Development and Evaluation of Transient Analysis Tool for Rocket Engine

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Abstract
Predicting of transient behavior is one of the most important design efforts in the rocket engine development. In order to address it, MHI developed its own engine dynamic simulation code called VISREC (**V**isually **I**ntegrated **S**imulator for **R**ocket **E**ngine **C**ycle). VISREC is a one-dimensional flow and heat analysis program using node-link network approach with adequate accuracy and speed for various types of analyses such as steady state engine balance analysis, engine transient analysis, mechanism analysis and stability analysis. VISREC also has the user-friendly visual interface to build engine models, to run the programs and to output the data. In this paper, features of VISREC and some analysis results compared with the actual test data are presented. Especially difference of transient behavior between open expander cycle and closed expander cycle is investigated using the analysis models for both engine cycles which are validated by the analyses for the existing engines.

1. Introduction

Liquid rocket engines operate at very severe condition where high pressure and high temperature hot gas at 3600K and cryogenic coolant are separated by a thin wall, which causes very high pressure and thermal stress. Besides, liquid rocket engines start up and shut down in a few seconds to and from that severe condition, which causes a high thermal transient stress. In order to prevent "excessive" stress, controlling transient behavior by the timing of several valves is important but not easy. A lot of troubles happened during start and shutdown transient in a lot of past engines. Therefore predicting of transient behavior is one of the most important design efforts in the rocket engine development. In order to address it, MHI developed its own engine dynamic simulation code called VISREC[1] (**V**isually **I**ntegrated **S**imulator for **R**ocket **E**ngine **C**ycle)

2. Outline of VISREC

2.1 Analysis Method and Scheme

VISREC is a one-dimensional fluid analysis program based on a node-link network approach with features as follows.

(a) Treat fluid and heat flow.
(b) Can handle two-phase flow as homogeneous.
(c) Have wide range of fluid properties.
(d) Can define node-link connection easily.
(e) Have elements to set boundary conditions.

In the actual engine modeling, each element is selected from predefined component library. The library has the following several categories.

- General component : Tank, Duct, Valve, Heat exchanger etc
- Engine specific component : Chamber, Pre-burner, Turbo-pump, etc
- Control component : Linear, Integral, Non-linear, Logic etc
- User's module

In VISREC a flow network is built by using the node which solves energy and mass conservation laws and the link which solves momentum conservation law. Pressure, temperature and density are calculated in the node, and flow rate and heat transfer coefficient are calculated in the link. In the engine, tanks and other volumes and heat masses of chamber and ducts are treated as the nodes. Pump, turbine, valve, orifice, other resistances and heat transfer between metal and fluid are treated as the links. Some other components such as combustion chamber, pre-burner and turbo-pump rotation are modeled by optional subroutines.

2.1.1 Nomenclatures

Nomenclature

A	area [m^2]
C^*	characteristic exhaust velocity [m/s]
c	Spesific heat [J/kgK]
G	mass flow rate [kg/s]
g	gravitational acceleration [m/s^2]
h	specific enthalpy [kJ/kgK]
I	moment of inertia [kgf m s^2]
L	length [m]
P	pressure [kgf/cm^{2}A]
ΔP	pressure drop [kgf/cm^2]
Q	quantity of heat or heat flux [kJ/s]
T	temperature [K]
Tt	turbine torque [kgf m]
Tp	pump torque [kgf m]
Tm	dynamic/static friction torque [kgf m]
V	volume [m^3]
w	weight [kg]
α	heat transfer coefficient [J/m^{2}sK]
ρ	density [kg/m^3]
ν	specific weight [m^3/kg]
ω	angular velocity [m/s]

subscript

i,m,n,l	number of Node/Link
g	gas phase or combustion gas
l	liquid phase
c	combustion chamber
f	float
w	chamber wall
O_2	oxygen
H_2	hydrogen

2.1.2 Numerical Equations for Node/Link

A sample of node/link network system is shown in Fig.1 In Flow Node -n- in Fig.1, two parameters are calculated using fluid and heat condition, solving energy and mass conservation laws. In the case of single phase, pressure and enthalpy are calculated, while in the case of two phase, pressure and density are calculated. In Metal Node -m- in Fig.1, metal temperature is calculated by solving the heat balance equation of (1).

$$\frac{dT_m}{dt} = \frac{Q_{i-1} - Q_i}{c_m w_m} \tag{1}$$

In Flow Link -l- in Fig. 1, mass flow rate which passes through the Link is calculated by solving the momentum equation of (2).

$$\frac{dG_l}{dt} = \frac{10^4}{(L_n / A_n) + (L_{n-1} / A_{n-1})} \left(P_n - P_{n-1} - \Delta P_l + \Delta P_{pumpl} \right) \tag{2}$$

where ΔP_{pumpl}. is pump head term in case that Link -l- is a pump link. In Heat Link -i- in Fig.1, heat flux from Metal Node -m- to Flow Node -n- is calculated by solving the heat transfer equation of (3).

$$Q_i = \alpha_i A_i (T_m - T_n) \tag{3}$$

where heat transfer coefficient α_i is calculated by adequate equation for each heat transfer form. For the calculation of hot gas heat transfer inside chamber, Bartz equation is used.

