Analysis of the Flow in LOX Manifold in Liquid Rocket

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Abstract

The flow in the LOX manifold of liquid rocket has been investigated using a CAE technique with an objective of economical modeling of injection holes in order to reduce the overall computational cost of flow analysis during the optimal rocket design procedure.

The computational geometry is very close to that of the actual rocket design and the flow condition through the injection holes resembles that in the actual manifold of the liquid rocket. The result shows that the flow in the plane just above the injection holes is not uniformly distributed in terms of pressure and mass flow rate and this is attributed to the large-scale flow patterns present the LOX manifold. Thus, the flow physics should be understood correctly before making any attempt to model the injection holes.

In the present study, several boundary conditions which were designed to effectively replace the presence of injection holes have been tested and it was found that a simple modeling can be possible by mimicking the actual geometry of the injection holes. By using this simple injection hole modeling, it was able to obtain about 30% reduction in computational cost but it was still able to reproduce the flow patterns correctly. Also the flow has been analyzed after incorporating a couple of different types of pre-distributors in LOX manifold and the effect of those will be discussed.

Introduction

Liquid-propellant rocket systems have been widely used for the main propulsion system for various space applications. The main advantage of liquid system is its high performance compared with any other conventional chemical systems and has to do with the fact that it is highly controllable in terms of thrust modulation. On the other hand, disadvantages include the complexity of design process and high development cost associated with very complex and nonlinear physical behavior. Actually, from a fluid mechanics point of view, the design of liquid rocket requires a system integration technology because flows in LOX manifold, injector and combustion chamber interact one another constantly during the actual operation. In spite of the importance of this system approach, the flow analysis has been made separately and independently for LOX manifold, injector and combustion chamber due to the technical difficulty.

Considering the fact that the transfer of advanced missile technology from the countries which have already accumulated high-level technology to those who just started developing the liquid rocket is prohibited, Korea just took a first step toward independently developing a relevant technology for the design of liquid rocket.

Among many research areas required, an accurate prediction tool for the turbulent flow in LOX manifold is one of the very important ingredients of analysis. Since turbulence plays an important role in evolution of LOX, caution needs to be made when the RANS type calculations are to be performed. In addition to the usual effect of turbulence on the flow, there are several complications involving injection holes because they are likely to increase the computational cost by requiring an extensive number of grid points concentration near the holes. For the optimal design of manifold shape, a series of prediction of flow characteristics is unavoidable because changing design parameters would yield different flow characteristics. Of many important flow quantities, degree of uniform distribution of mass flux in the plane above the injection holes and the characteristics of flow oscillation are to be extracted and examined in order to make sure that they are within the given tolerance to avoid any instability.

Combustion instabilities have long been recognized as the most difficult problem in engine development. They were discovered in the late 1930s both in solid and liquid systems. Since then, they have occurred in nearly all new development programs. LOX manifold, which is supposed to continuously and uniformly supply combustion chamber with oxidizer, should be designed to prevent any flow condition that would possibly lead to non-uniform distribution of pressure and combustion instability. Since the LOX flow rate is about 3~5 times larger than that of the fuel, main duty of maintaining uniform spray pressure and mass flux of LOX1) is very critical for the safe operation.

Combustion process in a liquid rocket is never perfectly smooth; some degree of fluctuations of pressure, temperature, and velocity are always present. When these fluctuations interact with the natural frequencies of propellant feeding system (with and without vehicle structure) or the chamber acoustics, periodic superimposed oscillations, recognized as instability, occur. In normal rocket practice, it is known that smooth combustion occurs when pressure fluctuations during steady operation do not exceed about 5% of the mean chamber pressure. Combustion that gives greater pressure fluctuations at a chamber wall location which occur at completely random intervals is called rough combustion. Unstable combustion, or combustion instability, displays organized oscillations occurring at well-defined intervals with a pressure peak that may be maintained, may increase or may die out.2-3) One of the objective of present work is to get flow information as to the degree of non-uniform distribution of pressure (or mass flow rate) at the injection holes since this non-uniformity is directly related to the combustion instability. Recently, German research group conducted a very systematic research (experimental and computational) on the Vulcain rocket engine in order to achieve an uniform of pressure distribution using a pre-distributor. Also, Korea Aerospace Research Institute is making an attempt to improve the KSR-III rocket using a vertical/horizontal type pre-distributor.4-6)

