

Advanced Computer Science on Internal Ballistics of Solid Rocket Motors

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In this paper, described is the development of a numerical simulation system, what we call “Advanced Computer Science on SRM Internal Ballistics (ACSSIB)”, for the purpose of improvement of performance and reliability of solid rocket motors (SRM). The ACSSIB system is consisting of a casting simulation code of solid propellant slurry, correlation database of local burning-rate of cured propellant in terms of local slurry flow characteristics, and a numerical code for the internal ballistics of SRM, as well as relevant hardware. This paper describes mainly the objectives, the contents of this R&D, and the output of the fiscal year of 2008.

Key Words: Solid Rocket Motor, Internal Ballistics, Casting Simulation, Local Burning Rate

1. Introduction

In the quality assurance of solid rocket motors (SRM), some inspections are carried out employing non-destructive inspection (NDI) tools, such as X-ray and ultrasound inspections, as far as their capability is applicable for specific purposes. The production normality, however, cannot always be inspected directly by these methods. Therefore, part of the total quality of final products is always guaranteed by process and trend control, that is, the product quality is indirectly guaranteed with complements of direct product inspections.

The validity of SRM development is usually authorized through qualification-model (QM) static-firing tests. Sometimes problems may be discovered still in this phase of development if there is some overlook in previous development activities, and such findings are reflected in reconsideration of the design and manufacture. It may be more fortunate that such a failure comes out in QM tests than nothing of all problems come out. Problem seeds lurk in places not to be noticed easily. After several flights, such problems sometimes result in a major failure of the mission in some case. The lesson fee in the case becomes very high. Learning from the failure is useful, but sometimes, the failure influences the fate of the project, too. There is not a shortcut to the improvement of reliability. It is important to know where seeds of potential failures lurk and to take measures to avoid them beforehand. For this purpose, it is necessary to well understand, during the development of SRM, all the physical phenomena happening in the process of manufacture and operation. With this meaning, there is a great and growing

need for the further development of numerical simulation technologies in future.

Researches of numerical simulation of SRM have covered a variety of aspects, such as,

- SRM internal ballistics evaluation by burn-back simulation^{1,2)}, also with casting process effect^{3,4)}
- modeling and simulation of the random packing⁵⁾ and of the combustion of heterogeneous solid propellants⁶⁻¹⁰⁾ with aluminum agglomeration modeling¹¹⁻¹⁴⁾
- multi-dispersed multi-phase flow simulation including aluminum/alumina droplets^{11,15,16)}, model of aluminum agglomeration^{17,18)}, and simulation of slag mass accumulation of condensed phase¹⁹⁾
- simulation of vortex-shedding²⁰⁾ and thrust oscillation²¹⁾ with view points of adaptive control²²⁾ of effect of burning aluminum droplets²³⁾, of nozzle cavity effect²⁴⁾, of wall and inhibitor effect^{25,26)}, and of large solid rocket boosters²⁷⁻³¹⁾
- simulation of internal flow with respect to nozzle ablation³²⁻³⁴⁾ and to roll-torque generation³⁵⁾
- simulation of combustion stability³⁶⁾
- assessment of acoustic, vibration, and shock environments of SRM firings³⁷⁾, assessments of attenuation of radio frequency signal due to the SRM plume^{38,39)}, and so on.

In order to improve the reliability of SRMs, it is important to establish the accuracy of numerical simulation with progress of model refinement of each physical phenomenon checking with real firing results. One of good examples of such establishment is a bunch of researches on thrust oscillation problems observed during the second half of the burning period of P230 motor, the booster of Ariane-5, and numerical simulations have been applied to clarify the role of

vortex shedding from obstructs like inhibitors, from propellant grain edges, and from combustion surfaces, on acoustic pressure growth^{20,23,24,27,29,30}.

Another example is the lessons learned from the failure of nozzle-liner due to localized ablation (erosion) of a solid rocket booster (SRB-A) of the Japanese H-IIA launch vehicle⁴⁰. Of course, in this case, proper material selection for the ablative parts is essential on one hand, appropriate design of the contour of nozzle is very important. Numerical simulations of three-dimensional internal flows were greatly utilized in the return-to-flight activities of SRB-A.

Physical phenomena occurring in SRM are based on various disciplines, so the research on multi-disciplinary numerical simulations has proceeded and becomes another significant trend of numerical simulations of SRM^{28,41-44}. In order to integrate simulations of different disciplines, technical development of the computer science which makes it possible to treat simultaneously distributed scales of both the time and the space about each phenomenon is required. Future improvement on this technology is expected.