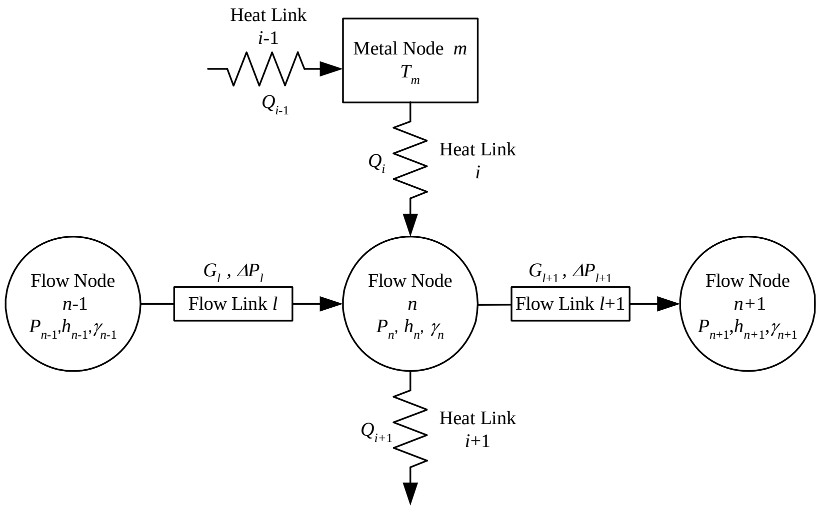

Fig. 1 Node/Link network system

2.1.3 Property of fluid

The fluid property functions for hydrogen, oxygen, helium, nitrogen, water/steam, H2/O2 combustion gas CH4/O2 combustion gas can be used in VISREC. An example of the fluid property functions is shown in Fig.2.

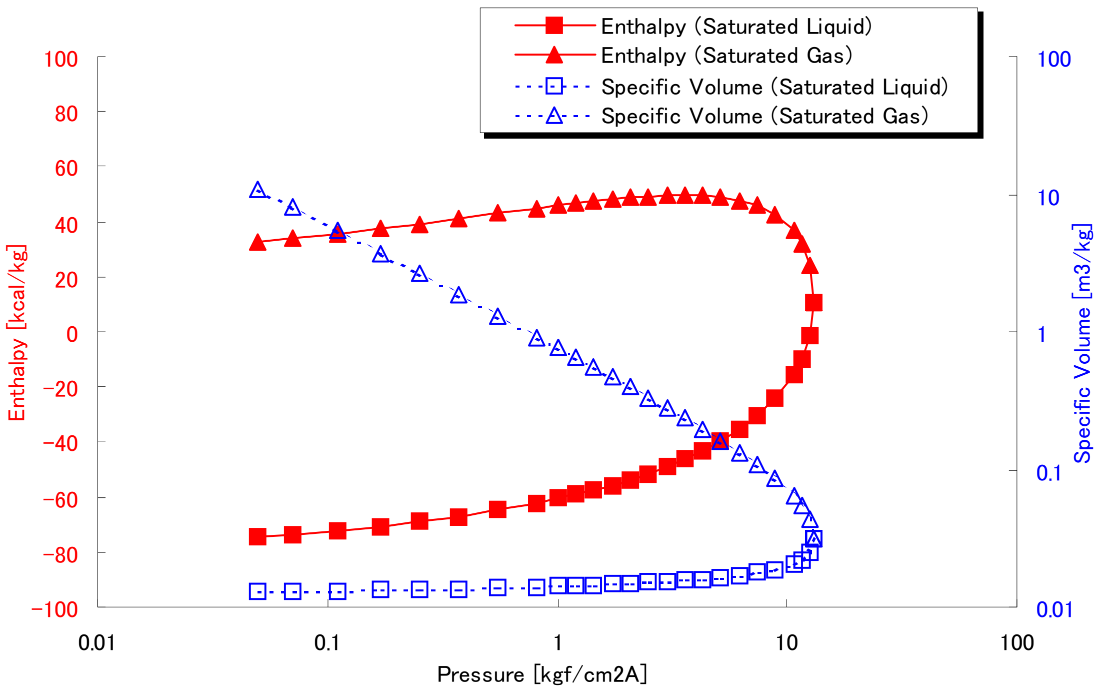

Fig. 2 An example of the fluid property correlation functions of hydrogen

2.1.4 Special models for rocket engine

In modeling of turbo-pump rotation, combustion chamber and pre-burner, special models are installed to VISREC other than standard node/link elements.

(a)Turbo-pump rotation

Turbo pump model calculates rotating speed by pump torque and turbine torque as follows. Pump torque and turbine torque are calculated in each link. Windmill torque can be taken into consideration.

$$\frac{d\omega}{dt} = \frac{1}{I}\left[(Tt - Tp) - Tm\right] \tag{4}$$

(b)Combustion chamber

Combustion chamber model calculates chamber pressure Pc as follows. Combustion gas properties of and C* are calculated from tables made using ODE program. This model can also calculate thrust.

$$\frac{dP_c}{dt} = \frac{P_c}{\rho_c V_c}\left(G_{O_2} + G_{H_2} - \frac{P_c A_t g}{C*} \times 10^4\right) \tag{5}$$

(c) Pre-burner

Pre-burner model calculates temperature and other fluid properties of combustion gas from the ODE table.

