Evaluation on the Characteristics of Liquefied Natural Gas as a Fuel of Liquid Rocket Engine

Hyuck-joon Namkoung, Poong-Gyoo Han and Kyoung-Ho Kim
Rotem Company
nkhj@rotem.co.kr

Key Words : Liquefied Natural Gas, Liquid Rocket Engine, Fuel, Regenerative Cooling, Characteristic Velocity, Specific Impulse.

Abstract

As a rocket propellent of hydrocarbon fuels, the characteristics of liquefied natural gas was evaluated with the viewpoint of the constituents and content, the cooling performance as a coolant, and characteristic velocity and specific impulse as parameters of the engine performance. Content of methane was a principal factor to determine the characteristics as a rocket propellant and more than 90 % of it was needed as a fuel and coolant in the regenerative cooled liquid rocket engine. Some constituents of the liquefied natural gas can be frozen by the pre-cooling of the pipe lines, therefore they can be a factor disturbing the normal working of engine. In case the content of methane is around 90% in the liquefied natural gas, a normalized stoichiometric O/F mixture ratio of 0.75 is suggested for a nominal operation condition to get the maximum specific impulse and characteristic velocity.

Introduction

Liquid Methane comes to light as LRE fuel for next generation replacing the hydrogen centering on RUSSIA and EUROPE. In Russia, which leads the world in this field of development of Methane Engine, Methane Engine Program named to RIKSHA has been in progress in 1990's. EU and RUSSIA have established a plan replacing launch vehicle launched by using a methane engine through the Volga project in 2000's in near future. Also in Europe, the use of a methane engine replacing a hydrogen engine as a fuel in LRE booster of Ariane 5 has been reviewed and methane engine has been considered in 2nd stage engine of J-II Rocket in Japan,. However, the case of launching by applying it to space launch vehicle has never been and the researching case replacing liquid methane by LNG as LRE fuel is rare. In general, liquid methane is friend with environment and excellent in an economical efficiency aspect and has high specific impulse in comparison to the fuel of any other hydrocarbon group [1,2]. Therefore it is possible to use the methane as a fuel of LRE.

Also, LNG is as a mixture of substances of several hydrocarbon groups including liquid methane more than 90% of volume ratio. Because refining LNG produces liquid methane, it is much cheaper than liquid methane in viewpoint of production cost and more efficient in comparison to not only hydrogen but also any other propellants such as Fig. 1. Especially, in case of more than 90% in methane volume ratio, several characteristics including thermodynamic and cooling performance is very similar to those of methane, and therefore we think that it is possible to use a LNG as LRE fuel replacing liquid methane and retaining merits of liquid methane as LRE fuel.

Accordingly, in this paper, the characteristics of LNG as a LRE fuel will be analyzed and evaluated by comparing it with liquid methane.

Main Subject

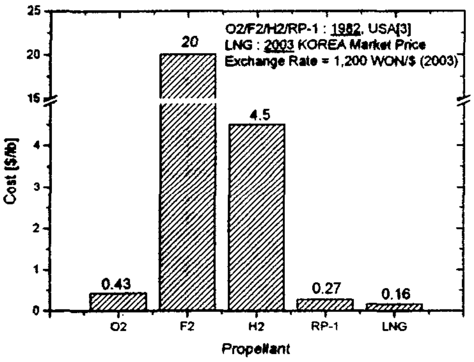


Fig.1. Production cost and market

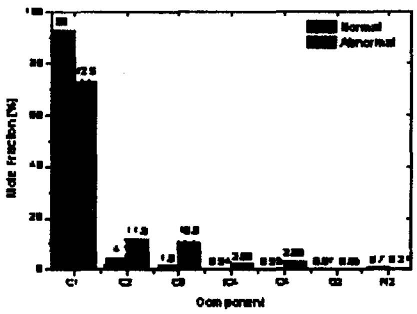
In order to evaluate the possibility of the use of LNG as LRE fuel, characteristic velocity and specific impulse on the constituents and content, thermodynamic, regenerative cooling characteristics and model combustor of 10tf level will be compared and evaluated with those of a liquid methane engine.

