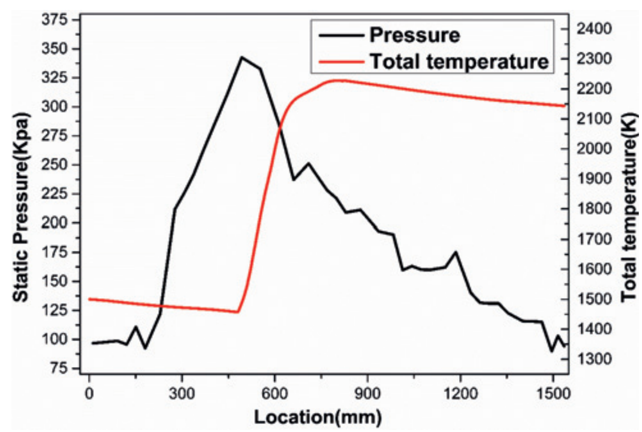


Figure 3: Pressure and total temperature axis distribution of case A1.

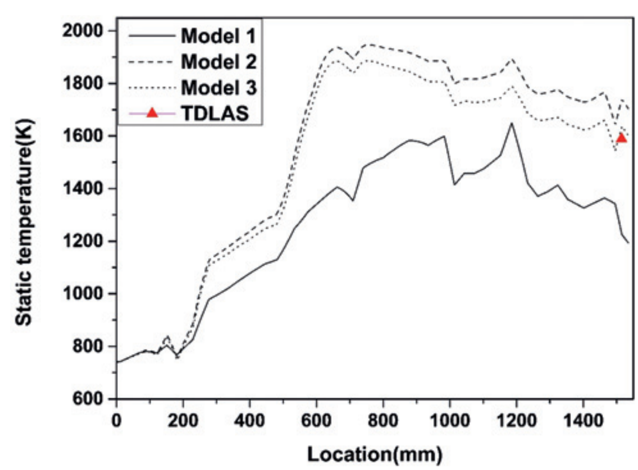


Figure 4: Static temperature axis distribution comparison of case A1.

Table 1: Conditions and results of cases.

Number	Injectors	Equivalence ratio	Mach number	Total temperature (K)	Total pressure (Mpa)	Combustion efficiency (%)
A1	Fuel 1,2	0.38	2.5	1,500	1.5	70.2
A2	Fuel 1	0.22	2.5	1,500	1.5	85.8

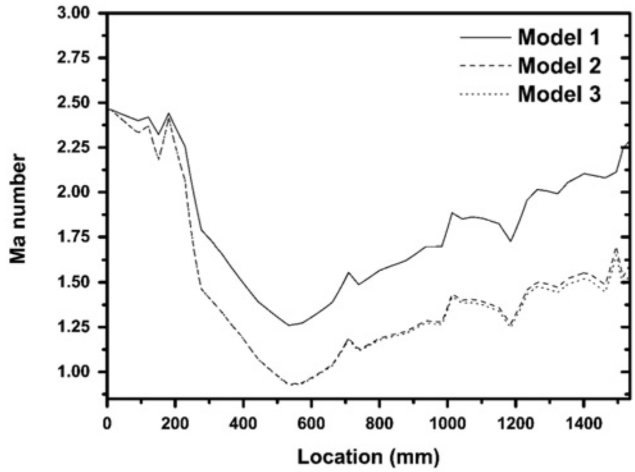


Figure 5: Mach number axis distribution comparison of case A1.

curves of model 2 and 3 indicate the subsonic flow along the high heat release rate area. Previous studies often used the position of pressure rise to judge the combustion mode. This case is proven to be Ramjet mode with calculated subsonic Mach number distribution by model 2 and 3. Modified models acquire similar judgement of ram/scram mode with pressure curve, which means the model considering heat release has the ability to distinguish the combustion mode. The sonic point is located near the aft wall of cavity where the heat release decreases rapidly.

