# A method to determine the domain of a rocket exhaust plume

Liu Zunyang, Sun Xiaoquan, Shao Li, Wang Yafu

(State Key Laboratory of Pulsed Power Laser Technology, Electronic Engineering Institute, Hefei 230037, China)

**Abstract:** Aimed at calculating the infrared radiation of a rocket exhaust plume exactly and efficiently, a method for defining the domain of an exhaust plume was reported. As a basic work, the flow field was calculated by using the CFD software FLUENT, and the radiation was calculated by means of Finite Volume Method (FVM). Then, variables that might be able to be used to differentiate an exhaust plume from surrounding atmosphere such as temperature and species composition were studied and the mass fraction of CO was chosen. When calculating the infrared radiation of an exhaust plume, only the part where the CO mass fraction bigger than the threshold was taken into account, and the rest were neglected. The change law of size of calculation domain, calculation time and infrared radiation with thresholds were studied. The results show that, as the threshold decreases, the size of calculation domain and the calculation time increase monotonously and rapidly, while the infrared radiation changes a lot at first and becomes stable at last. Besides, it was indicated by simulation experiments that the CO mass fraction 0.000 5 as the threshold is acceptable to define the calculation domain of the exhaust plume.

**Key words:** rocket exhaust plume; infrared radiation intensity calculation; domain definition; threshold

**CLC number:** TN21 **Document code:** A **Article ID:** 1007-2276(2014)03-0754-08

# 一种火箭尾焰区域确定方法

刘尊洋,孙晓泉,邵 立,汪亚夫

(电子工程学院 脉冲功率激光技术国家重点实验室,安徽 合肥 230037)

**摘 要**:为了准确、高效地计算火箭尾焰的红外辐射特性,提出了一种确定火箭尾焰区域的方法。作为基础工作,分别使用 FLUENT 和有限体积法(FVM)完成尾焰流场和红外辐射的计算。分析了可能用来区分尾焰和周围大气的变量,如温度和组分含量等,并选择 CO 的质量分数作为阈值变量。即,在选定阈值后,计算尾焰红外辐射时仅考虑 CO 质量分数大于阈值的区域,忽略小于阈值其区域对整体辐射的影响。分别研究了尾焰尺寸、计算时间和辐射强度随阈值的变化规律,结果表明,随着阈值的减小,尾焰尺寸和计算时间迅速单调增加,尾焰的红外辐射强度不断波动,且波动幅度逐渐变小,最终趋于平稳。另外,算例表明,选择 CO 质量分数为 0.000 5 作为阈值可以确定一个比较合理的尾焰计算区域。

**关键词**:火箭尾焰; 红外辐射强度计算; 区域确定; 阈值

---

**收稿日期**:2013-07-12; **修订日期**:2013-08-10

**基金项目**:国家重点实验室基金(10J006)

**作者简介**:刘尊洋(1984-),男,博士生,主要从事目标的红外辐射特性方面的研究。Email:liukp2003@163.com

**导师简介**:孙晓泉(1962-),男,教授,博士生导师,博士,主要从事光学技术方面的研究。Email:sunxq@ustc.com

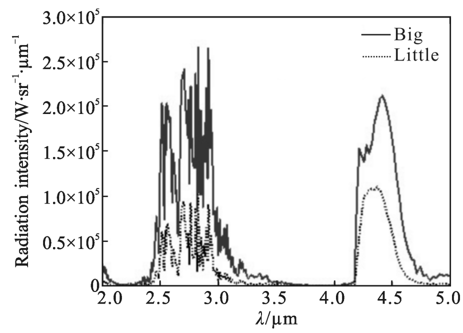
## 0 Introduction

Since infrared radiation from a rocket plume plays a significant role in base heating calculation, engine performance diagnostics as well as in identification and detection of rockets, its simulation has caused continuous interests over more than 50 years[1-2]. Over the years, significant progress has been made on both the models of flow field and radiation calculation and the results became more and more exact.