In the present study, the main objective is to understand the flow details and to establish the solution technique. Since the design parameters which determine flow characteristic in LOX manifold are numerous (such as internal chamber volume, path length of flow, entrance angle of LOX, the area of pre-distributor holes and pressure drop in LOX manifold), an economical way of computation is prerequisite for the optimal design procedure. In the present work, it was decided that the replacement of the actual injection holes with the reasonable boundary condition for the computation can easily reduce the computational cost. Thus, the several boundary conditions which were designed to replace the presence of injection holes effectively were tried and it was found that a simple modeling can be possible by taking into account of the effect of actual geometry of the injection hole.

After establishing the solution method, the effect of flow fluctuation of LOX by imposing some frequency characteristics to the inflow mass to the chamber.

Numerical methodology

The flow through the LOX manifold can be described by the incompressible Navier-Strokes equations. Since the Reynolds number is approximately $Re=10^6$ based on velocity and diameter of inlet, the flow is assumed to be turbulent. Since the computational geometry is very complex, numerical solutions were obtained by using a commercial package CFD-ACE+ of the company CFDRC.

Since the Reynolds number is not so low, the standard k-ε turbulence model was chosen for the turbulent modeling. For the justification of the specific turbulent model used, a separate experimental study is being conducted and the preliminary results show that the standard model is superior to the low Reynolds number version of the model.

The amount of grid points for the computational domain with injection hole modeling is approximately 600,000. The schematic diagram of the computational domain is shown in Fig. 1.

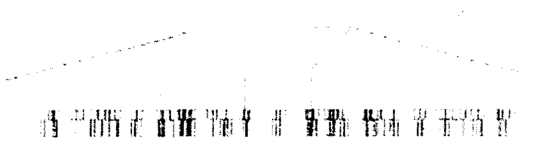

Fig. 1 Computational geometry without pre-distributor

Geometry data		Manifold condition(87K)	
D_{in}	59.5 mm	$\dot{m}_{in}$	5.4 kg/s
D_{inj}	2.2 mm	μ	0.0002 Pa·s
		ρ	1140 kg/m^3
		V_{in}	3.4 m/s

Table 1 Flow parameters and fluid properties

In order to establish the boundary conditions, experimental data of KSR-III has been used. For example, the inlet LOX velocity (or equivalently flow rate) was calculated to match the actual flow rate per injection hole of the KSR-III rocket. The turbulence intensity of 10% of the average inlet velocity is arbitrarily given. Other turbulence quantities like (k, ε) are prescribed based on the velocity and diameter of inlet and by the empirical formulas of CFD-ACE+. Working fluid was chosen to be liquid oxygen. The detail information about the inlet condition and fluid property at 87K are summarized Table 1.

Results and discussion

Velocity and pressure field

For the understanding of the flow pattern, it would be helpful to look at the streamlines. Even though the flow field exhibits 3-D characteristics, it is revealing to examine the flow pattern in the 2-D horizontal plane. Fig. 2 shows the flow pattern seen in a plane about 0.02m away from the injection holes. LOX is injected along the centerline on the left. It shows that there are one big roll on the left, and the other smaller cell on the right. The flow is circulating the chamber in counter-clockwise direction. This figure would suggest that there are large scale motions in the mean sense and the pressure distribution can not be uniform in the plane just above the injection holes due to these large flow motions.

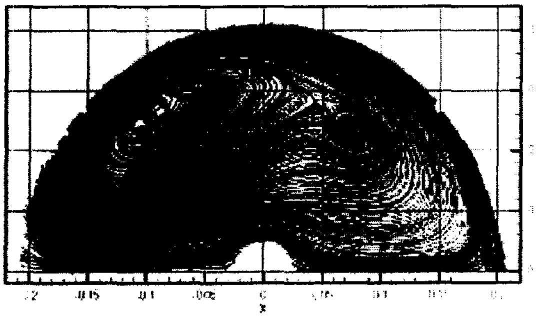

Fig. 2 Streamline pattern in horizontal plane (y=0.02m) in the LOX dome

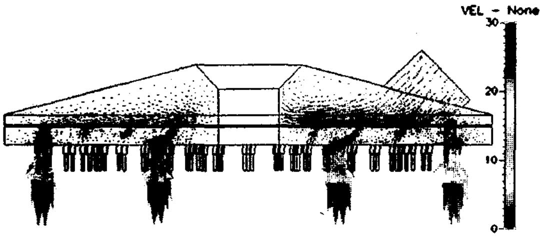

Fig. 3 Velocity vector in the plane of symmetry in the LOX dome without pre-distributor