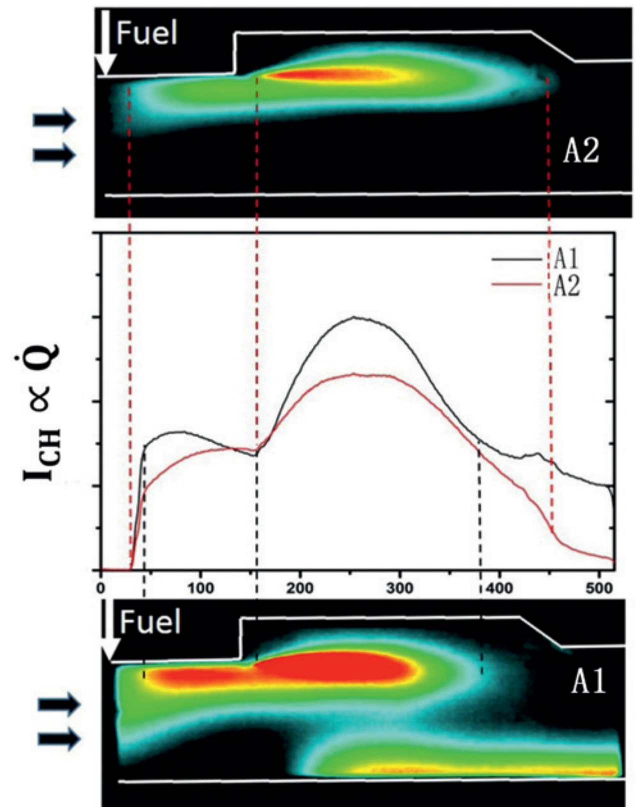


Figure 6: CH* pseudo-color image and heat release axis distribution for cases.

Comparison of case A1 and A2

Cases were chosen to investigation the ram/scram mode with 1-D model. With the same inflow condition, A2 was transformed into A1 just by increasing an injector. The results of the ramjet mode (A1) and scramjet mode (A2) are compared in this section. Figure 6 compares heat release distribution from CH* luminescence for case A1 and A2. In case A1, fuel 2 was ignited after the main reaction zone; the flame was stabilized in the cavity recirculation zone and anchored at the location where the shear layer was well developed. Two adjacent injectors of upper and bottom wall organize centralized heat release, which makes the “X-shock” propagate upstream further of the combustion zone and locate nearly in the middle of the duct, as Figure 8(a) indicates.

The static pressure rise has inconsistent characteristics relative to the heat release distribution, which were both drawn in Figure 7. Figure 8 shows the influence of

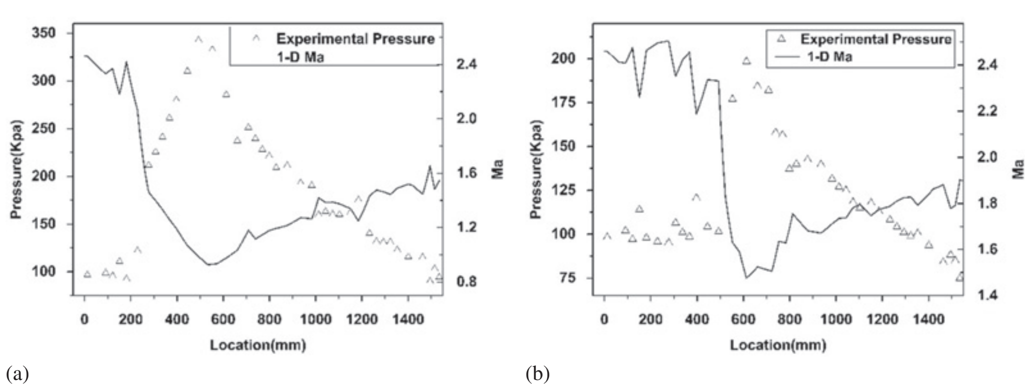
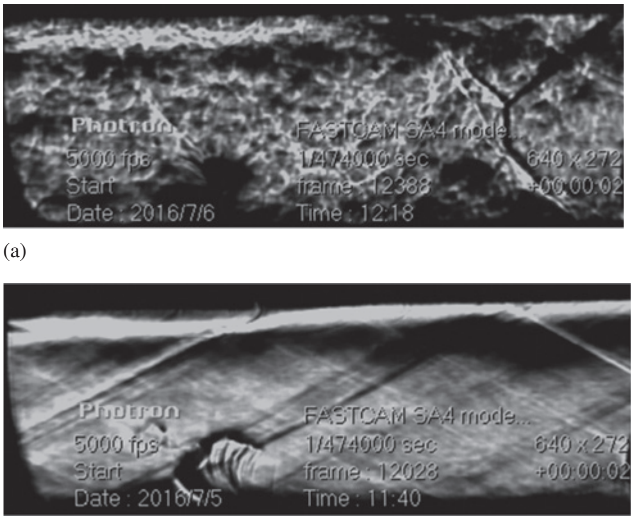