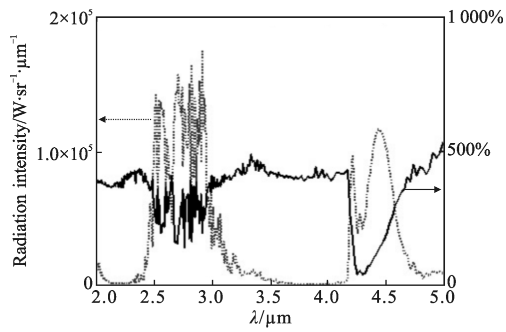
Several methods of flow field simulation were proposed, and the simulated flow field became capable of revealing the details of exhaust plumes. A. D. Devir [3] used GASP and INFRAD to calculate the flow field and infrared radiation of a Ballistic Evaluation Motor (BEM) and testified them with experiment data. Rodolphe Duval[4] reported a numerical simulation method which could calculate coupled radiative transfer and turbulent flows of aluminized solid propellant rocket engines. Jiang[5] studied a model calculating the after-burning flow field, Wang[6-7] used the FLUENT to calculate the after-burning flow field coupled with radiation transfer.

Radiation calculation methods with more accuracy have been proposed besides the classical models such as GASRAD[8] and SIRRM[9-10]. Surzhikov[11] studied Monte Carlor simulation methods thoughtfully from 2002 to 2005. Shuai[12-14] used backward Monte Carlo method and testified it. Cai[15], Fan[16] and Coelho[17] suggested the Finite Volume Method (FVM) to solve the radiation transfer equation (RTE) of liquid and solid rocket plumes. Zhang[18] and Dong[19] employed DOM to simulate the infrared characteristics of the solid rocket plume.

However, as far as the authors knew, efforts were emphasized on the calculation models, and there was little discussion on how to define the domain of an exhaust plume. Some papers[15, 16, 20-23] used a specified zone to calculate the infrared radiation, and some others didn't mention this aspect[13, 14, 16, 18, 23,24]. As is known to all, when ejected from the nozzle, the exhaust plume mixes with the air gradually without a clear boundary. Therefore, when calculating the radiation from an exhaust plume, the domain of the exhaust plume should be defined properly firstly. On one hand, if the domain is too small, the calculated spectral radiation might be inaccurate. On the other hand, if the calculation zone is too large, useless burden of calculation will be brought in. Figure 1 shows the spectral radiation calculation results of the same exhaust plume with different size of calculation domain. The differences on spectral infrared radiation suggest the necessity of choosing proper calculation domain.




(a) Spectral radiation intensity




(b) Amount and percentage of change on spectral radiation

Fig.1 Spectral radiation from one exhaust plume with different size of domain

This paper tries to develop an approach to define the domain of an exhaust plume for calculating the infrared radiation. As the basis of this work, the FLUENT is chosen to simulate the flow field, and the FVM is chosen to solve the radiation transfer equation.

The remainder of this paper is divided into three sections. The foundational work for domain determination, such as the method of calculating a flow field, issues about radiation transfer is presented briefly. This is followed by the studies of the approach for defining the domain of an exhaust plume. Then, the results and some discussions are provided. Finally, the concluding remarks are presented.

# 1 Calculation methods for flow field and radiation

## 1.1 Flow field

The FLUENT was used to calculate the flow field of an exhaust plume. The steady implicit density-based solver was chosen, and the mass conservation equation, momentum equations, energy conservation and species mass-conservation equations were solved together. The standardized-two equations were employed to solve the turbulent flow field.

