A Review of Studies on Temperature Field Changes of Solid Rocket Engines under Different Environments

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Abstract. At home and abroad this paper summarizes the present stage of solid missile motor and the loading of the temperature field of research, the analysis of environment includes variable temperature load, surface vessel, warehouse storage for a long time, cooling solidification, by special heat load, etc., the results verify the reliability of the principle, put forward some new model and algorithm formula, and provide certain guiding significance to the reality.

1. Introduction

Military equipment failure caused by various environmental factors will cause great economic losses and adverse social effects.During world war ii, Sixty percent of the avionics shipped from the United States to the far east are rendered useless by moisture and mildew before they are used.Britain's radar has an average MTBF of 116 hours in Europe, 61 hours in the Mediterranean and just 18 hours in south-east Asia.In the 1950s, 80 percent of the U.S. military's electronic equipment malfunctioned on the Korean battlefield because it could not adapt to the cold climate. The latest data shows that about 50% of the failure of American ammunition is related to the environment, and the damage of weapons and equipment caused by the environment accounts for more than 50% of the whole process of storage and transportation, exceeding the combat damage.

With the increasing complexity of weapons and equipment, the continuous application of new ammunition and new technologies, and the increasingly harsh operating environment, the reliability and safety of weapons and equipment become more prominent, and the storage complexity of missiles increases greatly.The safe storage and reliable use of missile ammunition directly affect the normal performance of weapons and equipment.

China's early missile launch mode is a primary regional highway mobile launch mode.Since then, underground well storage and underground thermal launch, underground well storage and ground launch, highway network area rapid mobile launch and other launch methods have been adopted in succession, which greatly improves the survivability and operational response speed of missile weapon system.

A certain type of missile is a roadbed mobile medium-range ballistic missile equipped by the rocket army.It is also an anti-ship ballistic missile that can attack ships at sea, including aircraft carriers. It can effectively curb the arrogance of countries with aircraft carriers led by the United States and enhance China's national defense strength.The engine material properties of the missile are shown in Table 1.

Table 1. Material performance parameters of SRM

Part name	c/[J/(kg·K)]	λ/[W/(m·K)]	ρ/(kg/m^3)	E/Mpa	v	α/K^{-1}
shell	512.0	38.95	7800	200000	0.3	1.10×10^{-5}
Thermal barrier	2260	0.18	1200	22	0.498	2.25×10^{-4}
Propellant/coating	115.0	0.57	1760	E(t)	0.498	8.60×10^{-5}

2. Research status at home and abroad

2.1. Foreign research progress

The thermal safety of solid rocket motors is very important.The 1973 NASA space vehicle design standards have pointed out [5]: The failure of thermal test or launch is mainly caused by the destruction of structural integrity.The same year, the French solid rocket propellant researchers think [6]: There are many reasons for the failure of solid rocket motor, but the main reason is related to the state of propellant.

The thermal conductivity of composite cylinder wall has a wide range of engineering application background, but many of the structure boundary conditions are complex, difficult to analyze and solve or even can not be solved, often using numerical methods to calculate.However, numerical solutions are not easy to understand the physical meaning of the parameters that affect the problem, so various approximate analysis methods have been developed.In 1970, Stehfest put forward the calculation formula of Laplace change numerical inversion, which provided a new method for approximate analysis in the field of heat transfer calculation. By comparing the experimental results and calculation results, the maximum relative error was less than 5%, indicating that the calculation method was reliable [7-8].

In 1983, HELLER.R.A studied the influence relationship of the engine under environmental load and proposed the temperature ribbon model [29],

$$\epsilon(t)=\epsilon_m+\epsilon_y\sin\omega_y t+\epsilon_d\sin\omega_d t \tag{1}$$

Among them

$\epsilon(t)$ Is the ambient temperature at a certain moment;

ϵ_m Is the annual average temperature of the region;

ϵ_y is the quarterly temperature variation amplitude in the region $\omega_{季}$ Is the change frequency of seasonal temperature, and its value is $2\pi/(365*24*3600)$, The unit is s^{-1};

ϵ_d Is the daily temperature variation amplitude in this region,, ω_d Is the daily temperature change frequency, and its value is $2\pi/(24*3600)$, The unit is s^{-1}.

Moreover, HELLER.R.A verified the accuracy and applicability of the model through relevant experiments, which provided a method basis for future studies and was widely used.

