The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Experimental and Numerical Study on the Ignition Process in GOX/CH4 Vortex Thruster

*De-Chuan Sun[1)] and Meng-Cheng Cao[2)]

[1), 2)] *School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, P.R.China*
[1)] dechuans@dlut.edu.cn

ABSTRACT

Vortex combustion cold wall rocket engine is a potential type of rocket engine which has very low wall temperature because of the bidirectional vortex in combustor. A lab scale cold wall vortex combustor was tested by experiments. In the hot fire test, an automobile spark plug was used to ignite the combustion. To study the uncertain ignition phenomenon, the transient ignition processes were simulated by CFD method. Reynold stress turbulence model was used to simulate the stronger vortex in the combustor. Spark ignition model and a simplified 5 step finite reaction rate mechanism were used to calculate the combustion of methane in oxygen. The unsteady results described the flame spread process and predicted the temperature increasing peak at ignition. The spark energy and position were changed to study their influence on the ignition. Simulation results show that spark position is not sensitive to the ignition but spark energy is the key parameter. For the vortex combustor, a minimum spark energy of ignition was found.

1. INTRODUCTION

Vortex Combustion Cold Wall (VCCW) rocket engine, proposed by Orbital Technologies Corporation in the early 21th century[1,2], is a potential type of rocket engine. The special vortex flow structures in the combustor can extremely cooling the wall of engine to make it stay in a very low temperature (100 Celsius for some smaller VCCW thrusters) when working. This technique brought us a very good prospect: The rocket engine will have lower cost and longer service life, and could be reusable like an automotive engine. So, VCCW engine has been attracting much attention of investigators.

A series of test and numerical simulation were performed to study the geometric and the flow parameters to achieve higher performance. In 2003, M. J. Chiavertini and

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[1)] Professor
[2)]Graduate Student

M. J. Malecki etc. investigated the different methods of injection with hot-fire test of oxygen and hydrogen VCCW engine[1]. Specific impulse efficiency of the engine can be reached to 96% and the wall temperature can be decreased to 80 Celsius after 5 seconds of steady burning. D. Fang, J. Majdalani and M. J. Chiavertini calculated the steady flowfield of VCCW engine in cold flow and chemical reaction conditions[2,3]. The difference between cold flowfield and reaction flowfield was compared. In 2005, M. J. Chiaverini and J. A. Sauer etc. studied the VCCW engine using methane/oxygen and hydrogen/oxygen, Specific impulse efficiency of the engine can be reached to 98%[4.]

To study this cold wall thruster, a series of theoretical analysis, numerical simulation, PIV experiments and hot fire test were carried out in our group recent years[5,6]. The influences of parameters' variation on the wall temperature, combustion efficiency and specific impulse efficiency were numerically simulated. At the same time, injection method and thrust chamber shape which could bring high-efficiency combustion were examined. In the hot fire test, an automobile spark plug was used to ignite the combustion. But this method was unreliable, the spark could not ignite the fuel in some tests. So, a series of numerical simulation were used to study the ignition process to find out the factors affecting the ignition reliability.

2. VCCW TEST

Fig. 1 shows the schematic of the flowfield in VCCW rocket thruster[1]. The oxidant is injected tangentially from the aft end of the combustor to form an outer oxidant vortex and flow toward the head of the thruster, then it mixes and combust with the fuel injected near the head of the combustor and then form a hot burning inner vortex. Under the isolation of the unburned oxidant vortex, the side wall can keep very low temperature.

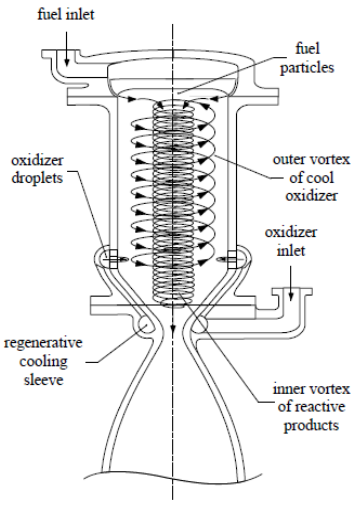


Fig. 1 Schematic of bidirectional vortices cold wall thruster

In our experiments, methane was chosen as the fuel and gas oxygen was as the oxidant. Fig. 2 is a photo of one successful hot fire test for the vortex thruster. In the

test, the chamber pressure is controlled by the mass flow rate of the propellants. Mixture ratio of oxidant to fuel was kept close to 4, the stoichiometric ratio of methane combustion in oxygen.