## 1.2 Radiation parameters

The narrowband model was used to calculate the radiation parameters of an exhaust plume gas. The average transmittance $\bar{\tau}_\omega$ near wave number $\omega$ is:

$$\bar{\tau}_\omega=\exp\left(-2\frac{\bar{\gamma}_\omega}{\bar{d}_\omega}\left(\sqrt{1+\frac{u\bar{\kappa}_\omega\bar{d}_\omega}{\bar{\gamma}_\omega}}-1\right)\right) \quad (1)$$

Where $u=P_iL(296/T)$, standardized to 0.101 MPa, 296 K; $P_i$ is the fraction pressure of $H_2O$ or $CO_2$, $L$ is the path length transmitted through, $\bar{\kappa}_\omega$、$1/\bar{d}_\omega$ and $\bar{\gamma}_\omega$ are the average absorption, spectrum line density, and average half width at $\omega$ respectively. These parameters can be obtained from the HITEMP database[25-26]. Radiations from other gases are neglected except for the two most important radiation gases: $H_2O$ and $CO_2$. The transmittance of the mixed gases is the arithmetic product of transmittances of $H_2O$ and $CO_2$.

## 1.3 Solution of the radiation transfer equation

The variation of the spectral radiation intensity along a path is described by the radiation transfer equation(RTE)[27]:

$$\frac{dL_\lambda(s,\omega)}{ds}=-\alpha_\lambda(s)L_\lambda(s,\omega)+\alpha_\lambda(s)L_{b\lambda}(s)-\sigma_\lambda(s)L_\lambda(s,\omega)+\frac{\sigma_\lambda(s)}{4\pi}\int_{\omega_i=4\pi}L_\lambda(s,\omega_i)\Phi(\lambda,\omega_i,\omega)d\omega_i \quad (2)$$

Where $L_\lambda(s,\omega)$ is the spectral luminance at point $S$ in the direction $\omega$, $\alpha_\lambda(s)$ is the total absorption coefficient at point $S$, $\sigma_\lambda(s)$ is the scattering co-efficient of particles at point $S$, $L_{b\lambda}(s)$ is the spectral radiation intensity of blackbody at point $S$, and $\Phi(\lambda,\omega_i,\omega)$ presents the spectral scattering phase function.

We just took the exhaust plume without particles into account, therefore, the effect of scattering could be neglected, and the RTE could be written briefly as:

$$\frac{dL_\lambda(s,\omega)}{ds}=-\alpha_\lambda(s)L_\lambda(s,\omega)+\alpha_\lambda(s)L_{b\lambda}(s) \quad (3)$$

The FVM was used to solve the RTE in this paper. Space within the interior of the exhaust plume domain was subdivided into discrete non-overlapping volumes. Following the control volume of spatial discretization, the angular space was subdivided into $M=N_\theta\times N_\varphi$ control angles. An instance of volume and angular discretization is shown in Fig.2. Assuming all variables as constant over each control volume and each control angle, the RTE in the control volume $P$ and control angle $m$ could be written as:

$$\sum_j^M A_{c,j}L_{\lambda,c,j}^m D_j^m=[-\alpha_{\lambda,P}L_{\lambda,P}^m+\alpha_{\lambda,P}L_{b\lambda,P}]V_P\Omega^m \quad (4)$$

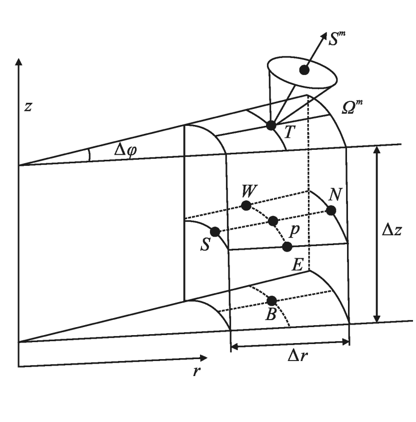



Fig.2 Schematic of control volume and control angle

The left of this equation presents the net loss of energy through all surfaces of the control volume $P$ in the control angle $m$. The right is the net gain of energy within the control volume $P$ in the control angle $m$. The detail of this equation and its solution can be found in Refs[15−16].