Analysis of constituent and content

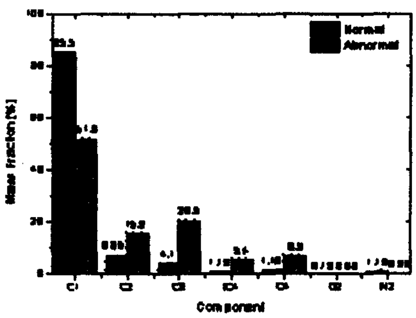
Constituents and content of LNG are different in a producing district, however it is known that ethane, propane, iso-buthane, oxygen and nitrogen etc. are included and contents of alkane group, which is large over penthane in carbon number, are included small[4]. In this paper, in order to analyze and evaluate constituents and content of LNG as LRE fuel, contents of LNG used in a sort of firing test, which is performed in Rotem, are gathered before the ignition of each firing test. After that, they are analyzed and evaluated by gas chromatography (GC-14B) using detection method of the thermal conductivity. As the results, table 1 shows volume ratio of constituents in each test condition [4]. As nomenclature used in table 1, C1 is methane, C2 is ethane, C3 is propane, IC4 is Iso-buthane, C4 is Neo-buthane, O2 is oxygen, and N2 is nitrogen. The 9 test conditions except L1 in which minimum volume content for methane is over 90% are classified into normal condition of LNG constitution. L1 is done into abnormal condition because content of ethane, propane and buthane of L1 is increased high and not come up to the other condition.

Table 1. Chemical constituents and thermodynamic properties of liquefied natural gas

Case		Chemical Formula				Mole fraction							Chamber Inlet		Mixture Ratio
		C	H	N	O	C1	C2	C3	IC4	C4	O2	N2	T[K]	P[MPa]	
W	W1	1.152	4.289	0.003	0.012	89.4	5.30	3.1	0.70	0.77	0.15	0.59	242.6	3.66	2.46
	W2	1.142	4.278	0.005	0.001	89.3	7.18	2.31	0.46	0.44	0.07	0.23	250	7.61	2.55
	W3	1.123	4.226	0.001	0.019	89.5	6.48	2.15	0.43	0.41	0.07	0.94	265.8	7.11	3.09
	W4	1.113	4.218	0.002	0.006	91.3	5.67	1.91	0.38	0.36	0.09	0.31	267.4	3.53	3.38
	W5	1.096	4.181	0.003	0.009	92.2	5.05	1.61	0.33	0.31	0.13	0.43	269.5	7.74	3.42
R	N1	1.073	4.143	0.000	0.002	95.3	2.40	1.45	0.33	0.36	0.02	0.10	315.8	4.93	2.0
	N2	1.071	4.105	0.002	0.000	95.4	2.39	1.43	0.32	0.35	0.02	0.10	315.8	5.24	2.51
	L1	1.466	4.926	0.001	0.005	72.9	11.5	10.6	2.09	2.69	0.05	0.27	162.6	4.88	1.27
	L2	0.984	3.899	0.001	0.068	95.3	0.82	0.41	0.04	0.03	0.05	3.4	186	4.82	2.92
	L3	1.011	4.017	0.000	0.004	99.0	0.46	0.17	0.06	0.1	0.02	0.21	195.2	4.88	3.11



a) Volume(=Mole) fraction



b) Mass fraction

Fig.2. Constituents and contents of liquefied natural gas

Fig 2 shows constituents and each volume ratio (mole fraction) of normal condition averaged on 9 cases and abnormal of L1. Regarding mass ratio, methane content in case of normal and abnormal one was over 80% and 50% respectively. The above discrepancy of constituent ratio can be an important evaluation factor for determination of possibility if LNG is used as LRE fuel replacing liquid methane engine or not. If content of methane is small such as L1, not only thermodynamic property but also engine performance will be affected much. These evaluations will be treated with detail in following chapter.

Cooling characteristics

In order to obtain the high thrust generally, high chamber pressure is required and the majority of commercial engines using hydrocarbon fuels are used in the condition over the critical point.

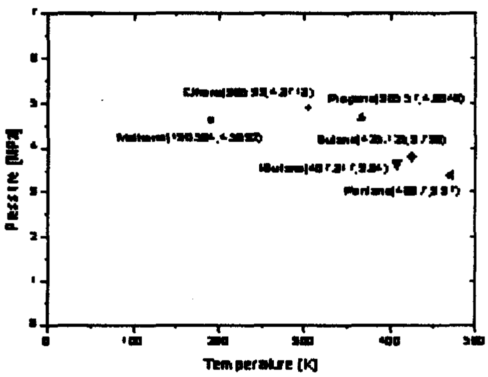


Fig.3. Super-critical condition of the constituents of liquefied natural gas

Supercritical temperature and pressure of the main constituents of LNG is 3.37 Mpa and 4.87 Mpa respectively as shown in Fig 3. Chamber pressure of model engine considered is 7.2 Mpa in this study, which was set up higher than the supercritical pressure of LNG. This is efficient not only to obtain high thrust but also to avoid the thermodynamic instability cased by the phase change of LNG.