One can consider a possible example of future multi-disciplinary simulation as follows. Firstly, simulation of propellant slurry cast into a motor chamber is coupled with a random packing simulation. By realizing this coupling, one can analyze variation of the local packing characteristic due to local slurry flow parameters such as viscosity and velocity. Moreover, one can evaluate pressure response characteristics and steady burning rate at a local position by three-dimensional heterogeneous combustion including aluminum aggregation and agglomeration effects. Such information constitutes non-steady burning-surface boundary conditions for simulations of the multi-dispersed, multi-phase flow of burning aluminum/alumina droplets and combustion gas inside a motor chamber. Such flow simulation can analyze also the acoustic, vortical, and combustive perturbation behaviors. The CFD simulation, moreover, if coupled with thermo visco-elastic analyses of a propellant grain, with ablation simulations of the throat and the nozzle liners, and with local regression analyses of a propellant grain, will make it possible to evaluate more realistic characteristics of the ignition process, erosive and unsteady burning, thrust oscillation, roll-torque generation, and total internal ballistics of SRM.

Development of computer codes for advanced three-dimensional internal ballistics prediction has already been started in several countries. In Japan the authors have conducted some investigation on slurry flows of composite propellant by dual-directional X-ray observation⁴⁵, experimental study on the mid-web anomaly⁴⁶, and numerical simulation of the internal ballistics⁴⁷.

Since April 2008, the authors set about the R&D of numerical simulation system for the advanced computer science on SRM internal ballistics (ACSSIB) which consists of casting simulation of slurry of composite propellant, modeling of local burning rate characteristics, and combustion pressure (internal ballistics) prediction. This paper describes mainly the objectives, the contents of this R&D, and the output the fiscal year of 2008.

2. Local Burning Rate Characteristics

To improve the accuracy of numerical simulation systems for SRM internal ballistics, well understanding and good databases on local burning rate correlations related to propellant casting processes are desired. The casting process impact on local burning rate is known as a term "midweb anomaly" or "hump effect"^{4,48-51}. Midweb anomaly is a phenomenon that the local burning rate, which is normally depends on pressure, initial temperature and fluid dynamics of internal flow, depends on propellant casting process i.e. propellant slurry flow. Some studies have measured the burning rate fluctuation during combustion directly, and the evidence of burning rate fluctuation has been shown^{4,49,51}. In the simulation system developing in ACSSIB, the local burning rate will be determined by tracing the casting process. Although it is known that the local burning rate is determined by the function of angles between layer of propellant sag (see section 5) and burning direction⁴, it is necessary to obtain the quantitative function and parameters by experiments for individual cases. In addition, physical mechanism of the phenomena has not been fully understood. Thus, the authors have been working on construction of database or mathematical correlation of midweb anomaly that should be applied to new numerical simulation system. The work consists of experimental and CFD of slurry casting (see sections 4 and 5).

The authors has confirmed that the midweb anomaly occur in small motors, which are center perforated internal and both end surface burning, and that burning rate directivity in motor grain⁴⁶ exists. In Fig.1, typical pressure history of small motor (Fig.2) including midweb anomaly is shown. The composition of test propellant is as same as practical composition of sounding-rocket motors. The main ingredients of present propellants are ammonium perchlorate (AP), aluminum (Al) and binder, which mainly consists of hydroxyl-terminated polybutadiene (HTPB). The composition is HTPB/AP/AL=14/68/18.

This motor was cast by the Process-A described in Fig.3. In this experiment, measured pressure exceeds the theoretical value by 4% in the period between 1s and 2s. The deviation of pressure-time curve from its theoretical, in which uniform burning rate is assumed, depends on slurry casting process. In Fig.4, comparison of pressure-time curve distortion, which is defined as the ratio of experimental and theoretical, is shown for two types of grain casting process as in Fig.3. Two firing tests are prepared for each processed grain. The distortion of pressure obviously depends on casting process in the first half period during 0s to 2s. But in the latter half period, the distortion of pressure is similar for both processes except for result of motor #2 by Process B. This result indicates that the midweb anomaly appears for both casting process, but the time when the pressure hump appears depends on casting process. Because the firing tests were done with same condition except for casting process, the distortion of pressure can be understood as the variation of total burning rate through web thickness. Thus, in case of Process A, the

burning rate increases toward outer direction from internal surface, and the value reaches the peak at about 30% depth of web. After the peak, the burning rate decreases until the end of burning. Here, the final peak after 3.5s is caused by unsteady effect due to the thinness of the web.