Fig. 3 shows velocity vectors in the vertical plane of symmetry. There is a wide variation of velocity magnitude. Very high velocity or velocity gradient near the injection holes implies that high concentration of computational grids is required in this region. Since the physical size of the hole is an order of magnitude smaller that that of the size of the dome, this imposes a severe restriction on the size of the grid and a time step. For the proper resolution of the flow, a large portion of the grids is put in this region for this case. This induces the need for the replacement of injection holes by a reasonable boundary condition for the repetitive computation of flow in the process of optimal design.

Fig. 4 displays the pressure distribution in the plane just above the injection holes. As mentioned earlier, the LOX is being fed through the injection hole to the combustion chamber and, thus the uniform distribution is prerequisite for the stable combustion process in the chamber. However, without pre-distributor, pressure on the inlet side can be considerably higher than that of the other side. In present result, the pressure difference is not noticeably large because of the low flow rate. In other words, the computational geometry has less number of injection holes compared to the actual design and this, in turn, causes the smaller LOX flow rate at inlet because the flow rate per hole is the same in both the computational and actual design. Although mass flow rate is not high, pressure drop across each injector hole is about 4.7 bar on the average. Fig. 5 presents the mass flux distribution in the same plane as in Fig. 4. It is noted that the distribution of the mass rate shows the tighter range than that of the pressure.

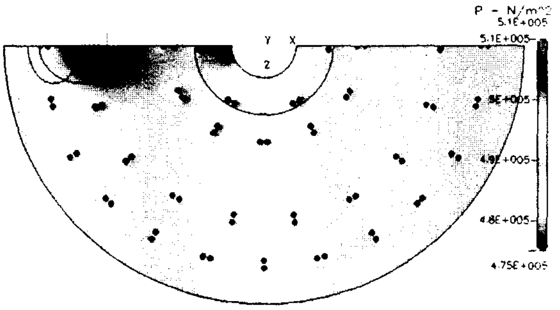

Fig. 4 Pressure distribution in the plane just above the injection holes without pre-distributor

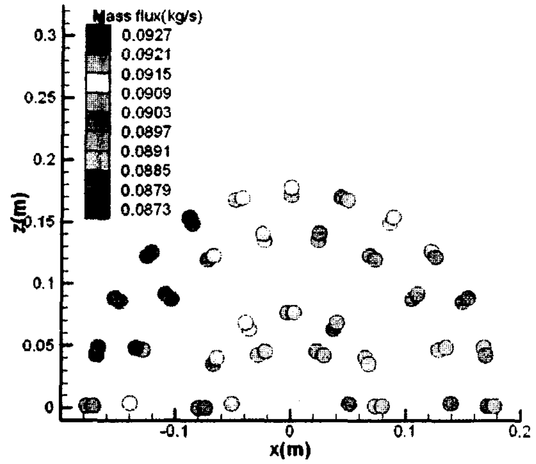

Fig. 5 Mass flux of each injectors in the LOX manifold without predistributor

Injection hole modeling

For the proper and accurate prediction of flow near the injection holes, several numerical issues should be overcome. For example, the size of the hole is significantly smaller than that of LOX manifold and, thus, the ratio of grid size is considerably small. This fact can be a big penalty for the computation because a huge number of grid points is required in the region slightly away from the hole to ensure the smooth variation of grid size. As mentioned earlier, in order to eliminate this problem associated with the large separation in dimensions, one needs to develop a way of reducing the computational cost without losing the accuracy of the solution. In the present work, several boundary treatments were tested to suggest an economical way of computation.