That is, the temperature of LNG that enters into combustion chamber is set up lower than supercritical one of constituents of LNG, and therefore it is classified into liquid phase. However, because the pressure of cooling channel inlet and combustion chamber excess the supercritical pressure of constituents of LNG and the phase change in cooling channel is a change into the supercritical phase, occurrence of bubble in cooling channel wall caused by the fuel boiling can prevent wall melting.

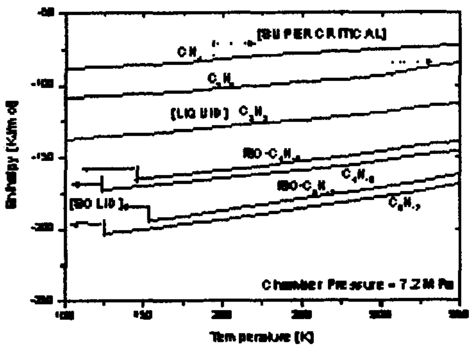
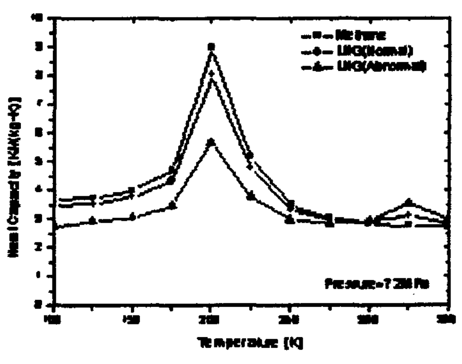
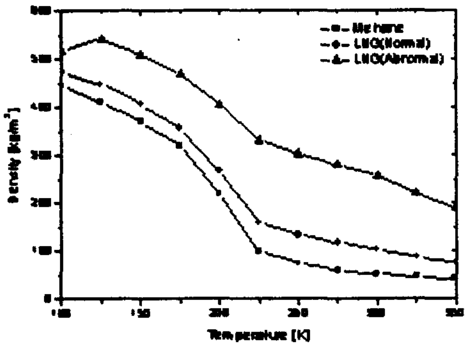


Fig. 4. Enthalpies of the constituents of liquefied natural gas.

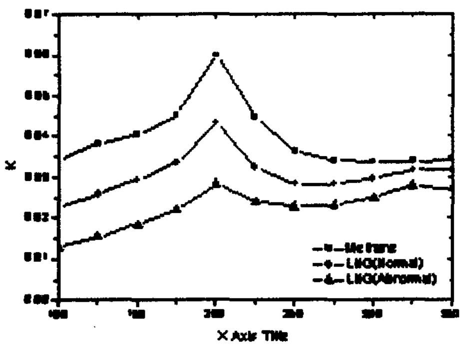
Fig. 4 shows the value of initial enthalpy calculated according to temperature variation of LNG entered into combustion chamber of test engine at 7.2Mpa. which was calculated by STRAPP (property calculation program). Discrepancy of initial enthalpy between methane and penthane amounts to one of methane and this discrepancy affects an engine performance severely. That is, the more contents of methane are, and the higher initial enthalpy of fuel is. And therefore engine performance such as characteristic velocity, its efficiency and specific impulse become improved. Also, ISO-buthane, buthane, penthane out of constituents of LNG exit in solid phase at 7.2Mpa of pressure and under about 150K of temperature. This can be restriction in using LNG as fuel. Generally, when firing test on engine or using engine in launch vehicle, it is necessary to cool in advanced, and then several constituents of LNG became over-cooled according to temperature of the used fluid (ordinary, liquefied nitrogen). And therefore, constituents of more than ISO-buthane may be condensed as shown in Fig. 4. This condensation phenomenon of some constituents can act as a factor disturbing the flow of LNG in passage of cooling channel and injector, and therefore abnormal working may be cased. Finally, if LNG is used as LRE fuel, it is necessary to note the condensation of some constituents and the possibility of abnormal working caused by it.



a) Heat capacity



b) Density



c) Material complex, K

Fig. 5. Principal material properties of liquefied natural gas

Fig 5 (a) shows both heat capacity of methane and mixture gas calculated multiplying constant-pressure specific heats of each constituent by its mass ratio at 7.2Mpa using STRAPP, which is heat capacity according to a temperature entered into combustion chamber. Under 300K, heat capacity of LNG is shown less than one of methane. When cooled regenerative by fuel, temperature increase of LNG will be higher in comparison with regenerative cooling by the liquid methane.