CapettiM IM, French D A et al. studied the distribution of thermal stress of solid engine from 2000 to 2003 by applying the linear thermo-viscoelastic constitutive relation of small deformation, and calculated and analyzed the thermal stress of shell composite propellant column under the load around the cyclic temperature [37-38].

In 1962, Ramey proposed a classical wellbore temperature heat transfer model [39], In 1994, Hansan et al. considered the joule-thomson effect on the basis of Ramey model, and introduced the heat diffusion time on the basis of Ramey model, and proposed the instantaneous temperature heat transfer model [40].

2.2. Domestic research status

Feng zhigang and zhou jianping of NUDT in 1994 [3] The mechanical response of solid rocket motor (SRM) propellant column during storage is analyzed due to the change of temperature load spectrum.Based on the constitutive relation of viscoelastic integral creep, the finite element model which

can analyze the thermal load of viscoelastic structure is derived, and the thermal stress problem of beam, wall thickness cylinder and real solid rocket engine is analyzed.

In 1997, Zhu zhichun [5]. Finite element method (fem) is used to calculate the three dimensional transient temperature field of a solid rocket motor (SRM) propellant column when it is solidified and cooled.

Li luxian, shen yapeng etc. [4] adopted a three-dimensional model was adopted to analyze the thermoviscoelastic quasi-static response of solid rocket engine propellant column under the action of curing temperature, internal pressure and axial overload by finite element method.

In 2001, Zhou yanhuang et al. demonstrated the importance and necessity of accurate temperature measurement, pointed out the irrationality of existing domestic weapon temperature determination methods, and discussed the feasibility and urgency of domestic artillery and rocket generally equipped with temperature device from the perspective of economy and cost-effectiveness ratio [28].

Developed for applicable to the need of rocket propellant initial temperature measuring device, 2002 Liu Qingcai, yan-huang zhou people using computer numerical simulation and experiment methods, such as several rocket propellant is studied in the first kind of boundary conditions of unsteady temperature field, the calculation results are in good agreement with the experimental measurements of the unsteady temperature field of the propellant temperature distribution change law and influence of the main thermal resistance, compares the temperature and quality of the meat thick 1/2 weighted average temperature, obtained the data in table 2 and table 3.

Table 2. Errors between mass weighted average temperature and one at the half of maximum thickness

Conditions	Maximum errors	Average square root errors
High temperature	3.9℃	2.9℃
Low temperature	-2.8℃	2.8℃

Table 3. Errors between mass weighted average temperature and one at 0.76 position of maximum thickness

Conditions	Maximum errors	Average square root errors
High temperature	3.9℃	2.9℃
Low temperature	-2.8℃	2.8℃

The comparison in the table shows that the mass weighting point is the best position to measure the temperature [25-26].

In the same year, in order to accurately predict the working performance of solid rocket engine, gong xiaohong, hou hanhu and others studied the relationship between the propellant temperature of the engine and the environment, proposed the concept and formula of the dynamic equivalent temperature of propellant column, and summarized the relationship between the equivalent temperature of propellant column of a solid engine and the influencing factors [14].

In 2004, according to the characteristics of artillery ammunition, liu yunan et al. established a two-dimensional axisymmetric model of ammunition, and derived a group of differential discrete schemes with the method of control volume integration in the cylindrical coordinate system [27].

Naval aeronautical engineering institute of gao-chun li, Yuan Shusheng, original nutrient-laden LAN, etc in 2005 to 2008, based on ANSYS software platform, with the aid of finite element theory, established a multilayer long hollow cylinder, as shown in figure 1, for the thermal load of solid rocket motor in response to the detailed analysis and numerical simulation, it is concluded that the corresponding temperature field and stress field, effective evaluation to the outside world the dangers of solid rocket motor under thermal loading [21-23].

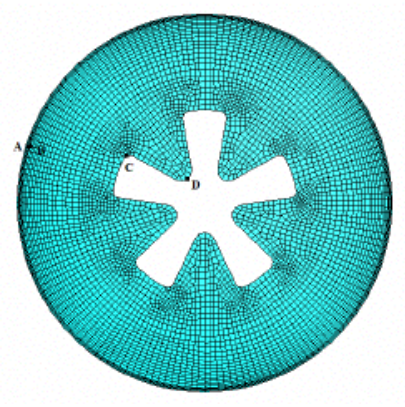

Figure 1. Long cylindrical finite element mesh

In order to solve the temperature distribution in the composite material, in 2005, wang guangming et al. established a mathematical model for the heat conduction of the composite cylinder wall according to the basic law of heat conduction.Laplace transform and Stehfest numerical inversion technology were used to perform multiple iterative inversion of Laplace transform, and the approximate solution of temperature distribution was obtained, which can be applied to the analysis and calculation of specific engineering problems [9].