Among many tries tested, Fig. 6 shows the geometry of the modeling which yields the best result. The cost saving was achieved by the reducing the length of the holes and but the accuracy was not lost much by maintaining the original shape of the hole. Since the geometry of injection hole resembles the circular pipe with sudden contraction, various choices for length of pipes in the region of the larger and smaller areas are possible. The shorter the pipe length is, the lower the computational cost is. But as the length of the pipe gets smaller, the accuracy is getting lower. Thus, there must be a compromise between the cost and accuracy.

For Fig. 6, the length of the pipe was 2 and 4 mm in the large and smaller pipes, respectively. Note that the original shape has 8 and 14mm respectively.

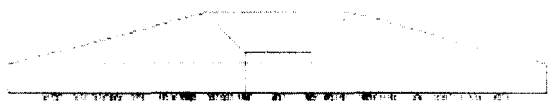

Fig. 6 Geometry of injector modeling with lower pipe(length=4mm)

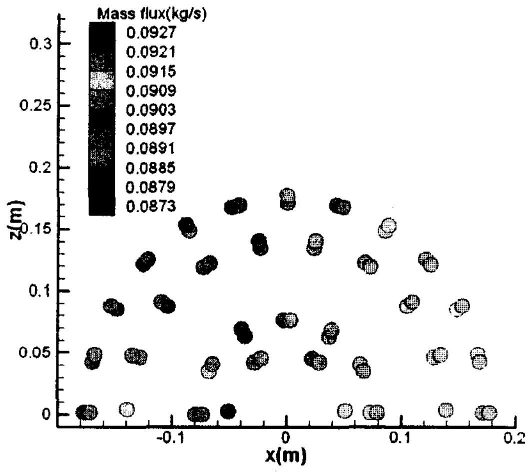

Fig. 7 Mass flux of each injectors by injector modeling

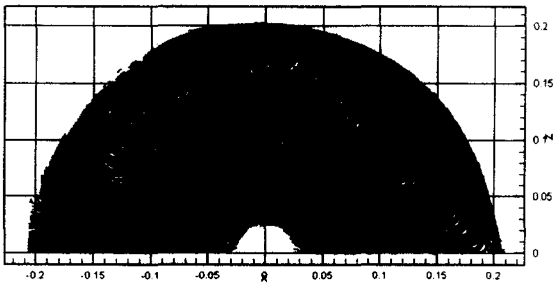

Fig. 8 Streamline pattern on constant y plane (y=0.02m) in the LOX manifold of injector modeling

Fig. 7 shows the flow rate through each injector hole after the re-calculation with this boundary modification. There is not much difference between the original and the modeled cases. If one compares the Fig. 2 with the Fig. 8, one can easily notice that the present way of boundary treatment is accurate enough for the flow analysis. Since the large scale flow pattern is likely to affect the distribution of pressure and mass flow rate, one should be able to predict the large scale flow motion for the present purpose.

The effect of pre-distributor

The main role of the LOX dome is to send the LOX uniformly to the injection holes for a better environment for combustion. One way of achieving this objective is to use a pre-distributor. There is a couple of examples found in the recent literature. In Korea, KSR-III engine was equipped with a vertical/horizontal type pre-distributor and European Vulcain engine was used with a horizontal type pre-distributor. However, there are not many studies available regarding the efficiency of pre-distributor, so two different cases were analyzed and compared. Figs. 9 and 10 show the velocity vector fields in the center plane of LOX manifold for two different types. For the vertical/horizontal type pre-distributor, the more uniform pressure and mass flux distributions were obtained. This is partly due to the effect of vertical part of the pre-distributor which was more efficient in distributing the LOX uniformly entering from the inlet at the expense of higher pressure drag.

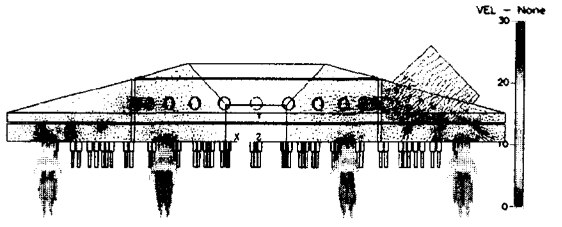

Fig. 9 Velocity vector in the plane of symmetry in the LOX dome with vertical horizontal type pre-distributor