Especially, because heat capacity tents to decrease by 30~40% in comparison with methane in condition of L1 that methane is included small, cooling performance as a coolant becomes declined greatly. And therefore, content of methane in LNG as fuel of LRE must be retained more than minimum 90% because content of methane has a severe effect on heat capacity and constituent and content and constituent of LNG is very important. Fig 5(b) shows the variation of density according to the temperature of fuel entered into combustion chamber. When variation range of temperature is assumed to be 120 ~ 130K, the density at exit of cooling channel become decrease under about 20% in comparison with its inlet condition and then, volume flow rate become increase over 5 times. And therefore, in case of LNG like liquid methane, not only a pressure drop by surface friction but also one by the variation of density is expected to increase highly. Designing cooling channel of engine, through the considering of density variation of LNG, the change of a geometrical shape into high aspect ratio (ratio between height and width) has to be considered. Also, through the increase of density, the volume size of reservoir tank can be smaller. Fig 5(c) shows the expression of property complex K that is consist of the forced-convection heat-transfer coefficient. by using the function of temperature. Generally, if the forced-convection heat-transfer coefficient in cooling channel can be calculated in Dittus-Boelters equation such as equation (1)

$$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \qquad (1)$$

Equation (1) is expressed such as equation (2) about convection heat-transfer coefficient, h

$$h = \frac{0.023}{d_h^{0.2}}(\rho V)^{0.8} K,\ K = k^{0.6}\left(\frac{c_p}{\mu}\right)^{0.4} \qquad (2)$$

In right term of equation (2), K is the property complex term of coolant, k is thermal conductivity, μ is viscosity coefficient and cp is specific heat. Also, in equation (2), h is a convection heat-transfer coefficient, ρ is density, V is a coolant velocity in cooling channel, and d_h is a hydraulic diameter of cooling channel.

Fig 5 (c) shows a discrepancy about 30% in the region of 100~350K coolant temperature regarding property complex term K of methane and LNG in which methane volume ratio is more than 90%. This means that cooling characteristics of LNG is worse than those of a liquid methane in the respect of function of a coolant such as the result in which the viscosity discrepancy of constituent of LNG is affected. That is, inner wall temperature in case of LNG is higher than those in case of liquefied methane and therefore, the discrepancy on property complex K should be considered in the design of cooling channel of LRE using LNG as a fuel. In case of L1, because the property complex K is decreased by 1/3 level in region of a low temperature, it is thought that L1 is not suitable in the respect of a function of coolant. Finally, the importance about a content of methane in the respect of cooling characteristics could be confirmed one more.

Comparison and analysis on engine performance.

Characteristic velocity and specific impulse is used as a factor which represent engine performance and propellant performance. In this study, it was used to perform quantitative analysis on characteristics as a fuel of LNG.

Especially, in order to measure engine performance, module engine for test such as mixing head, igniter, chamber, nozzle is introduced as shown in fig. 6, and table 2 shows a main specification for test engine.[5][6]

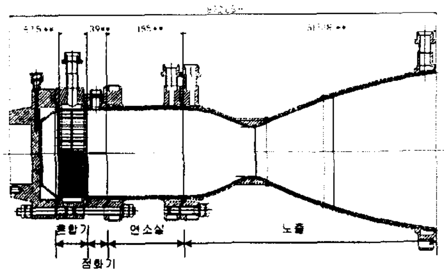


Fig. 6. Section view of experimental combustion chamber

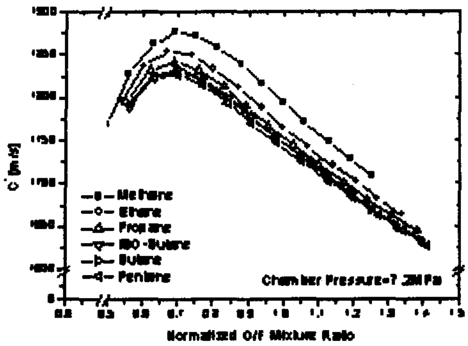
Table 2. Experimental engine spec.