## 2 Variable chosen for domain definition

As the radiation comes from the high temperature gases of the exhaust plume, temperature might be the best variable to define the exhaust plume domain. But when examining the temperature of atmosphere at different altitudes, it was found that the temperature varies greatly as the altitude increasing. Figure 3 shows the temperature of the atmosphere along the altitude. It can be found that, the atmosphere temperature changes with the altitude with no law and becomes very high at high altitude, therefore, temperature isn't a suitable variable for defining the boundary between an exhaust plume and atmosphere.

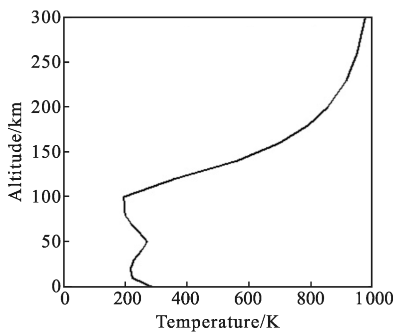



Fig.3 Temperature of the atmosphere along the altitude

Then, some other differences between an exhaust plume and atmosphere were studied. And it was found that species proportions of an exhaust plume were much different from that of the atmosphere. Besides, the species proportions of the atmosphere were stable. Therefore, the mole fraction or mass fraction of one proper species could be chosen as the variable to define the boundary. Species whose fraction is much more in an exhaust plume than that in the atmosphere might be considered as the proper one. The species compositions of dry clear atmosphere at the sea level are shown in Tab.1.

**Tab.1 Species volume fraction of dry clear atmosphere at the sea level**

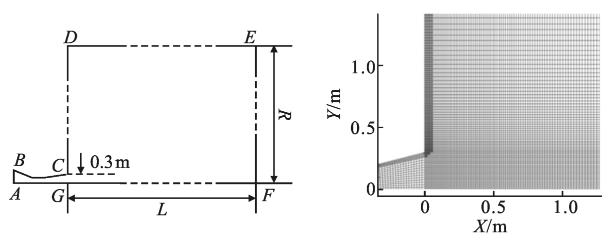
| Species | Volume percentage | Species | Volume percentage |
|---|---|---|---|
| $N_2$ | 78.084% | Kr | $1.14\times10^{-4}$% |
| $O_2$ | 20.947% | Xe | $8.7\times10^{-6}$% |
| Ar | 0.934% | $CH_4$ | $2\times10^{-4}$% |
| $CO_2$ | 0.032% | $H_2$ | $5\times10^{-5}$% |
| Ne | $1.82\times10^{-3}$% | CO | $6\times10^{-6}$% |
| He | $5.24\times10^{-4}$% | $SO_2$ | $1.0\times10^{-4}$% |

The dominate species in an exhaust plume are generally $H_2O$, $CO_2$ and CO etc [3,28,29]. $H_2O$ and $CO_2$ are the most important radiation species. However, in the atmosphere, the mass fraction of $H_2O$ varies a lot with the gas humidity and the mass fraction of $CO_2$ is much bigger than that of CO. Therefore, the mass fraction of CO was chosen as the variable for defining the boundary of an exhaust plume.

## 3 Calculation instance and discussions

### 3.1 Parameters of instance

The rocket was supposed to fly at the altitude of 10 km, and the parameters of the flow field were set as follows: considering the flow field's symmetry construction, half of the 2−D zone was chosen as the calculation zone shown in Fig. 4(a). The size of the calculation zone is 1 500 m×30 m, the radius of the throat and outlet of nozzle are 10 cm and 30 cm respectively. The boundary conditions definitions are shown in Tab. 3. The calculation grid near the nozzle is shown in Fig. 4(b). Neglecting the unimportant species, the species calculated in this paper are shown in Tab.4.