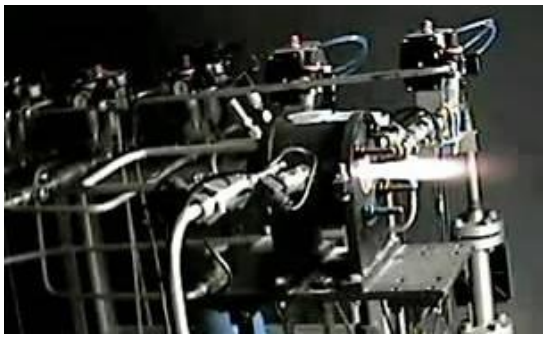
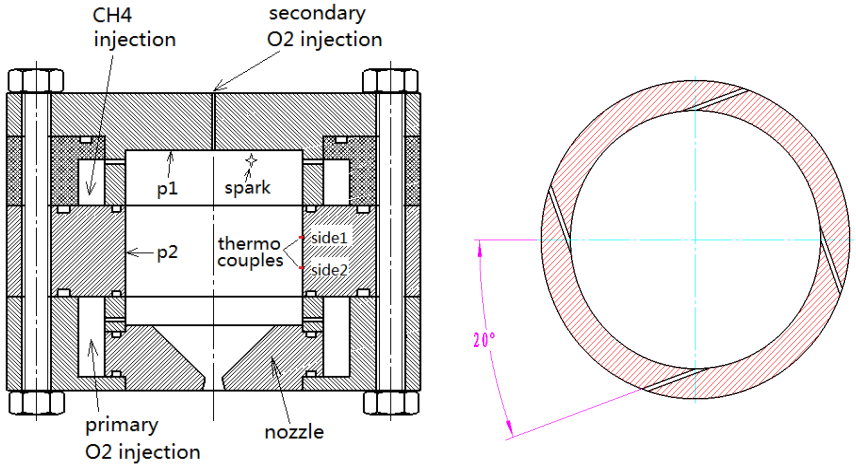


Fig. 2 Low pressure hot fire test of vortex thruster

In the model thruster, which inner diameter is 60mm, see Fig.3, there are 4 tangential oxygen injectors located at the aft end of the combustor and 4 straight radial methane injectors located near the head of the combustor. Two pressure sensors, p1 and p2, are fixed on the side wall and the head to measure the different local pressures. Two thermocouples are mounted on the inner side of the wall. One (side1) is at the middle and the other (side2) is towards to the nozzle, that is, the upstream of side1 for outer vortex. The distance between the two thermocouples is 2cm. Ignition spark was generated by an automobile spark plug located on the head of the combustor, away from the secondary axial oxygen injection.



(a) Cross section of the model (b) Top view of the primary O2 injection

Fig. 3 Test model thruster

Fig. 4 shows the temperature curve measured by the two thermocouples in one of the test. In all the tests, the inner side wall temperature was less than 200 Celsius and the working process was very stable. The spark plug started to work before the injection of methane and switched off when flame was observed. But the ignition of the

thruster was unreliable in the whole experiments. Sometimes the engine could be ignited simultaneously with the methane injection but sometimes it could not. To study this phenomenon, the transient ignition process in the test model was simulated by CFD. And some factors maybe affecting the ignition were also discussed.

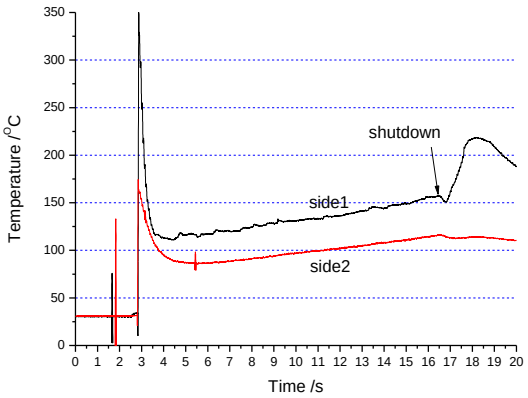


Fig. 4 Side wall temperature in test (test011, Pc=0.54MPa)

3 NUMERICAL METHOD

3.1 CFD model

The calculation grid is shown in Fig. 5. The thruster geometry was same as the experiment model except removing the nozzle divergence section. To simplify the calculation and to generate structured grid, the orifices of methane and oxygen are all set rectangular instead of the real circle but the mass flow rates and inlet velocity are remained unchanged. The total grid number was about 540,000 cells.