Figure 7: Pressure and Ma comparison of cases (a) Case A1, (b) Case A2.



(a)

(b)

Figure 8: Isolator schlieren results comparison of cases (a) Case A1, (b) Case A2.

shock waves extended to the upstream location of $x = 250$ mm. In addition, the 1-D model also estimates the subsonic zone of case 1. Reversely, case 2 keeps a supersonic flow along the combustor without a strong shock-wave in the isolator.

Conclusions

The dual-mode combustion was studied thoroughly in heat release distributions by CH* luminosity images and global combustion efficiency measurement. Wall heat flux was also considered in the modified 1-D model. The experiments were conducted in the main flow with Mach number of 2.5. The total temperature and pressure of the air were 1,500 K and 1.5 MPa. TDLAS and schlieren systems was applied in this paper.

– Relative heat release intensity received from CH* luminosity images could give more accurate result of supersonic combustion. According to the results of CH luminescence and TDLAS, the heat release distribution is closer to the actual state. Therefore, the one-dimensional result derived by this heat release result is more typical and can be used for more accurate analysis.
– Improved one-dimensional analytical model used the direct experimental results of heat release was developed; and the calculated averaged one-dimensional flow characteristics can reflect the characteristics of the flow field more accurately. Flow details make a contribution to the ram-scram transition. Because the improved one-dimensional model using the equations of heat release is closed, so we abandoned the hypothesis of the core flow area. At the same time, the influence of boundary layer is not considered in this example, the calculation result is the average flow parameter of the whole section. Despite affect the separation and reattachment region and improved average parameters calculated one-dimensional analysis method can better reflect the true state of the combustion chamber, avoiding the core flow area estimation inaccuracies bias.
– Wall heat flux plays a critical role for improvement of the model. In future, various methods of combustion organization should be examined to study the influence of heat release intensity. One-dimensional analysis of wall heat flux analysis can be added to further improve the accuracy of analysis.
– The dual-mode combustor shows the ram mode features in concentrate heat release condition. But without ignition and cavity, the upper wall injector fails to form efficient combustion. In contrast, the air of the scram mode keep a supersonic flow.

Nomenclature

m	Mass flow rate (kg/s)
P	Static pressure (N/m^2)
T	Static temperature (K)
C_p	Specific heat at constant pressure (J/(kg*K))
q	Heat release (J)
A	Core-area of combustor flow (m^3/s)
M	One-dimensional Mach number
ρ	One-dimensional density (kg/m^3)
Y	One-dimensional specific heat ratio
h	Enthalpy of flow (J)
L	Luminosity intensity of combustor
X	Volume fraction

Subscript

t	Stagnation value
w	Wall value
total	Total value
average	Average molecular weight
in	Conditions at the entry of isolator
out	Conditions at the exit of combustor
local	Local value of the gas

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