(a) Calculating zone (b) Grid near the nozzle outlet

Fig.4 Calculating zone and grid near the nozzle outlet

**Tab.3 Boundary conditions definitions**

| Zone | Boundary type | Pressure/MPa | Temperature/K | Velocity |
|---|---|---|---|---|
| *AB* | Pressure inlet | 4 | 3 000 | – |
| *CD* | Pressure far field | 0.101 325 | 288 | 0.2 Ma |
| *DE* | Pressure far field | 0.026 5 | 223 | 0.2 Ma |
| *EF* | Pressure outlet | 0. 026 5 | 223 | – |

**Tab.4 Mole fractions of species in the combustion chamber and in the free stream**

| Species | Combustion chamber | Free flow |
|---|---|---|
| $H_2O$ | 0.404 | 0 |
| $CO_2$ | 0.136 | 0 |
| CO | 0.111 | 0 |
| $H_2$ | 0.055 | 0 |
| $O_2$ | 0 | 0.211 |
| $N_2$ | 0.1 | 0.789 |
| HCl | 0.194 | 0 |

The radiation between 2–5 μm was calculated, and the band width of the narrow band model was chosen to be 12 $cm^{-1}$. The discretization methods of FVM were selected as follows: the direction was subdivided into $N_\theta \times N_\varphi = 13\times24$ discrete solid angles. In circular direction, the domain of the exhaust plume was discretized into 11 parts. In radial and axial direction, the spatial domain was discretized into fixed sizes $\Delta r$=0.6 m and $\Delta z$=6 m, meaning that, the number of control volumes would increase with the size of exhaust plume domain.

## 3.2 Results and discussions

The contours of CO mass fraction in the plume flow field are shown in Fig.5. With the purpose of finding a proper threshold, a series of CO mass fraction threshold from 0.003 to 0.000 06 were examined. The length of plume domain and time consumed for radiation calculation are plotted in Fig.6. It is clear that, the size and time increase rapidly as the threshold decreasing. The band radiation of 2.60–2.80 μm and 4.18–4.45 μm[30] are plotted in Fig.7. It is clear that, as the threshold decreasing, the band radiation changes a lot at first and becomes stable at last. The law of radiation changing with the threshold can be described as follows: while the threshold decreasing, the size of the calculated plume enlarges, on one hand, the new part of plume increases the total radiation of a plume; the outer cooler layer of plume will become thicker and absorb more resulting in decrement of total radiation. As the concentration and temperature of radiation gases in near field are much higher than that in far field, when the size of the plume is small, the radiation intensity changes greatly with the size; when the size is large, the radiation intensity changes little with the plume size.