In the calculation, three-dimensional Navier-Stokes equation with multi-component chemical reaction and Reynolds Stress turbulence model (previous CFD simulations show that k-ε model cannot obtain correct pressure distribution) were used. Gas mixture is assumed to be ideal gas. Second order upwind scheme was used for spatial discretization. Since ignition process is a transient process, heat transfer to wall during ignition process was ignored. Both combustion chamber wall and nozzle wall are assumed to be adiabatic. This calculation method was successfully used and verified in the cold flow7.

The mass flow rate of methane and oxygen are 4.04g/s and 16.16g/s. For oxygen injection, the main flow rate is 14.544g/s and the secondary flow rate is 1.616g/s.

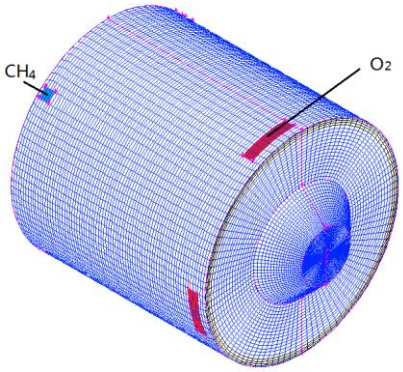


Fig. 5 Test model of vortex thruster

3.2 Mechanism of Methane Reaction

Generalized finite-rate chemical kinetics model was used in calculation to simulate the combustion of methane. For reaction flows, a general finite rate reaction equation may be written as

$$\sum_{s=1}^{ns} \nu'_{sr} M_s \Leftrightarrow \sum_{s=1}^{ns} \nu''_{sr} M_s$$

Where ν'_{sr} and ν''_{sr} are stoichiometric coefficients for the reactions, and Ms represents an arbitrary molecule in the reaction. The source term for species "s" is given by

$$\omega_s = M_{w,s}(\nu''_{sr} - \nu'_{sr})[\sum_{s=1}^{ns} \beta_{s,r} C_s][K_{fr} \prod_{s=1}^{ns} (C_s)^{\alpha'_{sr}} - K_{br} \prod_{s=1}^{ns} (C_s)^{\alpha''_{sr}}]$$

Where $\beta_{s,r}$ is the third body coefficient for a reaction, C_s($C_s = \rho_s / M_{w,s}$) is the species concentration. α'_{sr} and α''_{sr} are concentration exponents. K_{fr} is the forward reaction rate and K_{br} is the backward reaction rate for reaction "r". They are given by Arrhenius formula respectively.

$$K_{fr} = A_{f,r} T^{\eta_{f,r}} exp[-E_{a,f}/(R_u T)]$$
$$K_{br} = A_{b,r} T^{\eta_{b,r}} exp[-E_{a,b}/(R_u T)]$$

In the calculation, a reaction mechanism which contains 5 elementary reactions was used to simulate the combustion of methane8. The parameters of the mechanism are illustrated in Table 1.

Table 1: Five-step reaction mechanism of CH4 and O2

Reactions	Ln(A)	Ea/R [K]	β
2CH4+O2=>2CO+ 4H2	34.53	35872	2.618
2H2 + O2 => 2H2O	34.53	8193	-1.421
2CO + O2 => 2 CO2	34.53	13574	-0.098
2H2O => 2H2 + O2	12.01	50000	0.093
2CO2 => 2CO + O2	34.53	48202	-0.177

3.3 Solving Process

To simulate the ignition process in the test model, a steady state, multi-component and non-reactive mixed flowfield was calculated first and its result was as the initial condition. Then, the spark energy was added to ignite the mixture gas.

The spark model is based on the work done by Lipatnikov[9]. The spark was assumed to occupy a sphere volume which radius is 0.4mm and located at the position according to the test model, where x=2mm, y=9mm, z=0mm. Spark energy was set to 0.03j and duration was set to 0.1ms.