In order to analyze the transient temperature field and the distribution of thermal stress and strain, yu Yang et al. adopted the finite element model based on the time-temperature equivalence principle and the simple material assumption of heat flow in 2007 to obtain the position of the danger point and compared the structural integrity of the composite charge column at different storage temperatures.The results show that the irrationality of the structure of charge column is the main reason for the damage of the structural integrity of composite charge column under low temperature storage condition [13].

That same year, Ding Yongjiang, strong LanFei using finite element method, analyzed under the temperature load, the modulus, poisson's ratio, material parameters, such as thermal expansion coefficient of solid rocket motor grain structure integrity, compared the curing temperature and when the grain strain trend along with the change of material parameters, and find some useful rules, provides the reference for later researchers [19].

In 2009, pan wengeng et al. simulated the thermal stress of some engine tubular propellant columns under ambient constant temperature and cyclic load [15], Figure 2 places a constant temperature for solid rocket motor T = 30 ℃, the temperature of the load after loading to solve the temperature distribution, the temperature change along the path curve is shown in figure 3.

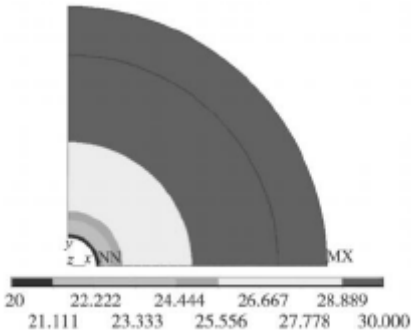

Figure 2. Constant temperature condition

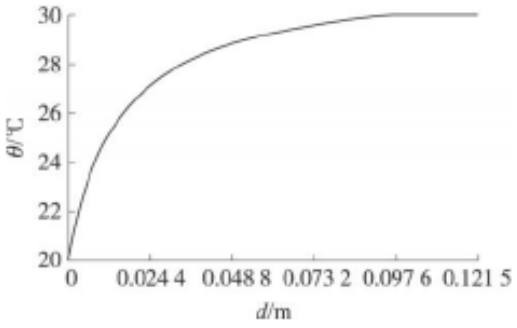

Figure 3. Temperature versus distance curve

When the model is subjected to cyclic variable load again, there is a significant difference in the temperature field of the propellant column inside the engine, and the temperature distribution cloud

diagram is shown in figure 4.Take the point on the interface between the shell and the insulation layer as B, the point on the interface between the insulation layer and the charge column as C, and the point on the interior of the charge column as D. The curve of the three points with temperature change is shown in figure 5.

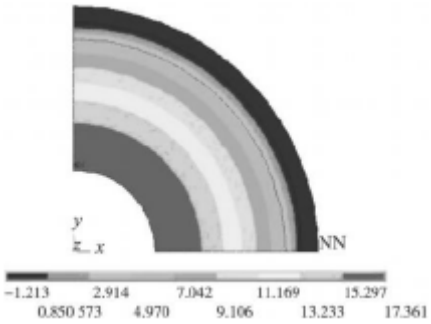

Figure 4. Week of variable load

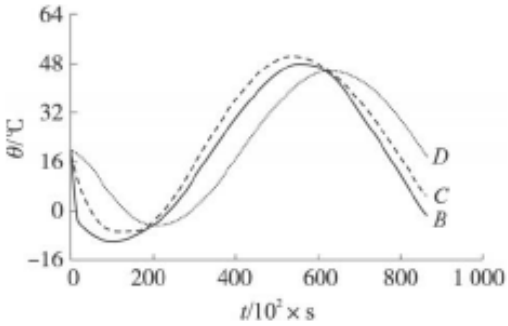

Figure 5. Temperature curve at three points over time

2010, eddy to study the influence of the external environment of solid rocket motor performance, based on the thermal viscoelastic model of propellant charge, using the finite element method for temperature change of the grain temperature stress are analyzed, and the external environment is studied different initial temperature and rate of temperature riseinfluence on column temperature stress, the determination of stress within a certain star medicine column dangerous points [11-12].