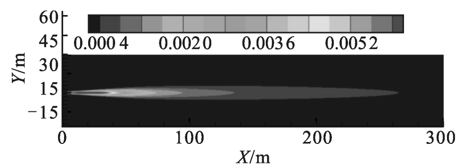



Fig.5 Contours of CO mass fraction of the exhaust plume flow field

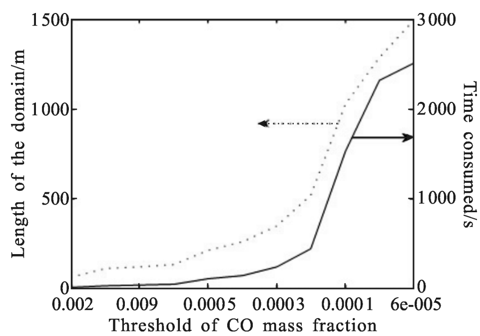



Fig.6 Length of plume domain and time consumed for calculation

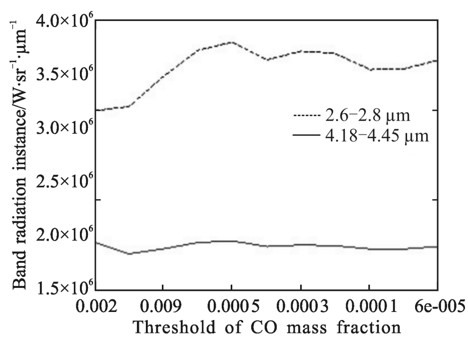



Fig.7 Band radiation

The radiation of the plume with the size of 30 m× 1500 m was calculated as a standard one. The percentage of difference between radiation in band 2.60 μm×2.80 μm and 4.18 μm×4.45 μm of plume defined by every threshold and the standard one are plotted in Fig.8. It can be found that the differences between radiations of the two bands are less than 5% when the threshold is less than 0.000 9, and the radiation intensity reaches the max value at 0.000 5. When the threshold is chosen as 0.000 5, the band radiations are about 2.5% and 1.8% greater than the standard one in corresponding bands, while consuming only 1.5 percent of time. It can be deduced that the radiation from the part where the mass fraction of CO is less than 0.000 5 is very weak, besides, this part is very large and the calculation is very time consuming according to Fig.6. Therefore, considering both accuracy and efficiency, the mass fraction of CO at 0.000 5 was suitable to be chosen as the threshold of the plume.

The spectral radiation instance of the plume defined by the threshold of 0.000 5 and the standard one are plotted in Fig.9. It can be found that the two spectral radiation curves consistent well with each other, meaning that there is little difference between the calculated spectral radiation of the two cases.

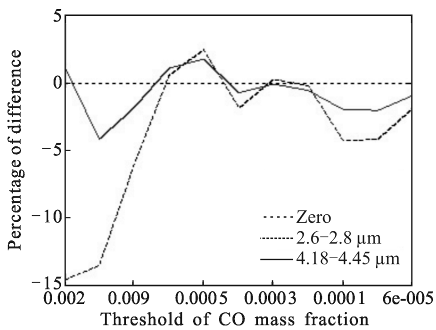



Fig.8 Percentage of differences of band radiation between plume defined by threshold of 0.000 5 and the standard one

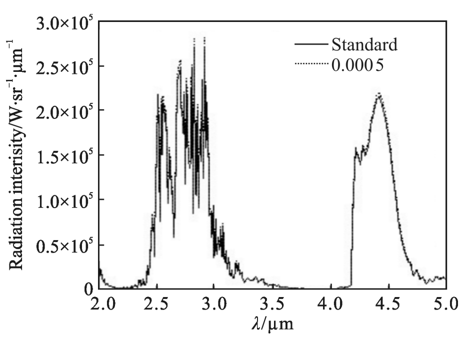
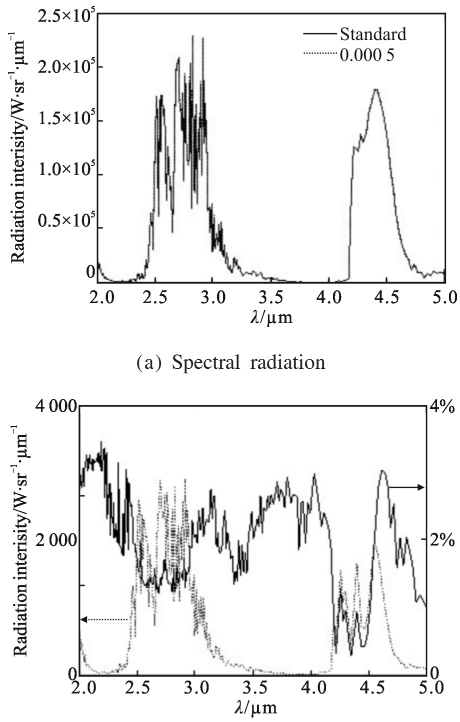



Fig.9 Spectral radiation of plume defined by threshold of 0.000 5 and the standard one

As a validation, the spectral radiation of exhaust plume at an altitude of 5 km was calculated, where the free flow pressure and temperature are 0.540 48 MPa and 256 K. The spectral radiation instance of the plume with the threshold of 0.000 5 and the standard one are plotted in Fig.10 (a), and the amount of differences and the percentage differences between the two cases are plotted in Fig.10 (b). It can be found in these two figures that there is little difference between the calculated spectral radiation defined by the threshold of 0.000 5 and the standard one. Therefore, the mass fraction of CO as 0.000 5 is suitable to be used as the threshold to define the domain of this plume.