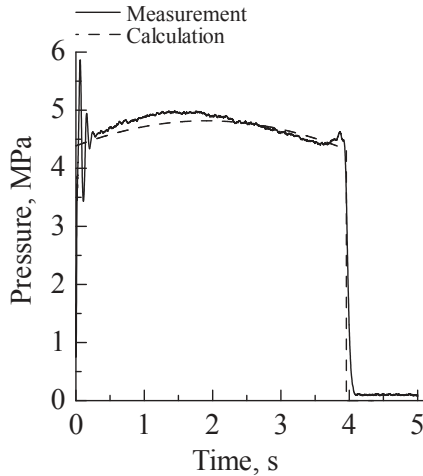


Fig.1. Typical pressure and thrust-time curves affected by midweb anomaly.

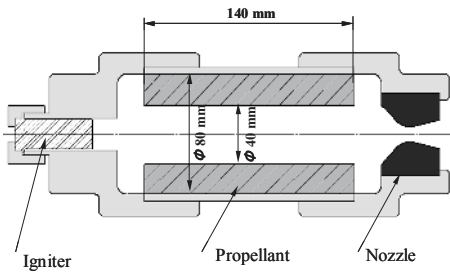


Fig.2. Schematic of small test motor.

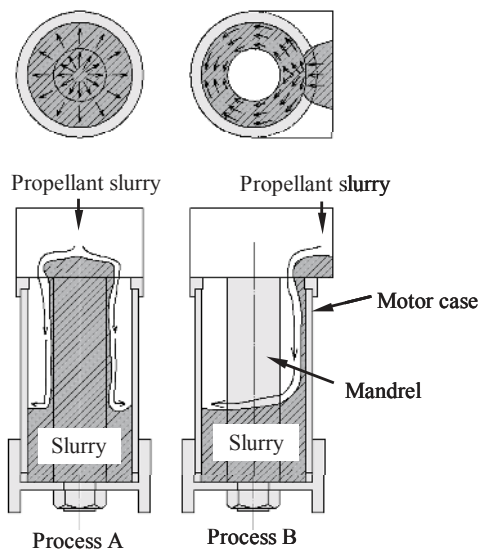


Fig.3. Process of propellant slurry casting.

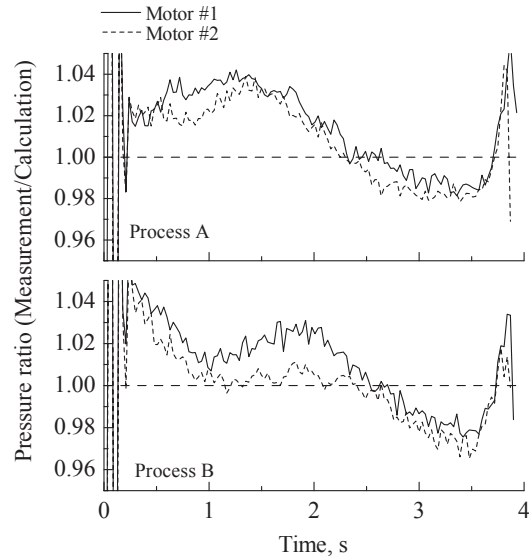


Fig.4. Characteristic pressure-time curve distortion for each casting process.

The burning rate fluctuation through web thickness has dependence on burning direction^{4, 46, 48-51}. The burning rate along longitudinal axis as shown in Fig.5 is measured for each processed grain.

The longitudinal burning rate variations in the inner, middle and outer web position are shown in Fig.6. Although the level is different for each degree, the minimum burning rate is proved in middle of the web except for the case of 180° degree of process B. The burning rate fluctuation along web is opposite to the results from motor firing test described above. Authors have been confirmed that propellant density is almost uniform along web depth by the similar experiments and results⁴⁶). Thus the opposite characteristic of burning rate fluctuation along web depth can be understood as the burning rate directivity, which has been reported in earlier studies^{4,46,48-51}). In case of Process B, the different characteristic is observed at 180° phase.

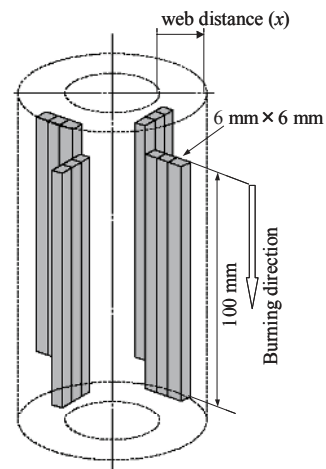


Fig.5. Sampling position of burning rate measurement sample and burning direction.