Missile solid rocket motor has strict requirements to the storage environment, 2011, hong-yan liu, Li Guobao [1] on shipboard case of solid rocket motor is studied, the shipboard environment temperature load model is established, the heat transfer model of solid rocket motor, the carrier of solid engine temperature load under the action of heat transfer simulation analysis, according to the simulation results, can further study the internal charge and interface between stress situation, in the evaluation of solid rocket motor carrier using reliability and the storage life.

In the same year, long bing et al. analyzed the thermo-stress coupling simulation of the engine under low temperature and temperature cyclic load, focused on the study of the influence of temperature load on the solid engine, and obtained the temperature distribution and stress-strain response of the engine under the two loads [17].

In 2012, deng bin et al. considered the influence of natural convection heat transfer between the shell and the air, carried out thermally coupled finite element analysis on the structure of solid engine, and discussed the variation law of temperature and strain response under different convection heat transfer coefficients [24].

In 2015, zhou hongmei et al. established the solid rocket engine charging mathematical model and physical model, and used numerical simulation to simulate the curing and cooling process, and obtained the stress and strain law of solid propellant column in the curing and cooling process [10]. Based on the alternating temperature model of sinusoidal function, yuan jun carried out the heat transfer analysis of solid rocket engine and studied the time delay and distribution law of the temperature of propellant column.According to the temperature law of the charge column with large aspect ratio, an equivalent temperature algorithm is proposed based on the results of thermal analysis [16]. Based on the finite element method, shi runlong conducted a transient temperature field simulation calculation on the cooling process of the engine, and determined the time when the engine reached the temperature balance during the cooling process, providing data support for the engine insulation test and temperature gradient test [18].

3. Conclusion

In terms of the literature reviewed, since the 1970s, the temperature field of solid missile engine and its charge has been studied abroad, and many important theories have been put forward.The domestic research on solid missile engine and its charging temperature has been carried out since the 1990s.However, based on the comprehensive analysis of the research results at home and abroad, no one has conducted analysis and research on the environmental impact of the missile solid engine in the state of imminent launch in the case of power failure in the field. Therefore, this aspect can be selected as the research content and the research can be carried out on the basis of previous studies, which is of great military significance.

References

[1] Liu hongyan, li guobao. Analysis of heat transfer of solid state engine under ambient temperature loading on shipboard [J]. Tactical missile technology, 2011 (1): 44~48.
[2] Zhu Zhichun. Finite element analysis of three-dimensional temperature field of solid rocket engine propellant [J]. Propulsion technology,1997, 18 (2)
[3] Feng zhigang, zhou jianping. Analysis of temperature stress of solid rocket motor propellant in long - term storage [J]. Propulsion technology, 1994 (6): 43 -49.
[4] Li Luxian. Thermal viscoelastic finite element analysis of three dimensional charge column [J]. Propulsion technology, 1997 18 (3).
[5] Anon. Solid propellant grain structural integrity analysis [R]. NASA Space VehicleDesign Criteria Monograph, NASA SP-8073, 1973
[6] Alan davina. Solid rocket propellant technology [M] Beijing: yuhang publishing house, 1997: 78~80.
[7] STEHFEST H. Algorithm 368 numerical inversion ofLaplace transforms}.11 .Communications of ACM, 1970, 13 (1): 47-49.
[8] EHFEST H.Remark on algorithm 368 numerical in-version of Laplace transforms}. 11. Communications ofACM, 1970, 13 (10): 624-625.
[9] Wang guangming, li huayu. A new method for solving the unsteady heat conduction problem of composite cylinder wall is presented. [J]. Journal of petroleum university (natural science), 2005: 29 (2).
[10] Zhou hongmei, wang bin. Analysis of temperature and stress field of solid rocket engine propellant during solidification and cooling. [J]. Missile and space launch technology, 2015: 1
[11] Wang yufeng, li gaochun. Analysis of temperature stress of solid charge under variable temperature environment [J]. Journal of aerospace, 2010: 31 (9).
[12] Wang yufeng, zhang yong. Accumulation damage analysis of HTPB propellant column under variable temperature environment. [J]. Journal of projectile and guidance, 2010: 30 (6).
[13] Yu Yang, tu ningfei, zhang ping. The three - dimensional structural integrity analysis of a free - loaded composite charge column [J]. Solid rocket technology, 2007, 30 (1); 34~38.
[14] Gong xiaohong, du xin, hou han-hu. Research on temperature measurement of tactical solid rocket engine [J]. Solid rocket technology, 2002, 25 (4): 59-62.
[15] Pan wengeng, wang xiao-ming, Chen rui. Analysis of influence of ambient temperature on engine charge column [J]. Journal of nanjing university of science and technology, 200933 (1): 117-121.
[16] Yuan jun. Analysis of temperature field of solid engine propellant under alternating ambient temperature. [J]. Solid rocket technology, 2015: 38 (6).
[17] Long bing, chang xin long. Structure analysis of solid - state engine under temperature load. [J]. Journal of projectile and guidance, 2011: 31 (2).
[18] Shi runlong, zhang liang. Simulation method of engine temperature load response. [J]. Industrial technology, 2015: 17 (67).
[19] Ding yongqiang, LAN feiqiang. The influence of material parameters on the structural integrity