2.1.5 Numerical Integration Method

Numerical equations for node/link network are automatically transformed to equation (6).

$$\frac{d}{dt}\boldsymbol{x} = \boldsymbol{f}(\boldsymbol{x}) \tag{6}$$

where x is vector and f(x) is vector function in n dimensions.

The integration method can be chosen from three implicit and one explicit schemes in VISREC. If local truncation error is greater than the inputted tolerance, time step t will be shortened and Jacobian will be recalculated. The process of calculating Jacobian takes advantage of sparsity of Jacobian to reduce the execution time.

2.2 Graphical User Interface (GUI)

VISREC can execute all of the tasks through GUI from modeling to data dumping. Engine model is built by dropping icons from libraries, connecting them and inputting data into each icon on pop-up windows. Connecting relations of network are recognized automatically by only connecting icons. Fig.3 shows total image of graphic system and Fig.4 shows libraries for engine components and control components. VISREC can be executed by command on GUI and executing status including values of typical parameters can be monitored on the modeling screen or on the trend graph. After the execution, analysis results of any parameters selected on GUI can be converted into graphs by graphing module of VISREC. They can also be dumped into a simple text file to be used on the other commercial softwares.

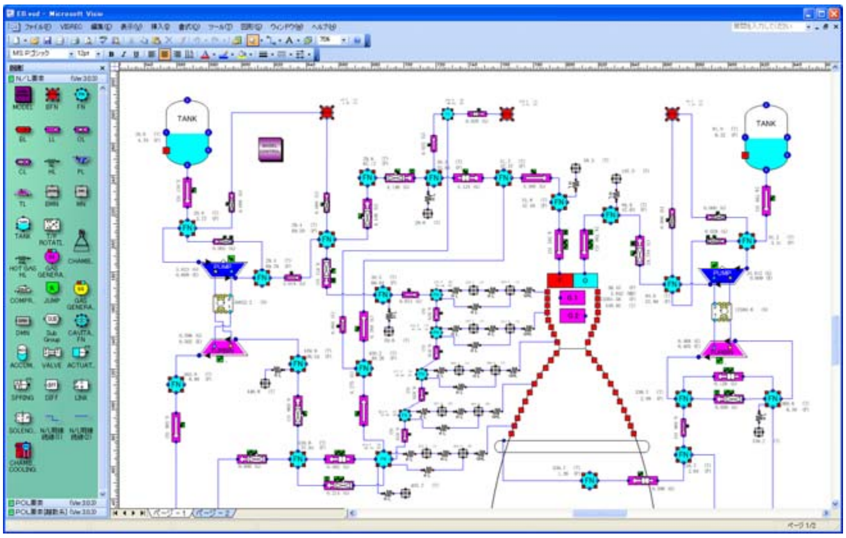

Fig.3 Total image of VISREC graphic system

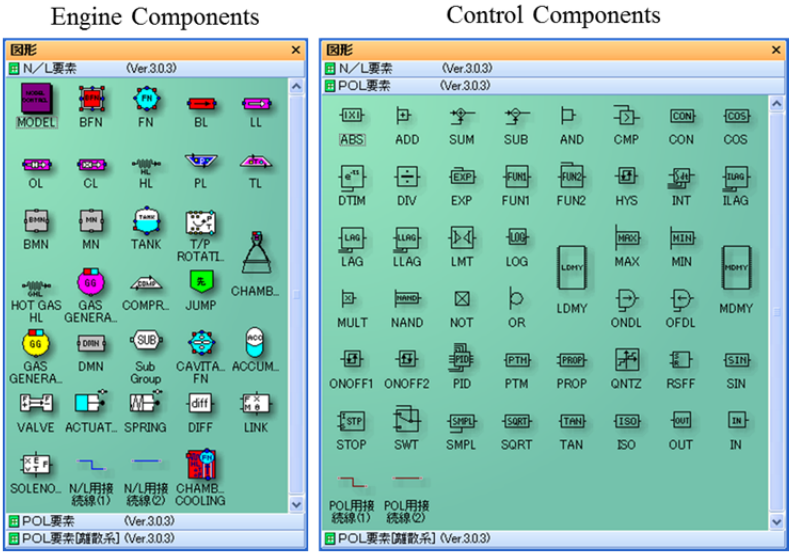

Fig.4 VISREC Component Library

2.3 Analysis variations

Other than a rocket engine start/shutdown transient analysis, VISREC can handle some types of analyses.

1) Steady-state engine balance
VISREC can perform steady state engine balance analysis with the same analysis model for transient analysis. This analysis includes “Standard Analysis” in which the engine balance under fixed engine configuration is calculated, and “Rated Analysis” in which the values of some parameters are searched to achieve the target engine balance. In the “Rated Analysis” two target parameters and two control parameters can be selected from engine output parameters and engine input parameters respectively.

