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Study on the Application of Emulsified Fuel in small Jet Engines

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Abstract

The numbers of small aircrafts such as air taxis and drones are expected to be growing. Therefore, it is very important to minimize fuel consumption and CO2 emissions from those small aircraft engines due to recent worldwide concern on both economic and environmental impact. The current study investigated on emulsified fuels to improve combustion efficiency and reduce both CO2 and fuel consumption in small jet engines. From the small jet engine experiment using emulsified fuel, it was found that the combustion efficiency is improved by up to 5.8%, and the fuel consumption rate is improved by up to 1% for the case of emulsified fuel compared to conventional jet fuel.

Keywords: Emulsified fuel, Small aircraft, Fuel consumption, Combustion efficiency

1. Research Background

Modern aero engines are facing to increasing demands for lower emissions and also to rising fossil fuel prices. In addition, the number of small aircraft such as drones, air taxis and private jets are expected to increase rapidly, and it is important to improve the combustion efficiency of small engines and reduce emissions including CO2 and NOx. One way to solve these problems is to use emulsified fuel. Emulsified fuel is a mixture of conventional fuel, a small amount of water, and an emulsifier. This fuel is said to cause micro-explosions when burned, reducing unevenness in combustion. Fig 1 shows the concept of micro explosion. Fig 2 shows comparison between pure jet fuel and emulsified fuel. This is thought to improve combustion efficiency, and at the same time reduce specific fuel consumption rate (SFC) and CO2 emissions. The presence of water also suppresses combustion temperature, which is believed to reduce NOx. In a previous study, using a micro gas turbine for power generation, it was reported that fuel consumption could be reduced by 5.46% when water was added by 12%. It was also found that CO emissions could be reduced by up to 12.32% and NOx emissions by up to 35.16% [1]. There have been several other studies on emulsified fuels such as those conducted using only combustors, but none using small jet engines [2]. Therefore, in this study, we investigated the characteristics of emulsified fuel using a small jet engine. We operate Merlin 100 small jet engine using several types of emulsified fuel, measured the various engine parameters, and evaluated the performance of each emulsified fuel compared to conventional pure jet fuel.

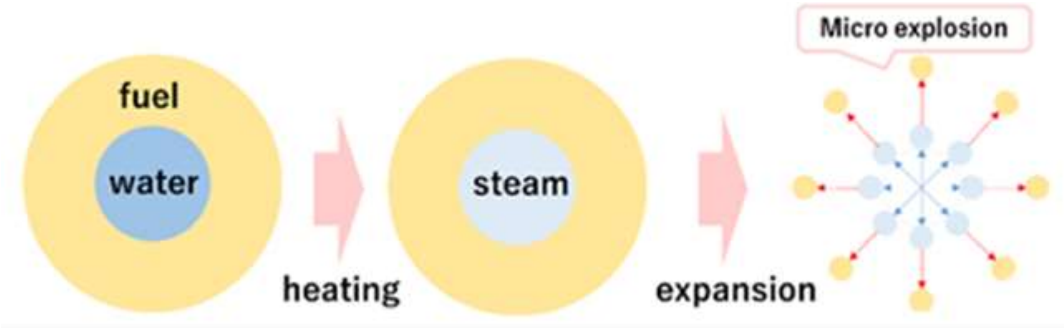

Fig.1 Concept of micro explosion

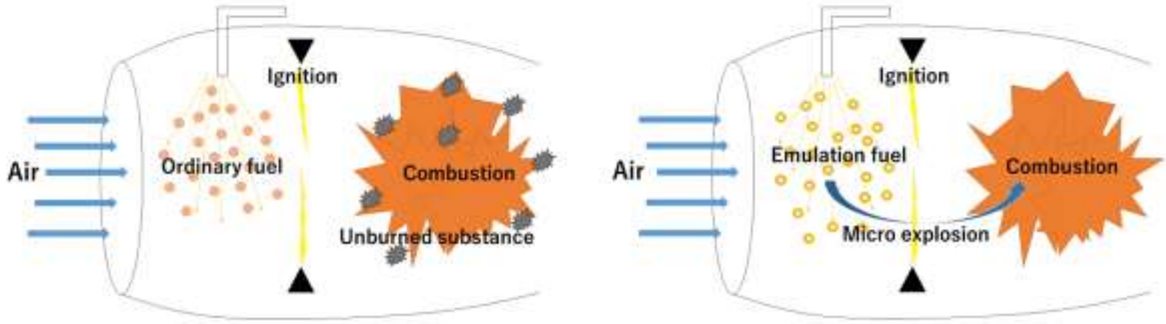

Fig.2 Comparison between pure jet fuel (conventional jet fuel) and emulsified fuel