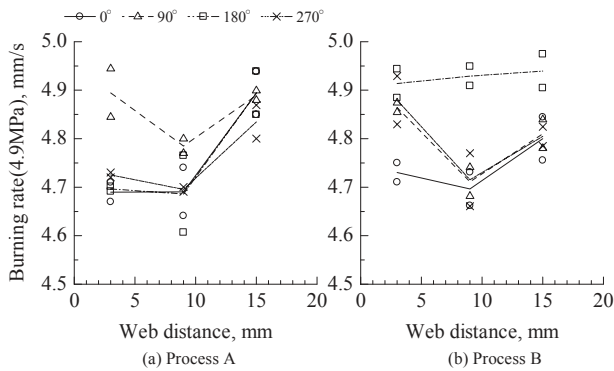


Fig.6. Longitudinal burning rate fluctuation along web distance.

The phase locates on the unique position where the slurry flow from 90° phase and 270° phase collide. In this phase, the slurry velocity turns sharp up direction⁴⁵⁾. Thus the unique characteristic at 180° phase is supposed that it is due to unique slurry flow pattern. In the present R&D of numerical simulation system for SRM internal ballistics, the experimental data on burning rate fluctuation as describe above is confronted with slurry flow simulation shown in the after section. Then the local burning rate database or correlation will be obtained for applying to new numerical simulation system.

3. Observation of Propellant Micro-Structure

Although the characteristics and qualitative relation among local burning rate and slurry casting process has been obtained by earlier studies, the physical understanding has not been progressed enough. On the other hand, recently, nonintrusive and microscopic observation of composite propellant microstructure has been done by micro X-ray computer tomography (CT) device⁵²⁾. The micro X-ray CT has high spatial resolution that is enough to observe the arrangement of submillimeter AP particles in propellant, which is considered as the main course of burning rate fluctuation^{48, 50)}. In this study, the microstructure (i.e. the arrangement of submillimeter AP particles) of motor grain that shows the burning fluctuation is observed by the micro X-ray CT device (inspeXio SMX-90CT (Shimadzu Corporation)) to reveal the relation between local burning rate and local arrangement of AP particles.

The setup of apparatus is shown in Fig.7. To obtain the shape and overall distribution of coarse size AP particles, the resolution is adjusted to 23.6μm/pixel. Thus the dimensions of a piece of propellant are limited as 10mm×10mm×6mm, and sampled from a propellant of small motor as shown in Fig.8.

The X-ray system shots the image of horizontal plane (10mm × 10mm), and the plane images are obtained at intervals of 23.6 μm along vertical direction (6mm). The slice images are saved to PC for a while and are constructed to three dimensional by the post-processing. A sample slice image trimmed as 3mm × 3mm area is shown in Fig.8. In this image,

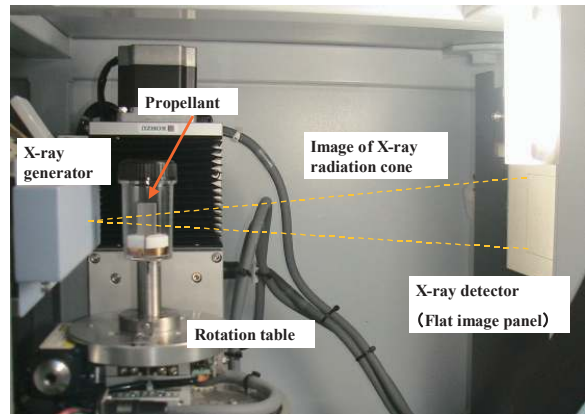


Fig.7. Set up of inside of micro X-ray computer tomography device.

the light area means high density area. The size of aluminum powder and fine AP powder are much smaller than coarse and medium AP particles, and disperse into binder uniformly. The average density of mixture of binder, Al powder and fine AP powder is lower than pure AP density. Thus the light closed area shown in Fig.8 means the pure AP region and the scale of each light closed area roughly agrees to prepared AP particles.

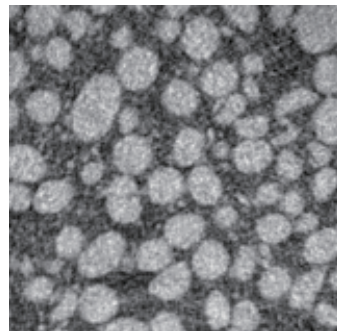


Fig. 8. A two dimensional slice image of propellant sample. This image is enlarged the 3mm×3mm area. The light closed areas are coarse AP particles.