2) Low cycle combustion instability analysis
VISREC has components which can simulate cavitation volume at the pump inducer and combustion delay in the combustion chamber. Those are main drivers for the engine system delay which can cause low cycle combustion instability. In order to evaluate the stability, VISREC has two methods. One is the linearized method where the engine transfer function is derived from the Jacobian at the steady state. In the other method, oscillation is applied to the non-linear engine model itself and the engine transfer function is derived from the input and output.

3) Mechanism analysis
VISREC has some components for mechanical parts such as actuator, spring and their connector. Valve actuator and valve body movement can be simulated by assembling them. Valve movement model can also be incorporated in the engine system model, and the combined analysis with actuator force and fluid force can be performed.

4) Control analysis
VISREC can handle simulations of control circuit using its control components. For more advanced or complicated analysis, VISREC has a module to link with MATLAB/Simulink. Simulink has a role to analyse control circuit and the data are exchanged with VISREC in the shared memory, synchronizing their clocks.

3. Analysis samples using VISREC

VISREC has been used to support Japanese engine development of LE-5B, LE-7A, MB-XX, LE-X and other small engines. In this paper, start transient analysis results for open expander cycle engine and closed expander cycle engine are presented, comparing with the actual operating data. A simple schematic diagram for both engine cycles are shown in Fig.5. In both engine cycles heated hydrogen after chamber cooling is used to drive turbine. In the open cycle the used turbine drive gas is dumped, while it is injected to combustion chamber in the closed cycle. It is generally known that because of this difference, characteristics of these two cycles are totally different in spite of the same "Expander" cycles.

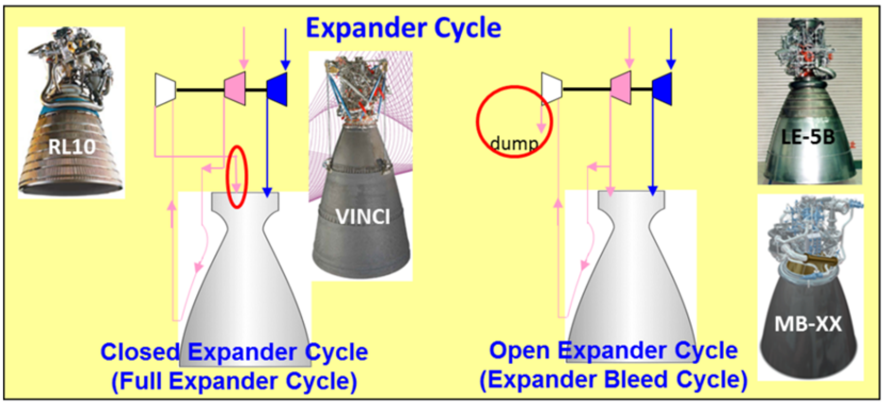

Fig.5 Schematic Diagram of Open Expander Cycle and Close Expander Cycle

After verifying the analysis models with the data, transient behaviors of two cycles are compared, varying some engine parameters and valve timings.

3.1 Analysis results of open expander cycle engine

Typical Japanese engine was modelled and the analysis results were compared to the test data. Fig. 6 shows analysis model, Fig.7 shows valve sequence. Typically among the 3 propellant shutdown valves of MFV (Main Fuel Valve), MOV (Main Oxidizer Valve) and CCV (Chamber Cooling Valve), CCV and MOV opens first almost at the same time and MFV opens later. Fig.8 shows the analysis results compared to the test data. The analysis simulates the test very well.