3.4 Ignition Requirements

To ignite the mixed gas, three elements must be present[10,11]. The first requirement is that the concentration level of enthalpy must be sufficient to induce the reaction, thus generating an igniting kernel. The second requirement is that the amount of enthalpy is sufficient to grow the initial reaction kernel immediately after it is created. The third requirement is that the equivalence ratio of oxidizer to fuel near the energy source (spark) must be within an appropriate range. The excess oxidizer coefficient defined below represents oxidizer to fuel when compared with stoichiometric combustion.

$$\alpha = \frac{\dot{m}_o / \dot{m}_f}{\dot{m}_{o,st} / \dot{m}_{f,st}}$$

$\alpha = 1$ means a stoichiometric mixed gas, $\alpha > 1$ a oxidizer-rich mixture, and $\alpha < 1$ a fuel-rich mixture.

4. CFD Results and Discussion

4.1 Initial flowfield

As mentioned above, the initial flowfield was a non-reactive flowfield. Typical flow pathlines that track the motion of oxidant are shown in Fig. 6. It clearly displays an outer vortex spiraling toward the head end and then change to an inner vortex spiraling toward to the nozzle. The background color of the cross section and the thruster head are the mass fraction of oxygen.

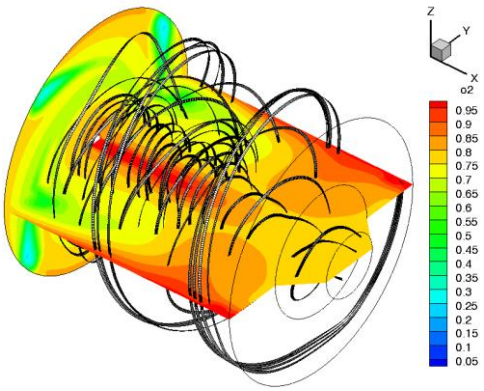


Fig. 6 Colored pathlines in the vortex thruster

Fig. 7 shows the distribution of methane mass fraction through the combustion chamber. The upper figure is the x=3mm section and the lower figure represents the cross sections (z=0) of the thruster. From the distribution of the mass fraction of methane, one can observe that methane diffuse to most places in the thruster but nearby the oxygen entrance. There is still some methane in the outer vortex near the side wall, so the theoretical interface of outer and inner vortex12, where $r = \sqrt{2}$, is not the interface between fuel and oxidant.

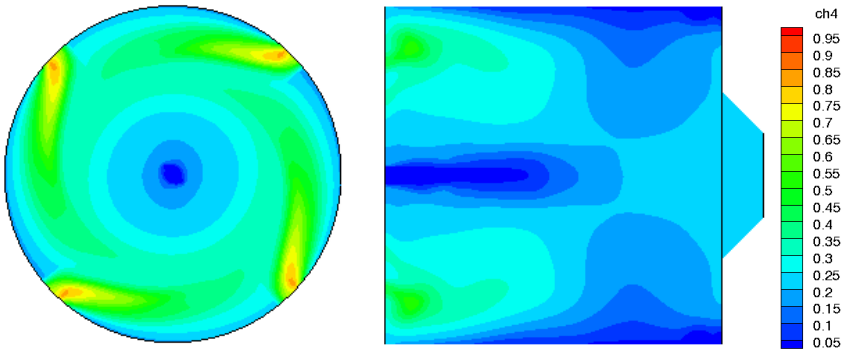


Fig. 7 Methane mass fraction distribution

4.2 Ignition process

By using the simulation method mentioned above, the ignition process was calculated for 22.95ms. In the calculation, time step size was set to 0.01ms and data save step was 0.05ms.