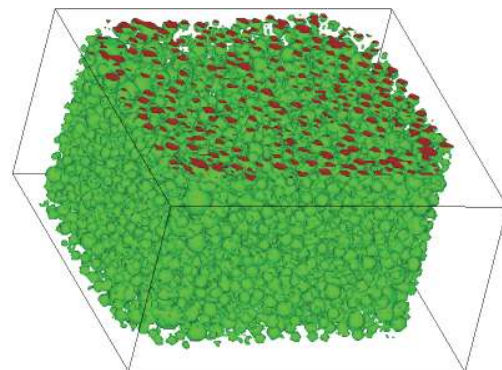


Fig. 9. Computer graphic of AP particles in sample propellant (10mm × 10mm × 6mm). The green zone corresponds to coarse AP particles. Red zone correspond to cross section of upper surface.

The set of two-dimensional slice image is reconstructed to three-dimensional by post-processing. After correction of contrast fluctuation due to beam hardening effect, coarse AP particles are distinguished separately as 3D volume shown in Fig.9, and the center coordinates, major axis, minor axis and their direction of each particle are defined. The method and tool of the post-processing is developed by cooperation with KGT Inc. Although there are necessity to improve the accuracy of beam hardening correction and particle separation method, the microscopic data of AP arrangement can work for physical understanding of burning rate fluctuation.

4. Internal Ballistics Prediction

In the past, the internal ballistics (combustion pressure) prediction was made by estimating the burning surface regression mathematically. This method, however, is not adequate for an arbitrary three-dimensional shape change of the burning surface. The burning surface does not always keep smooth geometry because of the effect of the distribution of local burning rate, the erosive burning, the pressure oscillation, and so on. Therefore, there is a need for the numerical simulation code that can simulate the surface change history of complicated 3D propellant including the effect of the local burning rate variation. This code can also be useful for risk analyses when the grain has a crack and/or air bubble in it. In some previous researches, the methods of 3D burning surface simulation have been proposed in some previous researches conducted in America⁵³⁻⁵⁵, France³, China⁵⁶ and Turkey^{2,57}. Ref 53 shows that the code can treat not only 3D ballistics analyses but also deal with several options such as for segmented motors, for dual propellant motors, for defining case insulation and for exporting the burning surface data for CFD. In Ref 3, the researchers reported original approach toward the influence of burning rate differences between batches. They conducted grain filling computations first, and its results were used for the surface burn-back simulation. In Ref. 2, the methods combining the result of burn-back simulation and CFD of combustion gas were discussed.

In this work, it is proposed that VOF-PLIC (Volume of Fluid – Piecewise Linear Interface Construction) method, one of the simulation methods of handling free surface in Eulerian way, can be utilized to simulate the surface change history of complicated 3D propellant considering the distribution of local regression rate. This method is favorable because it can simulate the dynamic change of arbitrary surface and has a good characteristic for mass conservation. Because the method can be used for arbitrary surface, it is applicable to the propellant with cracks and bubbles inside. Moreover, by combining the computed mass flow rate from propellant surface with other characteristics such as combustion gas properties and throat area, the pressure history in a combustion chamber can be obtained for a solid rocket motor. This code will make the design of solid rocket motors more reliable and improve its quality. The distribution of local burn rate used in the burn-back simulation can be obtained from the numerical simulations of the filling process of solid propellant flows. The factors affecting the local burn rate include cracks

and bubbles in the propellant that can be picked up by micro-focus X-ray computer tomography or ultrasonic wave test.

As an example, the results of burn-back simulation of a rocket motor are shown in Figs 10-12. In the computations, two models are considered; nominal motor and the motor with thin gaps between propellant and insulation. For the simulations, data collected at the static firing test are used for nozzle throat ablation. Erosive burning is also modeled. For the computations on the thin-gap motor, two situations are assumed, namely: the thin gaps start burning upon the burning surface accession; and the thin gaps start burning right after ignition. Fig.10 shows the shape of motor case and beginning propellant surface. Fig.11 illustrates several grain burn back steps and Fig.12 shows the pressure history. The result of nominal case agrees well with that of static firing test, and the result of thin-gap case shows high pressure. As can be seen in this example, this code can simulate the influence of the local burning rate and the complex shape of propellant.

In the future, the code is planned to be more accurate and useful through the comparison with several motor firing tests. We plan to conduct the combustion pressure prediction using the local burning rate estimated by the casting process simulation of slurry of composite propellant.

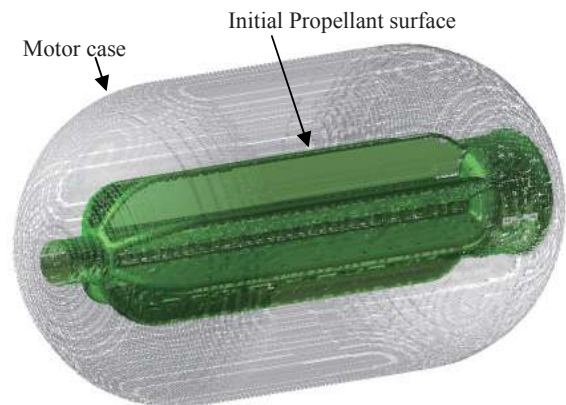


Fig. 10. Initial surface of propellant and motor case model.