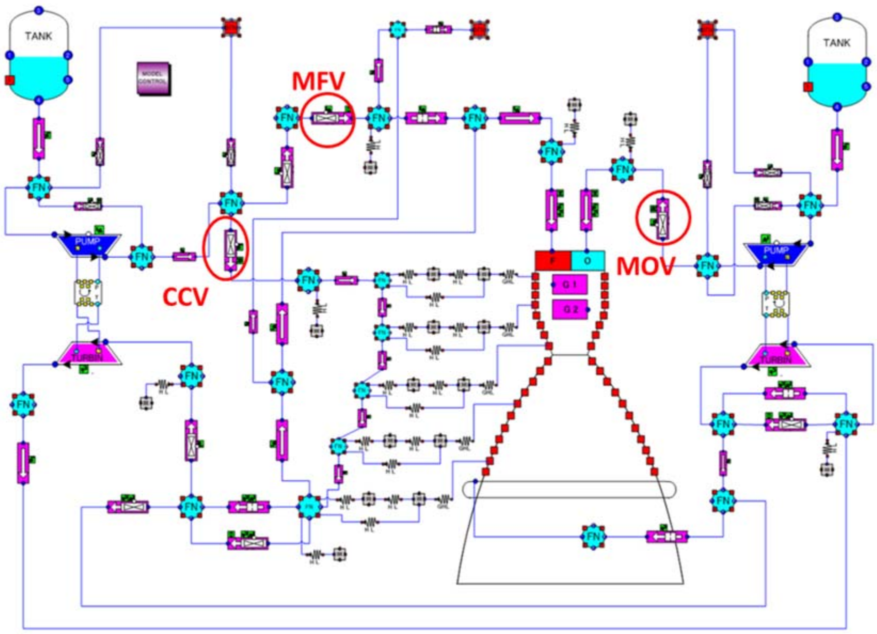

Fig. 6 Analysis model for open expander cycle engine

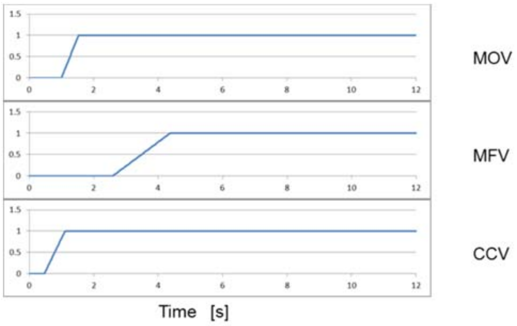

Fig. 7 Valve timing for open expander cycle engine

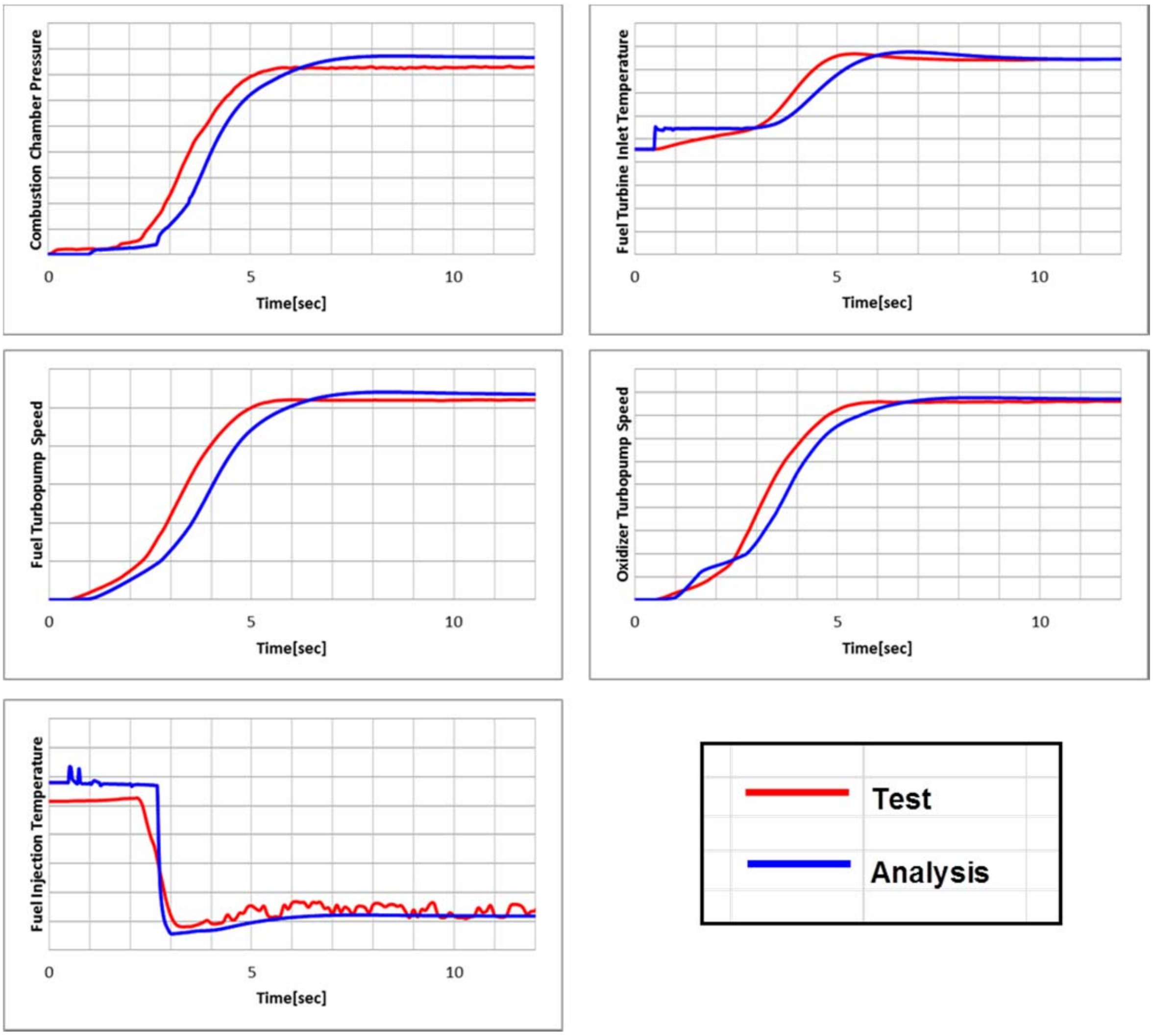

Fig.8 Analysis results of open expander engine

3.2 Analysis results of closed expander cycle engine

A publically accessible technical report on the RL10A-3-3A engine [2] is used to obtain engine system information, component configuration including performance, and test data. Fig.9 shows a schematic diagram of the RL10A-3-3A engine and Fig.10 shows its start valve sequence. Important valves of the RL10A-3-3A engine are OCV (Oxidizer Control Valve), FSOV (Fuel Shut Off Valve), TCV (Thrust Control Valve) and FCV (Fuel pump Cooldown Valve). OCV and FSOV correspond to MOV and MFV in the open expander cycle respectively. This engine initially starts slowly with FSOV opened, OCV slightly opened and 1 FCV opened. Then OCV is opened to almost full open position just after FCV is closed. At this timing the engine starts up very quickly. Finally OCV and TCV are controlled to reach the target steady-state balance. Fig.11 shows analysis model and Fig.12 shows the analysis results compared with the test data. The analysis simulates the test very well.