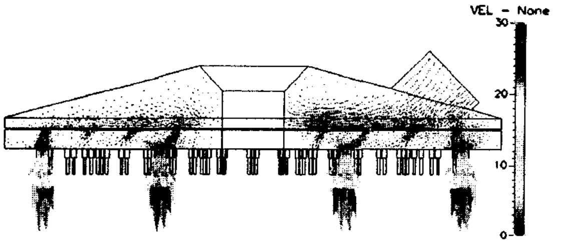

Fig. 10 Velocity vector in the plane of symmetry in the LOX dome with horizontal type pre-distributor

Figs. 11 and 12 show the distribution of flow rate for two types of pre-distributor. Comparing with the results which were obtained without pre-distributor, one can notice that better results are obtained. Of the two types, the vertical/horizontal type pre-distributor turns out to give more uniform flow rate overall However, it was found that for the horizontal/vertical pre-distributor, the result is very sensitive to the relative location of holes present in the pre-distributor and injection plate. Thus, more thorough analysis will be required for the design of more efficient configuration of pre-distributor.

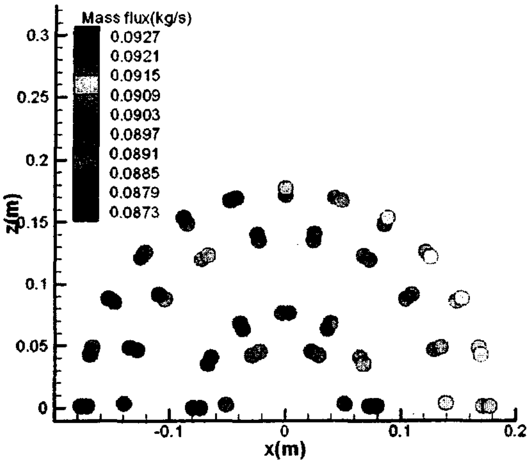

Fig. 11 Mass flux distribution through injection holes in the LOX dome with vertical horizontal type pre-distributor

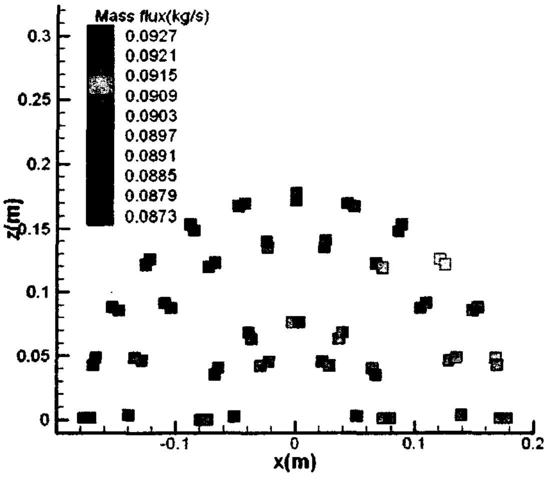

Fig. 12 Mass flux distribution through injection holes in the LOX dome with horizontal type pre-distributor

The effect of pulsation of the inlet flow

Sutton$^{2)}$ showed a series of time-sequenced diagrams of frequency vs. pressure amplitude measurement taken in the oxygen injector manifold of the Vulcain HM 60 engine during the first 8 seconds of a static thrust chamber test while operating at off-nominal design conditions. Chugging can be seen at low frequency (up to 500Hz) during the first few seconds and a natural frequency around 1500Hz is attributed to the natural resonance frequency of the oxygen injector manifold structure where the high-frequency pressure transducer was mounted. The continued oscillations observed at about 500 and 600Hz are probably resonances associated with the feed system. In order to understand the response of flow to the pulsation of inlet LOX flow, several frequencies were imposed to the inlet flow but only one case will be reported here. There are several ways of imposing the time characteristics but in order to simply the situation, it was assumed that inflow behaves like a sinusoidal signal.