Fig.8 shows velocity magnitude and excess oxidizer coefficient at the cross section through the spark. Around the spark, tangential velocity is about 260m/s and axial velocity is about 30m/s. In most region of the cross section, α is between 0.4 and 0.5 except the region near the injection of oxygen and methane. Fig. 9 shows the isothermal surface during the ignition process. Two cross sections are colored with temperature in the figure. At the beginning of ignition, spark's effect is to heat the mixed gas to generate a ignition high temperature kernel. The figure at 0.05ms shows the 400K isothermal surface, in the volume that enclosed by the isothermal surface, the highest kernel temperature is about 1947K and the kernel volume is very small. At 0.1ms, the end of ignition duration, the volume enclosed by 400K isothermal surface become larger and flow with the swirling gas, and its kernel temperature reach to 2101K. During 0~0.1ms, the ignition kernel is created but the mixture is not ignited. This result can be indicated by the fact that the length of heated mixture's volume is almost equal to the length of flow path in the second figure in Fig. 9, in where the gas goes 260m/s*0.1ms=26mm. Immediately after the spark's disappear, mixture gas is ignited. One can observe that the temperature increase rapidly and the flame front propagate with a high speed faster than flow. The flame immediately spread toward to the wall (figure at 0.3ms) and the high temperature zone nearly fulfill the whole combustor (figure at 0.35ms) until 1ms. After 1ms, the high temperature zone begins to shrink back due to the action of cold flow. After dozens of milliseconds the flowfield tends to be steady. This process is corresponding with the temperature curve in tests

(see Fig. 4) in which all the temperature sensors detect a rapid increase of temperature and then decrease. Of course, the measured temperature peaks lower than and lag behind the real value because of the delay of thermal couples.

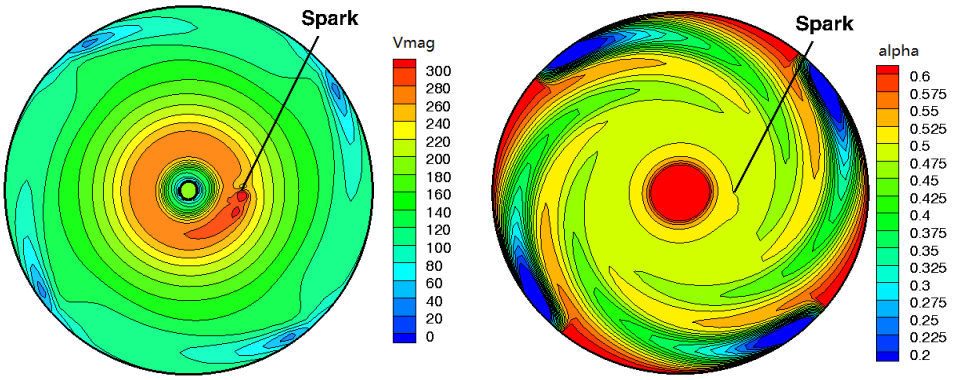
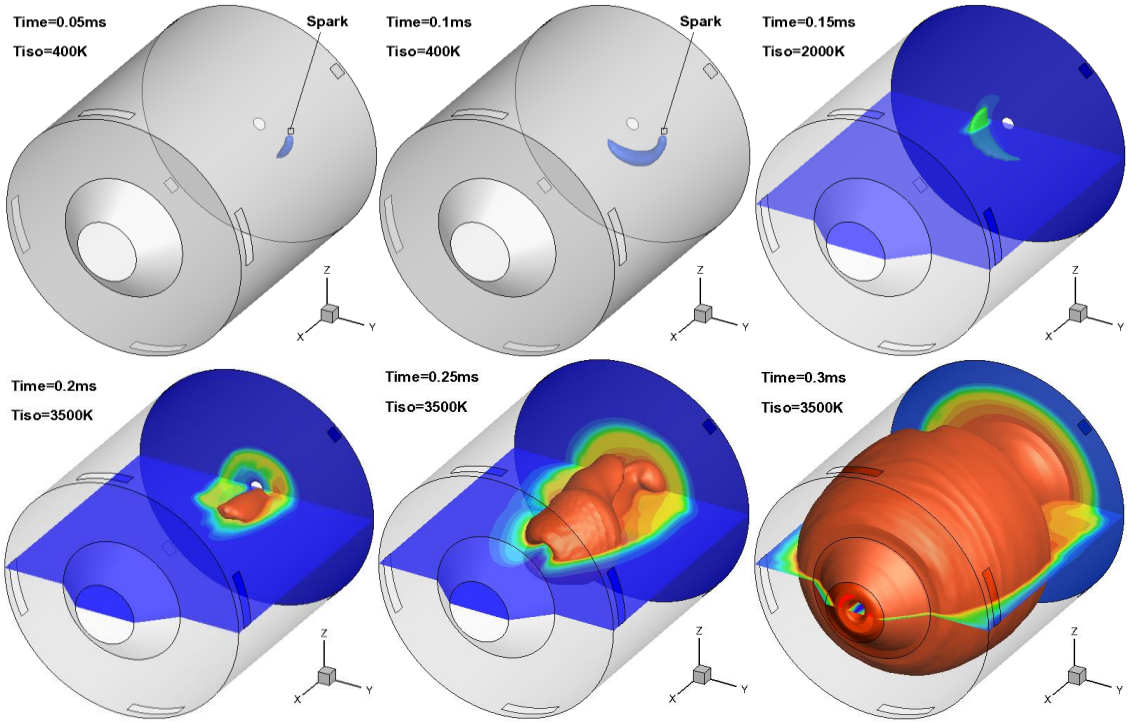