2. Experimental Method

Some emulsified fuel is applied to a small turbojet engine whose name is Merlin 100. The engine specification and experimental set up are shown in Table.1 and Fig. 3. Measured points of temperature, pressure and thrust are also shown in Fig.3 [3]. Fig.4 shows the picture of the experiment setup and Fig. 5 shows inside cut view of the engine.

Table.1 Merlin 100 Engine specifications

Engine name	Merlin100 turbojet engine
Total weight	0.994kgf
Dimensions	ϕ 90mm × 210mm
Rated Thrust	100N(152,000rpm時)
Maximum speed	152,000rpm
Exhaust velocity	550-850℃
Speed at idle operation	42,000rpm
Thrust at idle operation	4N
Maximum fuel flow	350ml/min（At rated thrust)

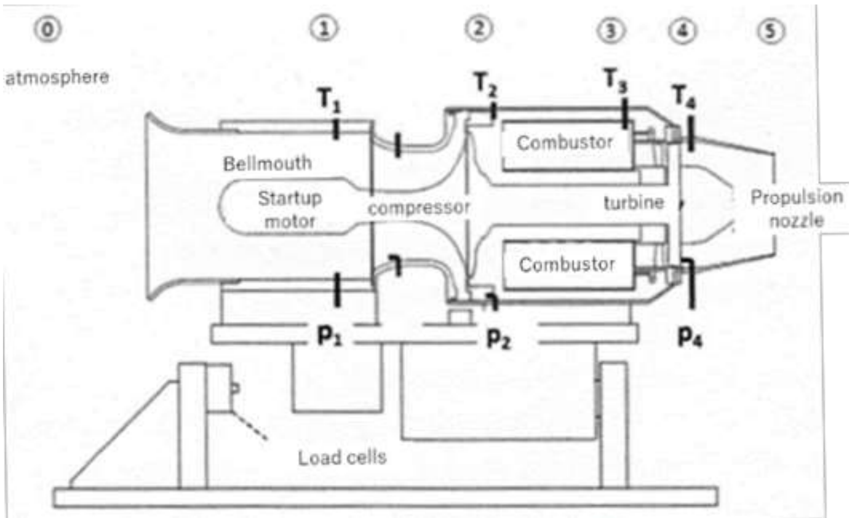

Fig.3 Measured points

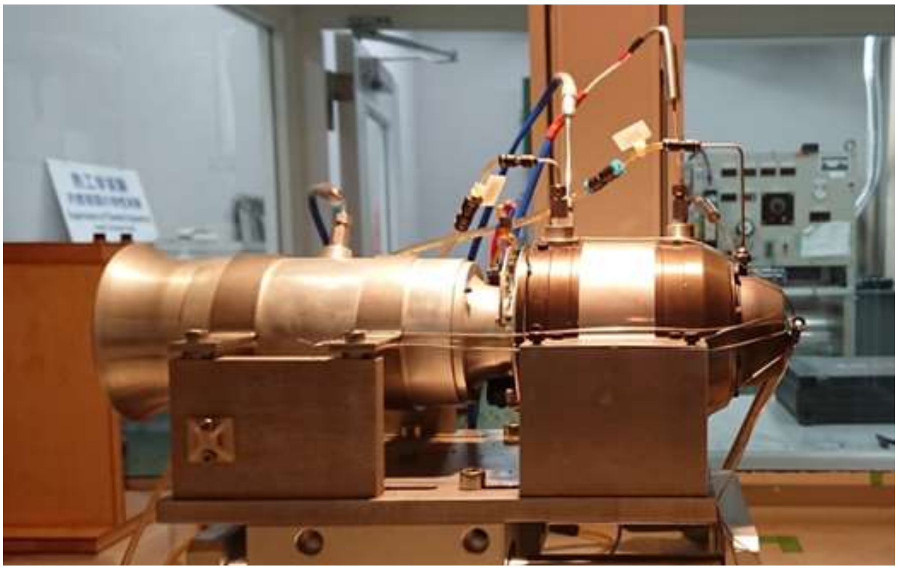

Fig.4 Merlin100 jet engine test set-up


Fig.5 Inside cut view of the engine

3. Fuel

3.1 Selection of emulsifier

Emulsified fuel is a mixture of jet fuel and a small amount of water. When mixed these two substances will separate immediately. Therefore, in this experiment, we have to prepare a fuel that is difficult to separate each other by using emulsifier. Emulsifier selection criteria are evaluated based on stability and viscosity after emulsification. Candidates are dish detergent, isopropanol, and Aqua Spark +. A large number of sodium lauryl sulfates is reported to be used in the literature for emulsified fuels in reciprocating engines. Isopropanol is also used as a drainage agent for automobiles. This emulsifier has been used for many years and was selected with the expectation of high reliability. In addition, Aqua Spark + is positioned as a high-performance drainage agent and was selected with the expectation of reliable emulsification and safety.

3.2 Stability of emulsified fuel with each emulsifier

The stability of emulsified fuels are compared using dishwashing detergent, isopropanol, and Aqua Spark+ as emulsifiers. Fig.6 shows the pictures of each emulsified fuel. Table.2 shows ingredients of each emulsified fuel.

Fig.6 Comparison of emulsified fuel and jet fuel