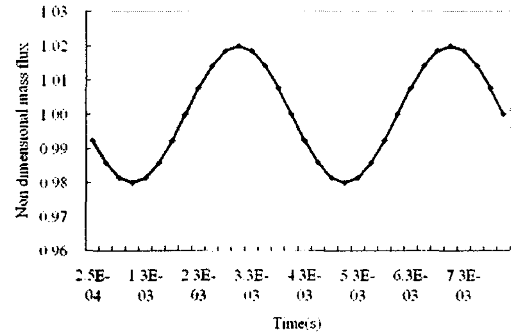

Fig. 13 Inflow boundary condition

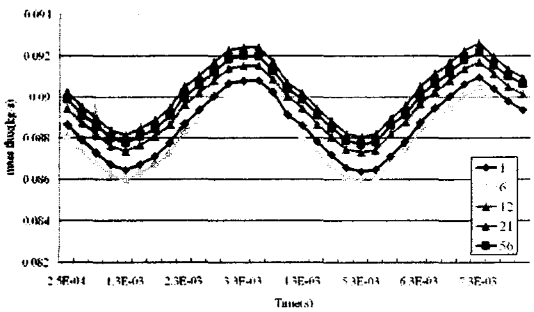

Fig. 14 Time history of mass flux at several holes

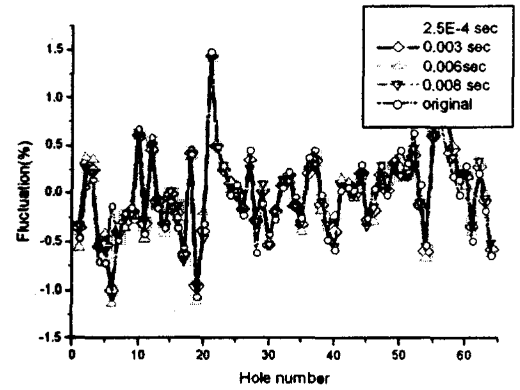

Fig. 15 Fluctuation of mass at injection holes

Thus, the inlet boundary condition is periodically prescribed as a function of time and has the amplitude of 2% of mean mass flux. Fig. 13 shows the inlet signal used for the present study. This curve is exactly a sine curve of 500Hz. One period is 0.002 second that is divided by 8 sections; therefore time interval to be used for the calculation is 0.00025 second. Fig. 14

shows the flow rate at several representative injection holes as a function of time. They exhibit the almost identical period specified in the inflow. Fig. 15 shows the estimated error based on mean mass flux at different detection times. The figure legend 'original' denotes the case with computation with uniform inflow. At all the times detected, the mass flux distribution shows the variation within 2% of the mean value, which can be acceptable for the smooth operation. Thus, the pulsation with 500Hz signal at inlet appears not to change the characteristics of mass flux distribution considerably.

Conclusion

The flow inside the LOX manifold has been analyzed by a CAE technique. Large vortical flow patterns are detected in the dome. Accurate prediction of these large scale flow patterns is likely to be critical since they are directly related to the distribution of pressure and mass flow rate in the plane just above the injection holes. Since the CAE technique was used for the analysis, it was not able to obtain information about instantaneous flow field. Since the dynamic characteristics may be important for the rocket operation, this can be a weakness of the present study. But the accurate prediction of unsteady nature is beyond the capability of the current resources and any attempt was not made in the present study.

The time-averaged flow fields give an intuition about the flow situation and this information was used to model the boundary condition for the injection holes. Since the injection hole incurs a prohibitively large increase of computational expenditure, an economical as well as accurate modeling will be beneficial from an engineering point of view. By using the simple injection hole modeling, it was able to obtain about 20% reduction in computational cost but it was still able to reproduce the flow patterns correctly.

The effect of pulsation of inlet mass flux induced by the turbo-pump has been investigated by imposing a sinusoidal signal to the inflow. The frequency imposed was 500Hz. The result shows that the flow inside the dome also fluctuates according to the inflow signal but the degree of uniformity of mass flux at injection holes does not depart far from the result without pulsation signal at inlet. However, more works will be required to understand the unsteady behavior of the flow in the dome by varying the frequency in the future.

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Appendix

Nomenclature

D_{in} (mm) : Inlet diameter in LOX manifold
D_{inj} (mm) : Outlet diameter of injector
$\dot{m}_{in}$ (kg/s) : Inlet mass flux of LOX manifold
V_{in} (m/s) : Inlet velocity of LOX manifold
Vel (m/s) : Magnitude of velocity vector
μ (Pa·s) : Viscosity
ρ (kg/m^3) : Density
k (m^2/s^2) : Turbulence kinetic energy
ε (m^2/s^3) : Turbulence dissipation rate