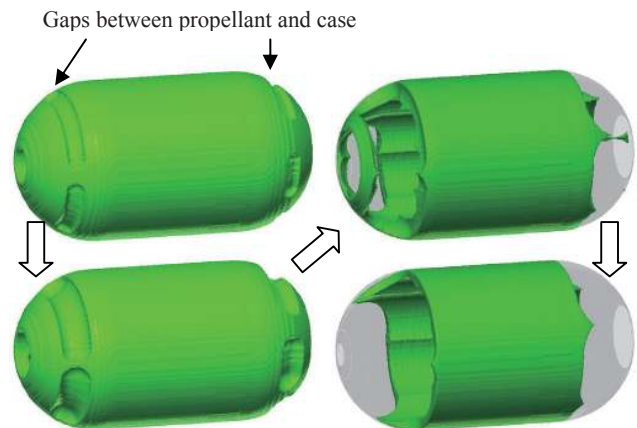


Fig. 11. Examples of burn-back simulation results.

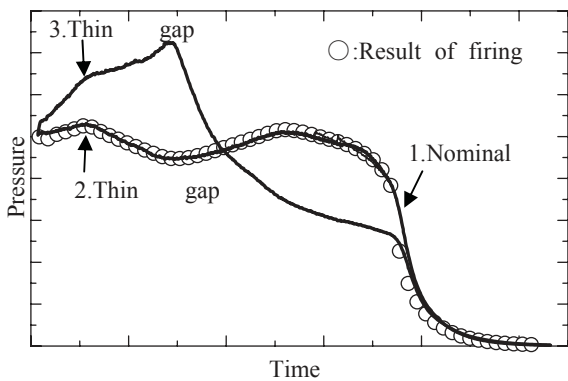


Fig. 12. Comparison of pressure time history analysis and firing test.

5. Casting Simulation of Propellant Slurry

Slurry flow simulation has not been conducted so far in the design of SRM. For the improvement of SRM reliability, detailed analyses of combustion, thermo-structure, and internal flow should be sought. In such analyses the needs are growing on the information of the local property of the propellant. In order to grasp such local characteristics and physical properties, it is necessary to understand the phenomena in the manufacturing process, such as mixing and casting. In the past not much has been done in Japan as to the test and the analyses to grasp the detailed motion of the propellant in casting. Therefore, there are currently not sufficient number of tools and models for this purpose. For example, the propellant slurry could be non-Newtonian fluid, however, there is no proper constitutive relations about the normal and shear stresses.

Sometimes the local burning rate anomalies can be identified in static firing tests. Possible causes include burning rate difference between binder rich layers and AP rich layers, and the cracks and bubbles in the propellant. They occur at casting and hardening the propellant. The burning effect concerning the casting process is not apparent because the propellant slurry is neither homogeneous nor visible. The casting process analyses are desired to investigate the flow of propellant. It is also necessary to declare the effect of slurry flow to local burning rate in order to predict the ballistic response of composite propellant. In this study we make numerical simulations to establish the slurry flow properties and flow field during a casting.

In this study, we focus on the relation between burning surface and propellant “layer” (binder or AP rich layers). The casting simulation is made to gain the distribution of angle of propellant layer.

Air and the propellant are modeled. For accuracy, the propellant slurry should be modeled as Non-Newtonian fluid, because the propellant is mixed high viscosity binder, AP and Al particles. However, as the purpose of this study is to examine the high viscosity slurry flow, the slurry is assumed as Newtonian fluid. The VOF (Volume of Fluid) method is

employed in order to represent free surfaces. As have been discussed previously, the method is good at volume conservation. The governing equation is Navier-Stokes Equation and the equation of continuity. Energy transfer is not included. The analysis code is FLUENT Ver.6.3 from ANSYS.

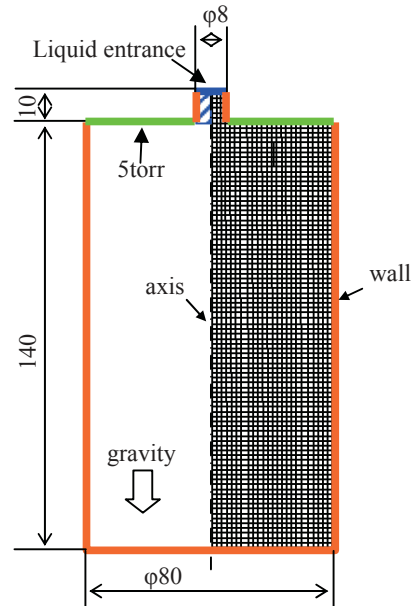


Fig. 13. Casting simulation model 1.