Table.2 Ingredients of each emulsified fuel

	Pure jet fuel	Emulsion fuel		
	①	② Isopropanol	③ Aqua Spark +	④ Dishwashing detergent
Jet fuel [%]	100	95	95	95
Water [%]	0	2.5	4	4
Emulsifier [%]	0	2.5	1	1

Emulsified fuel containing isopropanol separated immediately after stirring. As can be seen in Fig.6 ②, water has accumulated at the bottom and separated. From this, it was found that isopropanol was inferior in stability. The emulsified fuels with Aqua Spark+ and with dish detergent did not change in appearance after being allowed to stand for a while. However, emulsified fuel with dish washing detergent looks like yogurt and seemed to viscous for fuel application. Therefore, we chose emulsified fuel with Aqua Spark+, which seems to have a viscous property close to that of jet fuel.

3.3 Stability of emulsified fuel for Aqua Spark+

The comparison was made by changing the amount of emulsifier using Aqua Spark. Table.3 shows ingredients of each fuel. Fig. 7 shows the state of the emulsified fuel immediately after stirring. From the left, it is the No. 1, No. 2, No. 3, and No. 4 emulsified fuels. Fig.8 shows the state of the emulsified fuel after 1 hour of stirring, and a slight amount of precipitate is seen at the bottom of No. 2, No. 3, and No. 4. Since the precipitate is heavier than kerosene, it is presumed to be water. From Fig. 8, it is considered that there is a boundary between No. 1 and No. 2 where no precipitate is formed. In the jet engine test, an experiment was conducted using the No. 2 fuel for immediate use after stirring the emulsified fuel.

Also, this experiment was conducted using kerosene.

Table 3 Water to aqua spark ratio

	①	②	③	④
Kerosene [%]	95	95	95	95
Water [%]	4	4.5	4.75	4.875
Aqua spark+ [%]	1	0.5	0.25	0.125

Fig. 7 The state of the emulsified fuel immediately after stirring

Fig. 8 The state of the emulsified fuel after 1 hour stirring

3.4 Viscosity

The viscosity of Table.3 No. 2 emulsified fuel used in the experiment was measured. Fig.9 shows comparison of pure jet fuel and emulsified fuel.