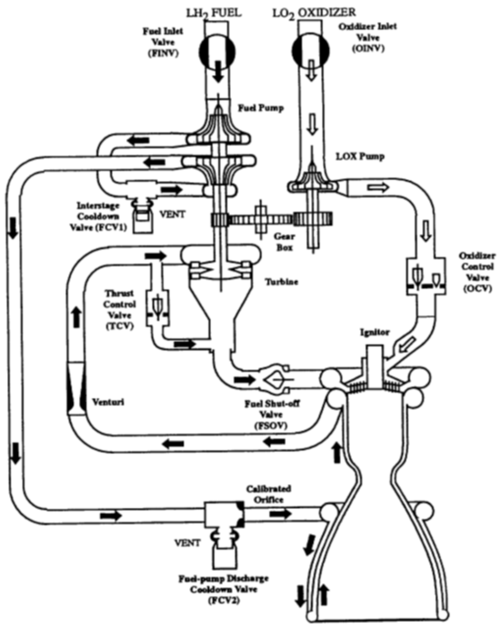

Fig.9 Schematic diagram of the RL10A-3-3A

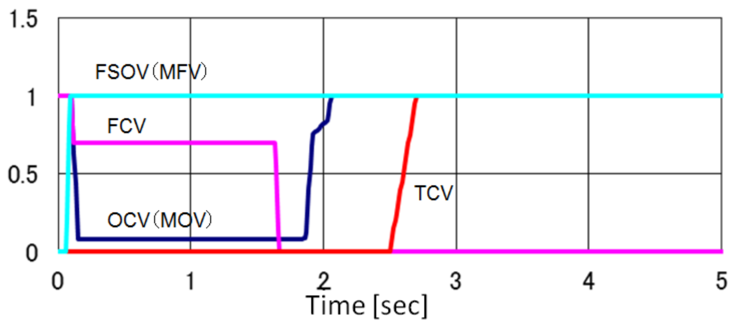

Fig.10 Schematic diagram of the RL10A-3-3A

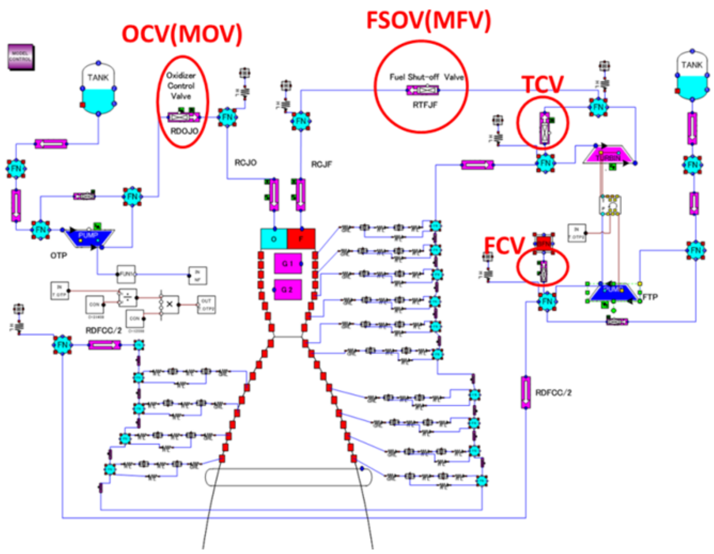

Fig.11 Analysis model of the RL10A-3-3A

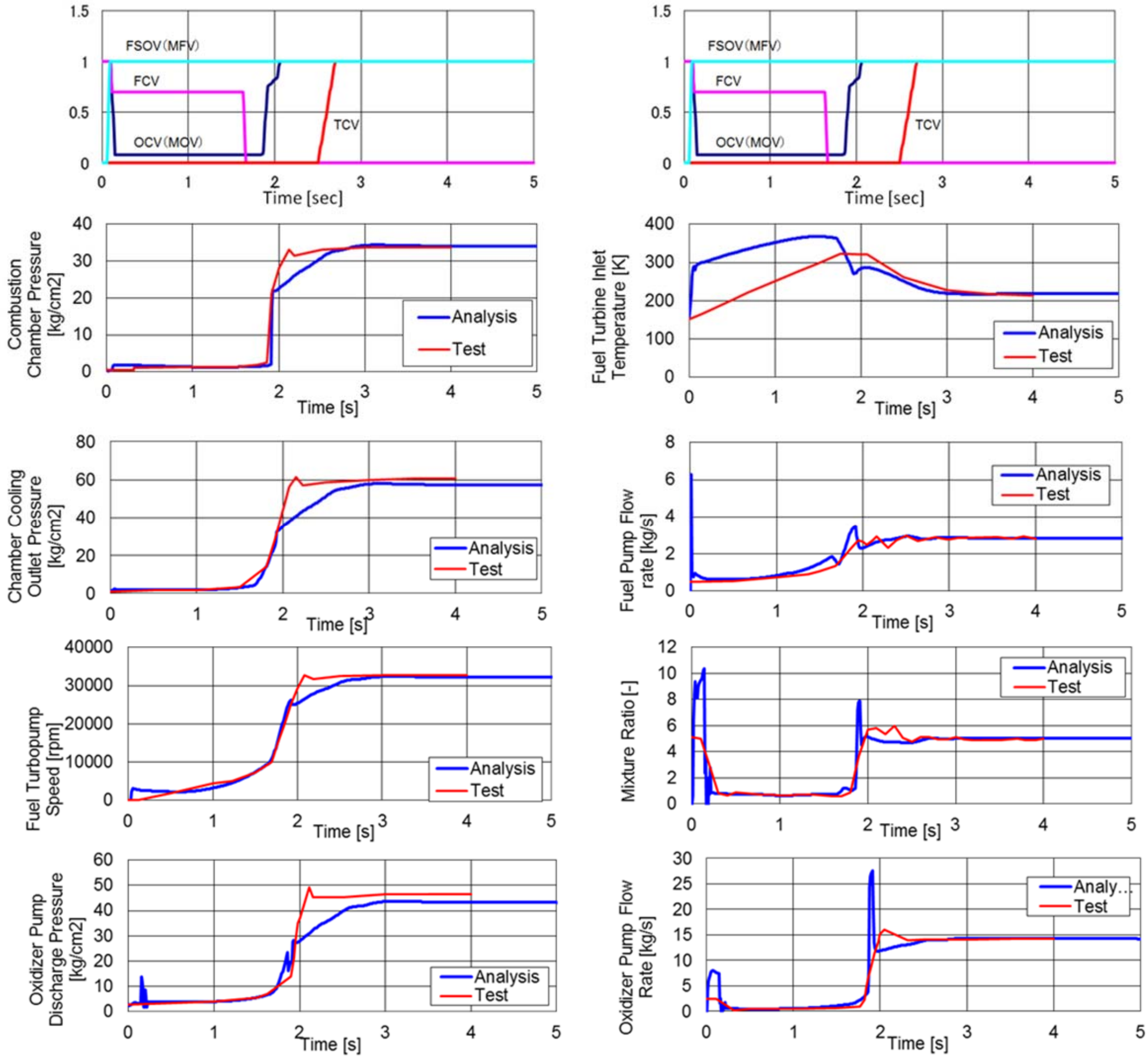

Fig.12 Analysis results of the RL10A-3-3A

3.3 Sensitivity comparison between two cycles

Open expander cycle and closed expander cycle transient behaviors are predicted and compared with the same models described above, changing engine parameters (pump efficiency, turbine efficiency, chamber cooling pressure drop, chamber heat transfer, tank pressures and hardware temperature) and valves sequences. The results by changing engine parameters are shown in Fig.13. Closed expander cycle has larger sensitivity than open expander cycle to the tank pressure and the hardware temperature. In the open expander cycle, time to reach the steady state changes as the change of the parameters, but the pattern does not change largely. On the other hand in the closed expander cycle, even the pattern of starting changes.

When the valve timing is changed in the open expander cycle, time to reach the steady state changes but the pattern does not change largely, similar to the cases changing engine parameters. In the closed expander cycle, the pattern changes when FSOV, OCV and FCV opening timing is changed. Especially when the OCV opening timing is forwarded, the closed expander cycle does not start as shown in Fig. 14. The figure also shows the turbine pressure ratio. Early OCV opening causes the early chamber pressure rising and it makes the turbine pressure ratio lower, then the turbine power is not enough to drive pumps. It is very interesting that the final steady state can be affected by the transient in the closed expander cycle. In the open expander cycle, the fuel driving the turbine is dumped and the turbine pressure ratio is independent to the combustion chamber pressure. Closed expander cycle may need careful setting and the control of the valve timings.