Fig. 8 Velocity magnitude and excess oxidizer coefficient at spark cross section (0.05ms)



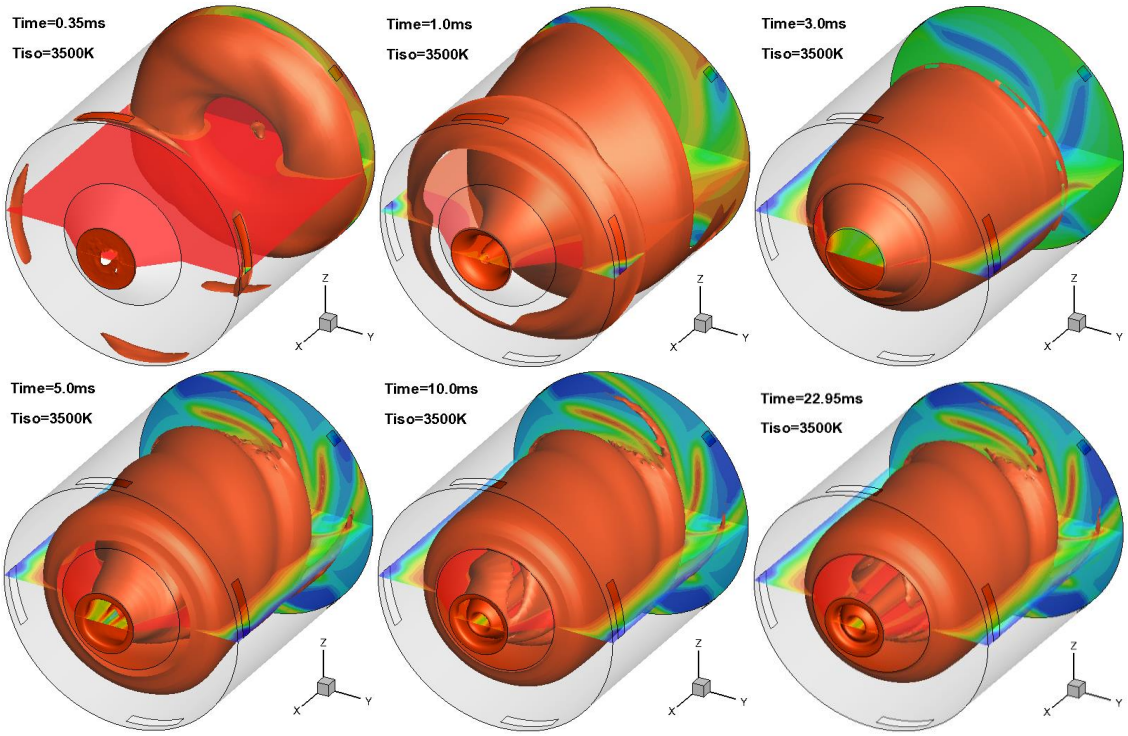


Fig. 9 Temperature isothermal surface in ignition process

4.3 Influence of Spark energy and position to the ignition

To study the influence of spark energy and position, same mesh and same calculation method were used to calculate the ignition process while the spark energy and position were changed. The maximum temperature in the thruster was monitored when solving the unsteady flowfiled. If the maximum temperature can reach and keep at a high value, such as over 3000K, that means the mixture gas is ignited, otherwise the ignition failed. Fig. 10 shows an unignited process in which the spark energy was set to 0.25mj and the spark duration was 0.1ms. A quickly increase of temperature is observed at the beginning of spark working and the high temperature zone, approaching 900K, is restricted into a very small volume near the spark. Because the reaction is not activated, the maximum temperature stays near 900K when the spark working and suddenly decreases after the spark stop.