(a) Spectral radiation

(b) Differences of spectral radiation

Fig.10 Radiation comparisons between plume defined by threshold of 0.000 5 and the standard one at the altitude of 5 km

## 4 Conclusions

This paper reported a method for defining the domain of an exhaust plume to calculate the infrared radiation. After analyzing several possible threshold variables, mass fraction of CO was chosen as the variable to define the boundary of an exhaust plume.

To get a proper threshold, comp arisons were made between the radiations of plume with the domain defined by a series of thresholds and the standard one with the size of 1 500 m×30 m. Conclusions were drawn as follows:

(1) The CO mass fraction is suitable to be used to define the domain of an exhaust plume for radiation calculation.

(2) According to the cases in this paper, as the threshold of CO mass fraction decreasing, the band radiation changed a lot at first and became stable at last, specially, when the threshold of CO mass fraction was less than 0.000 9, the differences of radiations in band 2.60–2.80 μm and 4.18–4.45 μm were less than 5% between the plume domain defined by the threshold and the standard one.

(3) According to the cases in this paper, CO mass fraction equaling to 0.000 5 was a proper threshold which could get a result 2.5% larger than that of the standard one, while using only 1.55 percent of time.

(4) As compositions of exhaust plumes and flight conditions vary from one to another, further more studies are needed to get a general threshold definition method.

## References:

[1] Nelson H F. Infrared radiation signature of tactical rocket exhausts [C]//St. Louis, Missouri: AIAA,AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conference, 1985: AIAA-82-0913.

[2] Rochelle W C. Review of thermal radiation from liquid and solid propellant rocket exhausts [R]. Huntsville: Marshall Space Flight Center, 1967: NASA TM X-53579.

[3] Devir A, Lessin A, Lev M, et al. Comparison of calculated and measured radiation from a rocket motor plume [C]// Reno, Nevada: AIAA,39th AIAA Aerospace Sciences Meeting & Exhibit, 2001: 2001-0358.

[4] Duval R, Soufiani A, Taine J. Coupled radiation and turbulent multiphase flow in an aluminised solid propellant rocket engine [J]. ***Journal of Quantitative Spectroscopy & Radiative Transfer***, 2004, 84: 513-526.

[5] Jiang Yi, Fu Debin. Numerical simulation for non equilibrium chemically reacting fluid field of the solid rocket motor exhaust plume [J]. ***Journal of Astronautics***, 2008, 29(2): 615-620.

[6] Wang W, Wei Z, Zhang Q, et al. Study on infrared signature of solid rocket motor afterburning exhaust plume [C]// Nashville, TN: 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2010: AIAA 2010-6847.

[7] Wang W, Wei Z, Zhang Q, et al. Infrared radiation signature of exhaust plume from solid propellants of different energy characteristics[C]//San Diego, California: 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2011: AIAA 2011-6140.

[8] Reardon J E, Lee Y C. A computer program for thermal radiation from gaseous rocket exhuast plumes(GASRAD)[R]. NASA-CR-161496, 1980:NASA-CR-161496.

[9] Ludwig C B, Malkmus W, Walker J. The standardized infrared radiation mode[C], 1981: AIAA-81-1051.

[10] Markarian P, Kosson R. Standardized Infrared Radiation Model (SIRRM -II) [R]. NY: Grumman Aerospace Corp, 1988: AFAL-87-098.

[11] Surzhikov S T. Monte Carlo Simulation of Plumes Spectral Emission [R]. Institute for Problems in Mechanics Russian Academy of Sciences(IPMech RAS), 2006:

[12] Shuai Y, Dong S K, Tan H P. Simulation of the infrared radiation characteristics of high-temperature exhaust plume including particles using the backward Monte Carlo method [J]. ***Journal of Quantitative Spectroscopy & Radiative Transfer***, 2005, 95: 231-240.