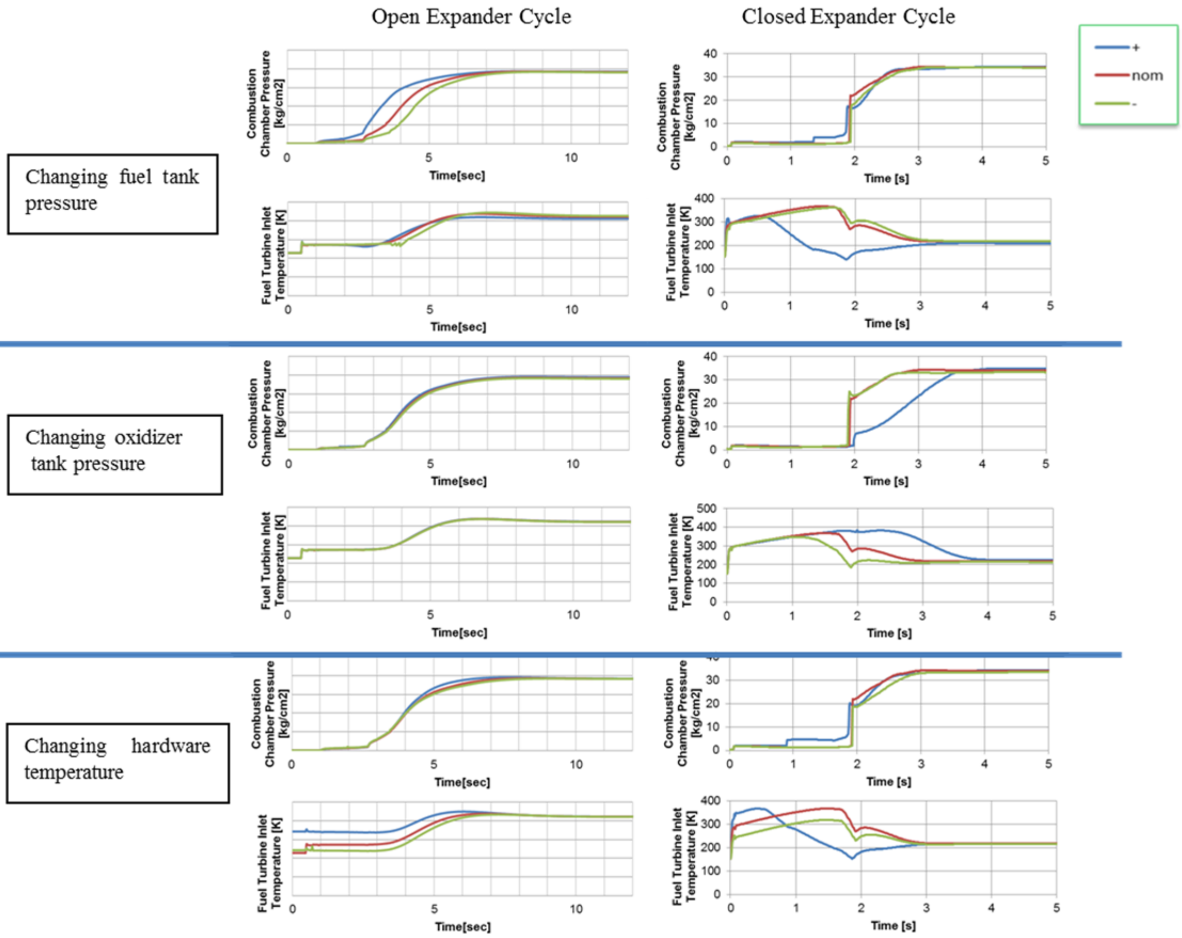

Fig.13 Analysis results by changing engine parameters for open expander and closed expander

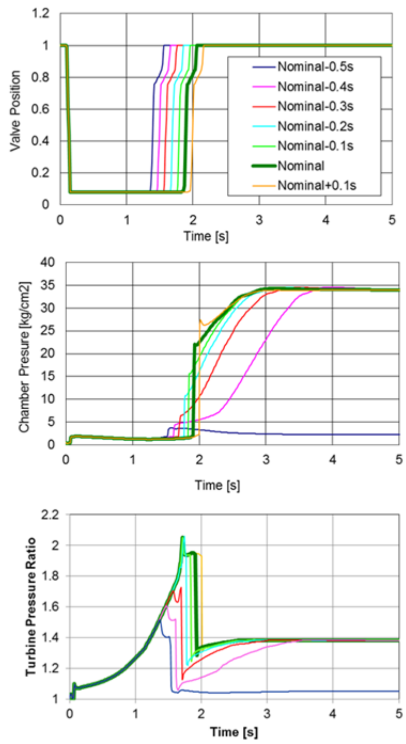

Fig.14 Analysis results by changing OCV timing for closed expander

4. Conclusions

A rocket engine dynamic simulation tool VISREC was developed by MHI and has been used for the development of Japanese liquid rocket engines. It gives us very easy way to predict the engine transient behaviour with adequate accuracy. Sample analysis results in this paper show its capability, and also a potential that the engine transient analysis can contribute to the initial decision on the engine configuration including the engine cycle in the new engine development.

References

[1] Atsumi M., and Ogawara A. 2002. Development of Visual Integrated Simulator for Rocket Engine Cycle. The fourth International Conference on Space Launcher Liquid Propulsion. #204.
[2] Thomas. T and Joseph. P. 1997. RL-10-3-3A Rocket Engine Modeling Project. NASA TM-107318.