Propellant	Fuel	LNG
	Oxidizer	Liquid Oxygen
Chamber Pressure		7.2 MPa
Mass Flow Rate	Fuel	8 kg/s
	Oxidizer	24 kg/s
Injector		Shear Coaxial Type
Throat Diameter		101.2 mm
Contraction Ratio		3.02
Expansion Ratio		9.83

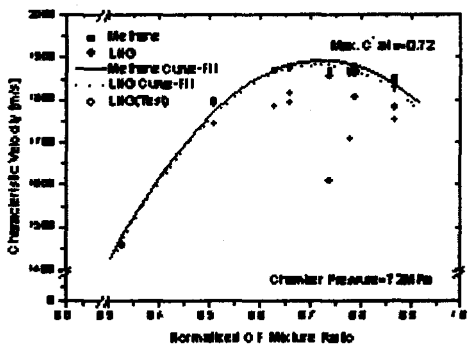
In order to analyze engine performance and obtain characteristic velocity and specific impulse, and characteristic velocity efficiency, CEC 86[7] code was used, it calculate the ideal values of characteristic velocity and specific impulse considering fast chemistry and assuming a chemical reaction in chamber to be a chemical equilibrium state in which reaction is independent on propellant mixture ratio.

Investigation on characteristic velocity.

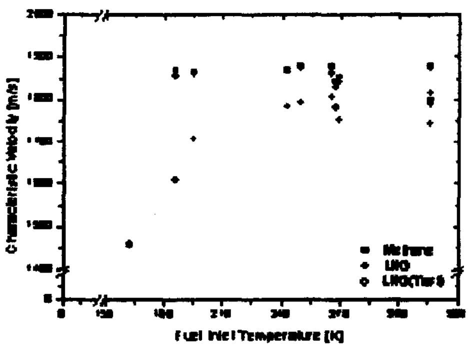
Characteristic velocity for test engine of 10ton level when liquefied methane and LNG is used as a fuel was calculated with CEC86 about the test condition of table 1. Fig 7 (a) shows characteristic velocity on an each constituent of LNG, when the number of carbon, characteristic velocity and mixture ratio of propellant, which represents the maximum characteristic velocity, is reduced. And therefore increase in content of the other constituents except methane in LNG acts an effect of decrease in specific impulse of engine. Finally, LNG, which takes a high content of methane, will be suitable as a fuel replacing liquefied methane.



a) Constituents of liquefied natural gas



b) OF mixture ratio



c) Fuel inlet temperature

Fig.7 Characteristic velocity

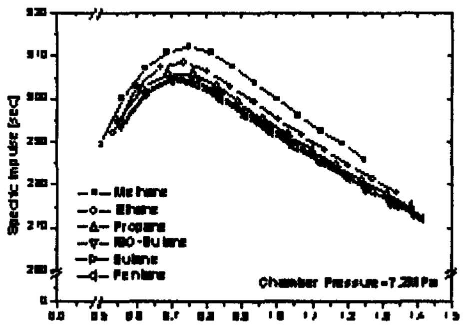
Discrepancy in characteristic velocity when methane and LNG as a fuel are used is less than 1% and characteristic velocity is maximum value at near 0.72 in propellant mixture ratio as shown in Fig. 7 (b). In case of L1 with a different constituent of LNG, characteristic velocity was decreased by 21% in comparison with the other conditions. And therefore, if content of methane is decreased in chemical constituents of LNG, characteristic velocity is less than those of mixture and L1 became improper in using as a fuel of LRE as shown in fig. 7(a). LNG which methane volume ratio contains about 90% was similar to methane in chemical equilibrium reaction analysis considering the fast chemistry. However, real process that reach to combustion through spray injection is different with the fast chemistry, and experimental results of characteristic velocity obtained by a ring test of LNG was different with an ideal results. In this study, firing test using liquefied methane has not been performed, however, it is thought that experimental value of liquefied methane will be similar to a normal LNG. Characteristic velocity is much less than those in the other test condition because of a low propellant mixture ratio. In total constituent composition, content of methane is about 72.8% as a mole fraction (about 51.6% as a mass fraction) because content of ethane, propane, buthane whose initial enthalpy is lower than those of methane are high as shown in table 1, which is caused by characteristics of a real spray injection.