[13] Shuai Yong, Dong Shikui, Liu Linhua. Simulation of infrared radiation characteristics of high temperature free-stream flow including particles by using backward Monte Carlo method [J]. ***Journal of Infrared and Millimeter Waves***, 2005, 24(2): 100-104.

[14] Shuai Yong, Dong Shikui, Tan Heping. Numerical simulation for infrared radiation characteristics of exhaust plume at 2.7 μm [J]. ***Acta Aeronautica et Astronautica Sinica***, 2005, 26(4): 402-405.

[15] Cai G, Zhu D, Zhang X. Numerical simulation of the infrared radiative signatures of liquid and solid rocket plumes [J]. ***Aerospace Science and Technology***, 2007(11): 473-480.

[16] Fan Shiwei, Zang Xiaoying, Zhu Dingqiang, et al. Calculation of the infrared characteristics of the solid rocket plume with FVM method[J]. ***Journal of Astronautics***, 2005, 26(6): 794-797.

[17] Coelho P J. Fundamentals of a new method for the solution of the radiative transfer equation[J]. ***International Journal of***

***Thermal Sciences***, 2005, 44: 809–821.

[18] Zhang Xiaoying, Zhu Dingqiang, Cai Guobiao. Study the infrared characteristics of the solid rocket plume with DOM method and the influence of altitude [J]. ***Journal of Astronautics***, 2007, 28(3): 702–706.

[19] Dong Shikui, Yu Jianguo, Li Donghui. Numerical modeling of infrared radiation properties of exhaust plume by the Discrete Ordinates Method in body-fitted coordinates [J]. ***Journal of University of Shanghai for Science and Technology***, 2003, 25(2): 159–163.

[20] Edwards D K, Babikian D S. Radiation from a nongray scattering, emitting, and absorbing solid rocket motor plume [J]. ***J Thermophysics***, 1990, 4(4): 446–453.

[21] Surzhikov S T. Three-dimensional model of the spectral emissivity of light-scattering exhaust plumes [J]. ***High Temperature***, 2004, 42(5): 763–775.

[22] Hao Jinbo, Dong Shikui, Tan Heping. Numerical simulation of infrared radiation properties of solid rocket engine exhaust plume[J]. ***Journal of Infrared and Millimeter Waves***, 2003, 22(4): 246–250.

[23] Nie Wansheng, Yang Junhui, He Haosheng, et al. The IR radiation characteristic of exhaust plume of the liquid rocket engine [J]. ***Journal of National University of Defense Technology***, 2005, 27(5): 91–94.

[24] Feng S, Nie W, Xie Q, et al. Numerical simulation of flow field and radiation of an aluminized solid-opellant rocket multiphase exhaust plume [C]//Miami, FL: 39th AIAA Thermophysics Conference, 2007: AIAA 2007–4415.

[25] Dong Shikui, Tan Heping, Yu Qizheng, et al. Infrared radiative spectral band-model parameters for water vapor in the 300–3000 K temperature range [J]. ***Journal of Engineering for Thermal Energy and Power***, 2001, 16(1): 33–38.

[26] Dong Shikui, Yu Qizheng, Tan Heping, et al. Narrow band model parameters of high temperature radiation for carbon dioxide of combustion products [J]. ***Journal of Aerospace Power***, 2001, 16(4): 355–359.

[27] Siegel R, Howell R J. Thermal Radiation Heat Transfer[M]. Washington D C: Hemisphere and McGraw–Hill, 1981.

[28] Nelson H F. Influence of participates on infrared emission from tactical rocket exhausts [J]. ***J Spacecraft***, 1984, 21(5): 425–432.

[29] Simmons F S. Rocket Exhaust Plume Phenomenology[M]. EI Segundo: CA: The Aerospace Press and American Institute of Aeronautics and Astronautics, 2000.

[30] Zhang Guangming, Sun Shengli, Zhang Wei, et al. Model and application of image plane illumination for the space-based infrared detecting of boost-phase missile [J]. ***Journal of Infrared and Millimeter Waves***, 2007, 26(6): 425–428.