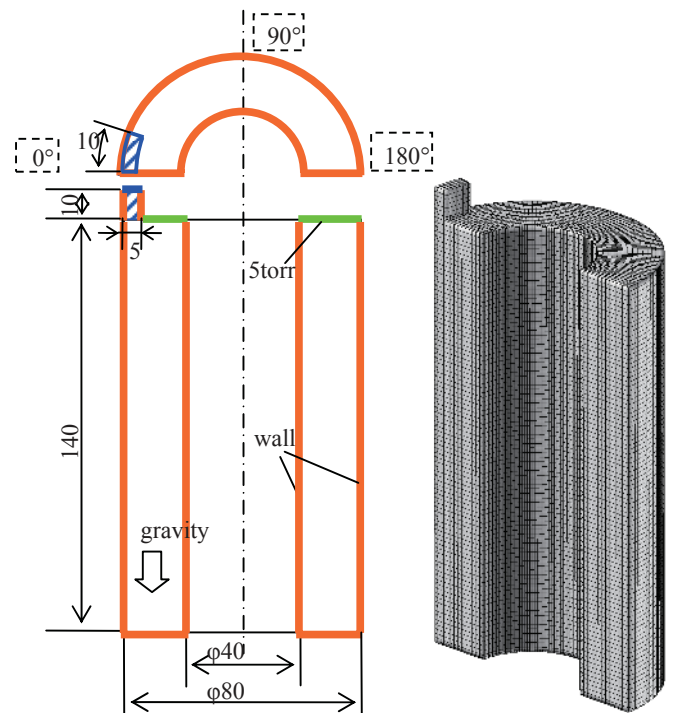


Fig. 14. Casting simulation model 2.

Two models with different entrance and shape of case will be discussed. Fig.13 and Fig.14 show models and numerical meshes. Two kinds of propellant viscosity are assumed, one of them is $500\text{Pa}\cdot\text{s}$ as a real propellant (right after mixed, $300\text{Pa}\cdot\text{s} - 500\text{Pa}\cdot\text{s}$) and the other is $50\text{Pa}\cdot\text{s}$ (defined as

expedient to show the sensitivity for viscosity). The viscosity does not change according to time.

Fig.15 and Fig.16 show slurry flow as model 1. The color are changed every 5 second in order to show the time and position of slurry. In this paper, this is called “layer of propellant”.

The layer of propellant sags down regardless of the viscosity. The slurry gets deeply into the layer of propellant that piled up on ahead. The layer of propellant, then, climbs along the wall. The low viscosity slurry moves widely and the angle between the wall and the layer is sharp. There are different layers at the same depth.

Fig.17 shows slurry flow as model 2. The slurry starts at 0 deg and flows toward 180deg pushing the layer beneath. At

180 deg, layer goes up as bumping against layer. The cross section shows slurry sags at 0deg and 90deg and swells at 180 deg. The shapes between layers are complex on the model 2.

The slurry layers of propellant, which came into another time, are complex and the shape is different from that of viscosity distribution or shape of the case. The result analysis will be verified by experiments. This result indicates the possibility to measure the angle of layer of propellant. The propellant surface burn-back simulation with local burning rate characteristics will be coded as the database of the relation between the layer shape and local burning rate will be arranged. In the future, we will conduct a survey of the phenomenon of the slurry, and the casting and burn-back simulation will be coordinated to simulate particularly ‘hump’ effect.