of charge column under temperature loading. [J]. Aviation weapon, 2007, 5.
[20] Zhu zhichun, CAI e. Finite element analysis of three-dimensional temperature field stress field of solid rocket engine propellant [J]. Propulsion technology, 1997 (2).
[21] Li gaochun, yuan shusheng, yuan weilan. Study on the thermal response of solid rocket motor.[J]. Journal of projectile and guidance, 2005: 25 (4).
[22] Li gaochun, yuan shusheng, yuan song. Study on thermal safety of solid rocket motor. [J]. Journal of dynamite, 2006.02: 29 (1).
[23] Former wei LAN, li junwei. Study on transient response of solid rocket motor to alternating ambient temperature. [J]. Journal of naval aeronautical engineering college, 2008.09: 23 (5).
[24] Deng bin, shen zhibin. Thermodynamic coupling analysis of solid - state engines considering convection heat transfer.[J]. Solid rocket technology, 2012: 35 (1).
[25] Liu qingcai, zhou yanhuang. Unsteady thermal conductivity and temperature field characteristics of a propellant. [J]. Propulsion technology, 2002.12: 23 (6).
[26] Liu qingcai, zhou yanhuang. Numerical study on unsteady temperature field characteristics of 130 rocket propellant. [J]. Journal of projectile and guidance, 2002.
[27] Liu Yunna. Numerical simulation of gun charge temperature distribution. [J]. Journal of the college of ordnance engineering, 2004.06: 16 (3).
[28] Yan-huang zhou. Research on the accurate real-time temperature measurement of modern rocket charge. [J]. Journal of ballistic, 2001.03:13 (1)
[29] HELLER R A.Thermal Storage Life of Solid Propellant Motors [J]. Soacecraft, 1983, 20 (2): 144-149.
[30] Hu quanxing, zhao jiwei. Natural storage environment model based on real weather data [C]// Proceedings of the 25th annual conference on solid rocket propulsion, 2008.
[31] Chen Ruxun. Design and research of solid rocket engine [M]. Beijing: aerospace press, 1991.
[32] charge column under typical thermal load [C]. // Proceedings of the third national solid state engine design technology academic exchange conference, 2011.
[33] Li Baoxuan. Solid propellant performance [M]. Xi 'an: northwest polytechnical university press, 1990.
[34] Yang qiangsheng, pu baorong. Advanced heat transfer [M]. Shanghai: Shanghai jiaotong university press, 1996.
[35] Kong Xiangqian. Application of finite element method in heat transfer [M]. Beijing: science press, 1998.
[36] Zhang Shuqian. Proficient in finite element analysis [M]. Machinery industry press 2016.4.
[37] Shiang Woei Chyuan .A study of loading history effect for thermoviscoelastic solid propellant grains [J]. Jounal of Computers and Structures 2000 77: 735--745.
[38] CapettiM IM, French D A. Numerical solution of a thermoviscoelastic contact problem by a penalty method [J]. SIAM Journal on Numerical Analysis 2003, 41(4): 1487- 1504.
[39] Ramey Jr H J. Wellbore heat transmission [J]. Journal of Petroleum Technology, 1962, 14 (04): 427-435.
[40] Hasan,Kabir. Aspects of wellbore heat transfer two-phase flow [J] .SPE Production & Facilities, 1994 9 (03): 211-216.