As shown in Fig. 8, excess oxidizer coefficient is different along the radius, so six different positions, 5mm, 9mm (above case), 15mm, 20mm, 25mm, and 28mm along the horizontal direction in Fig. 8 were chosen as the spark position. In these cases, spark energy was 30mj. Simulation results show that all of these cases can be ignited. This means the excess oxidizer coefficient in the model is proper for ignition and has low demand on ignition position.

To find out the minimum ignition energy, the spark energy was decreased to 25mj in these cases with different ignition positions. Simulation results show that no one was ignited successfully. So the minimum ignition energy is about 30mj.

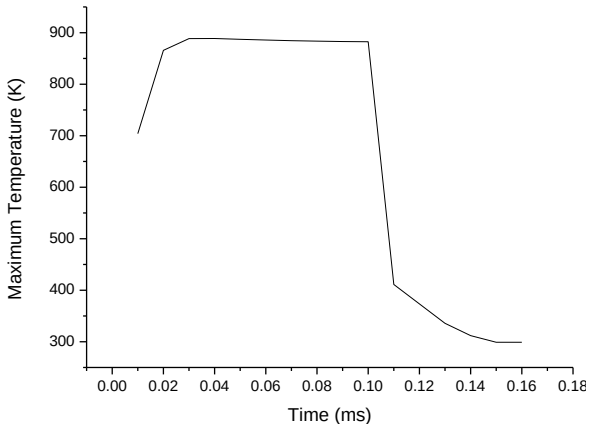


Fig. 10 Maximum temperature variation in case of 0.25mj spark energy

5. CONCLUSIONS

Five step reaction mechanism of methane can successfully be used to simulate the ignition process in vortex combustion thruster. The flame propagation is corresponding to the temperature peaks observed in experiments. Spark position is not a key parameter because of proper excess oxidizer coefficient at the head of the vortex combustion thruster. The minimum ignition energy is about 30mj.

REFERENCES

Martin J Chiavertini, Matthew J Malecki, J Arthur Sauer. Vortex thrust chamber testing and analysis for O2-H2 propulsion applications. AIAA-2003-4473.

Dianqi Fang, Joseph Majdalani, Martin J Chiaverini. Simulation of the cold-wall swirl driven combustion chamber. AIAA-2003-5055.

Dianqi Fang, Joseph Majdalani, Martin J Chiaverini. Hot flow model of the vortex cold wall liquid rocket. AIAA-2004-3676.

Martin J Chiavertini, J Arthur Sauer, Scott M Munson. Laboratory characterization of vortex-cooled thrust chambers for methane/O2 and H2/O2. AIAA-2005-4131.

Shang Liu. Preliminary study on vortex combustion cold wall thrust chamber. Northwestern polytechnical university master thesis. 2009

Jiangwen Yang. Investigation on the experiment system of vortex combustion cold wall thrust chamber. Northwestern polytechnical university master thesis. 2010

Dechuan Sun, Shang Liu. Experimental research on bidirectional vortices in cold wall rocket thruster. Aerospace Science and Technology 18(1) · April 2012

Meredith, A.G., Black, D. L.. Automated Global Mechanism Generation for use in CFD Simulations. AIAA-2006-1168.

A. N. Lipatnikov and J. Chomiak. Turbulent Flame Speed and Thickness: Phenomenology, Evaluation and Application in Multi-Dimensional Simulations. Progress in Energy & Combustion Science, 28:1-74, January 2002.

Nakaya, S., Hatori, K., Tsue, M., Kono, M., Segawa, D., and Kadota, T.. A Numerical Study on the Effect of the Equivalence Ratio of Hydrogen/Air or Methane/Air

Mixtures on Minimum Ignition Energy in Spark Ignition Process. The Japan Society of Mechanical Engineers, Series B, Vol.72, No.517, pp.818-824, 2006.

Toshiaki Iizuka and Eric Besnard. Numerical Simulation of LOX/Methane Glow Plug Ignition System. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 31 July - 03 August 2011, San Diego, California.

Anand B Vyas, Joseph Majdalani, Martin J Chiaverini. The bidirectional vortex. part1: An exact invisicid solution. AIAA-2003-5052.