Fig 7(c) shows that discrepancy of chamber inlet temperature of fuel has no effect on characteristic velocity, and discrepancy between methane and LNG can be negligible. However, experimental value obtained by firing test using LNG is very different relatively with ideal value and that characteristic velocity tends to increase when chamber inlet temperature of fuel is high. This is that theoretical analysis deal with a chemical equilibrium condition considering fast chemistry, while, in the real spray process, an initial inlet temperature became increased and initial enthalpy became increased and then specific volume and an exit velocity in the injector also becomes increased. Injector used in this test engine is shear coaxial type in which a velocity ratio between fuel and oxidizer is main factor for performance. It is thought that the more initial enthalpy of fuel and velocity ratio is increased, the higher efficiency of atomization and mixing is, and therefore combustion efficiency becomes excellent, and characteristic velocity becomes increased.

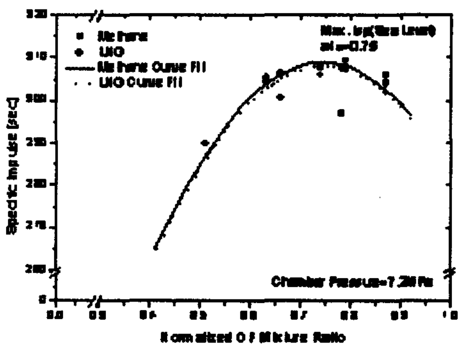
Investigation on a specific impulse

Fig. 8 shows specific impulse obtained by using CEC86 code, discrepancy between methane and LNG was under 1%. This is that real environments according to test condition in the chemical reaction considering fast chemistry are not affected.

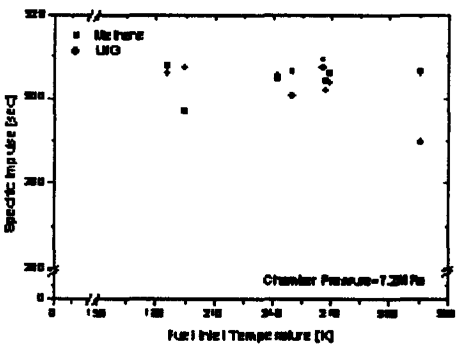
Here, in case of L1, which is different with the other condition in chemical composition, specific impulse is 180sec level, which is different with the other case by 21%. As shown in fig. 8, if the content of methane in LNG become less and the content of ethane, propane, ISO-buthane and buthane become higher, reduction of specific impulse may be severe.



a) Constituents of liquefied natural gas



b) OF mixture ratio



c) Fuel inlet temperature

Fig. 8. Specific impulse

Fig 8(a) shows the specific impulse of each constituent composing LNG. In case of methane, maximum specific impulse is shown at 0.75 of normalized propellant mixture ratio and when the number of carbon become increased, maximum specific impulse and mixture ratio that shows it become decreased. And therefore, specific impulse of LNG is expected to be less than those of liquefied methane. Especially, the less content of methane is, the less specific impulse is, as is expected. As shown in fig 8(b), when specific impulse is approximated to 2nd order polynomial expression, both methane and LNG has maximum specific impulse at around 0.75 of propellant mixture ratio as same as characteristic velocity. And therefore, propellant mixture ratio normalized with chemical equivalent ratio, which has a maximum characteristic velocity of fig. 7 (b), is 0.72. Because this value is similar to 0.75 of propellant mixture ratio, which has a maximum specific impulse, propellant mixture ratio is setup as appropriate at 0.75 in operating condition of LRE using LNG as a fuel.

Fig 8(c) shows that variation of specific impulse according to temperature of fuel entered into chamber is small, these results also are caused by a combustion analysis, which consider chemical reaction of propellants as fast chemistry, as same as in case of characteristic velocity. It is thought that they show trends similar to experimental results of characteristic velocity considering a real spray injection.

Conclusion

As a rocket propellent of hydrocarbon fuels, the characteristics of liquefied natural gas was evaluated with the viewpoint of the constituents and content, the cooling performance as a coolant, and characteristic velocity and specific impulse as parameters of the engine performance. And conclusions are as followings

1) Content of methane in LNG is an important factor which determine characteristics as fuel of LRE. In order to be used as a fuel of regenerative cooling LRE, methane content more than minimum 90% is required.

2) Cooling channel with high aspect ratio should be introduced considering the severe variation of density within the region of operating temperature

3) Cooling performance of LNG with 90 % level of volume content of methane is about 70 % of liquefied methane. It should be noted that possibility of abnormal operation of engine by condensation of constituent with number of carbon more than those of ISO-buthane and by pre-cooling exist.

4) Optimum operating condition of LRE using LNG that has content of methane more than 90% is at 0.75 of a propellant mixture ratio, which is normalized with mixture ratio of chemical equivalent ratio.

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