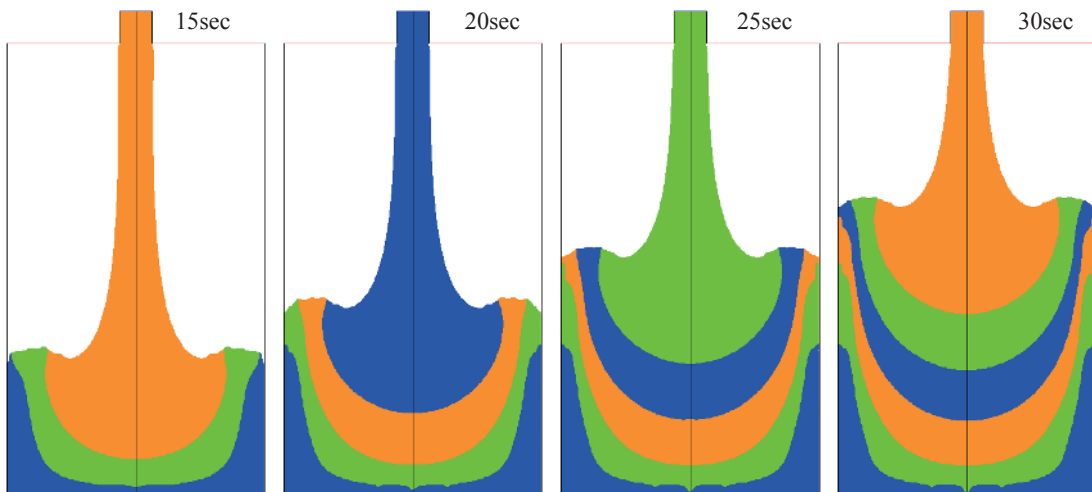


Fig.15. Result of slurry flow simulation model 1 (50Pa·s).

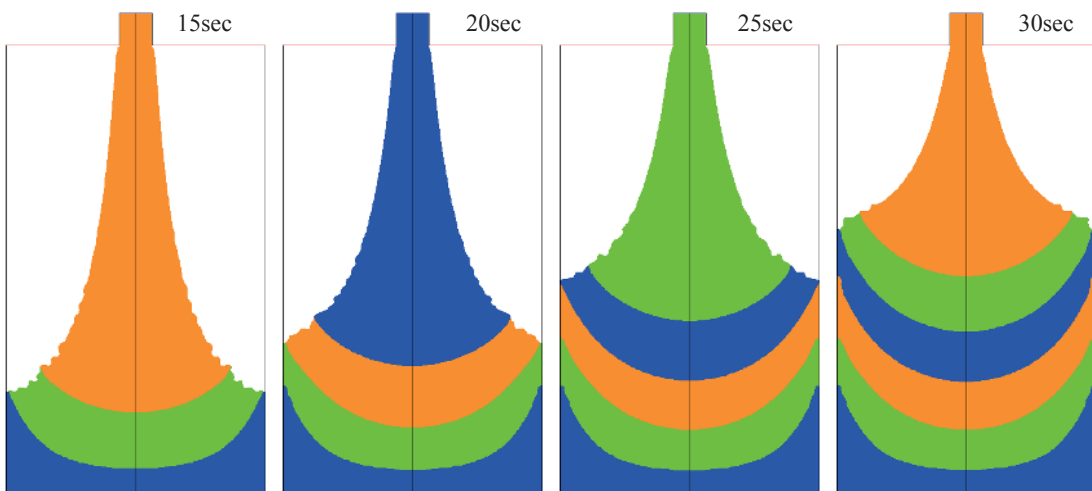


Fig.16. Result of slurry flow simulation model 1 (500Pa·s).

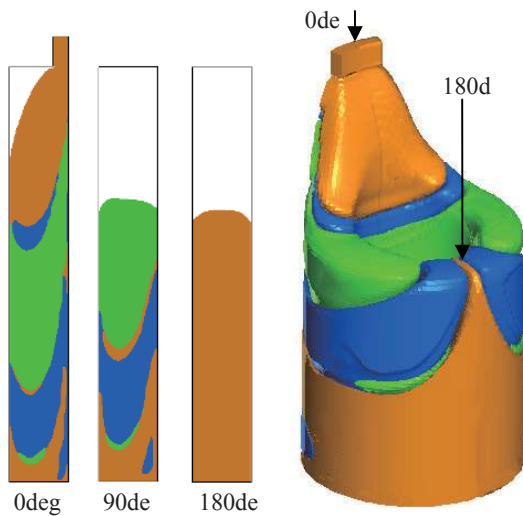


Fig. 17. Result of slurry flow simulation model 2 (500Pa·s).

6. Conclusions

In this study, to development of a numerical simulation system, what we call “Advanced Computer Science on SRM Internal Ballistics (ACSSIB)”, some database and techniques which should become base of new simulation system were obtained as below.

- (1) Burning rate fluctuation (i.e. midweb anomaly) is observed by firing test with small test motor.
- (2) Arrangement of coarse AP particles in the propellant sampled from motor grain is observed by micro-X-ray CT device.
- (3) The method to distinguish each AP particles separately is obtained. Then the arrangement of AP particles is obtained as computer graphics.
- (4) 3D surface burn-back simulation is carried out for practical shape of internal burning grain. Then, pressure-time curve is obtained.
- (5) 2D and 3D numerical simulation for propellant slurry casting is carried out. The characteristics of slurry sags are obtained for two levels of viscosity.

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