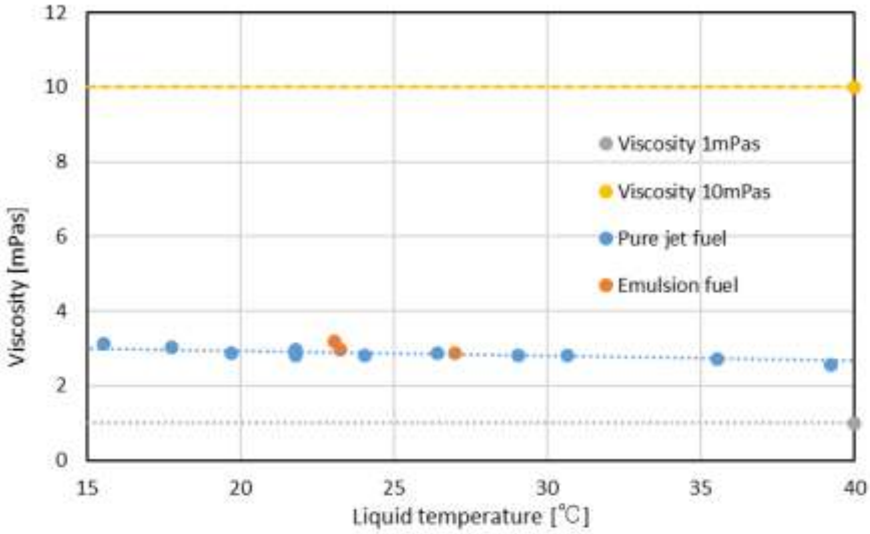

Fig.9 Comparison of pure jet fuel and emulsified fuel

From Fig. 9, it is concluded that there is little difference in viscosity between pure jet fuel and emulsified fuel.

4.Experimental Condition

In this experiment, some emulsified fuels are used in a Merlin 100 turbojet engine to evaluate its performance. The engine RPM range is 80,000 rpm to 152,000 rpm. 100% pure jet fuel and four emulsified fuels with different amount of water are applied in this experiment. The fuels line up is shown in Table.4.

Table.4 Fuel line up

	Base	emulsified fuel			
Jet fuel[%]	100	99	98	97	96
water[%]	0	0.9	1.8	2.7	3.6
emulsifier[%]	0	0.1	0.2	0.3	0.4

5.Results

5.1 Correction factors

Since the performance of the jet engine is affected by the temperature and pressure of the inlet air, the measured engine performance is modified to the reference condition (15℃, 1 atm). The coefficients used for the correction are shown below.

Temperature correction factor : $\theta = \frac{T_{01}}{T_{ref}}$ (1)

Pressure correction factor : $\delta = \frac{P_{01}}{P_{ref}}$ (2)

T_{ref} : Reference temperature $= 288.15$[K]
P_{ref} : Reference pressure $= 101.325 \times 10^3$[Pa]

T_{01} : Intake air temperature[K]
P_{01} : Intake air pressure [Pa]

5.2 Thrust

The corrected thrust is obtained from the following equation, where F is the actual measured thrust. Fig. 10 plots the thrust increase with RPM for each fuel case, and Fig. 11 shows the thrust difference at full power 152,000 rpm relative to the 100% jet fuel as the reference value of 1.

$$\text{Corrected thrust}: F_c = \frac{F}{\delta} \tag{3}$$

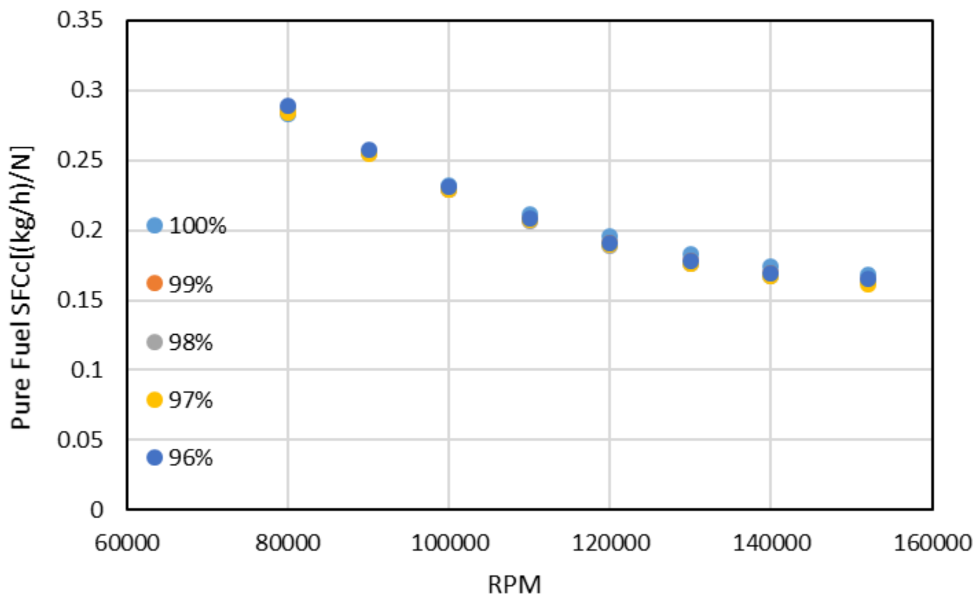

Fig.10 Comparison of corrected thrust F_c

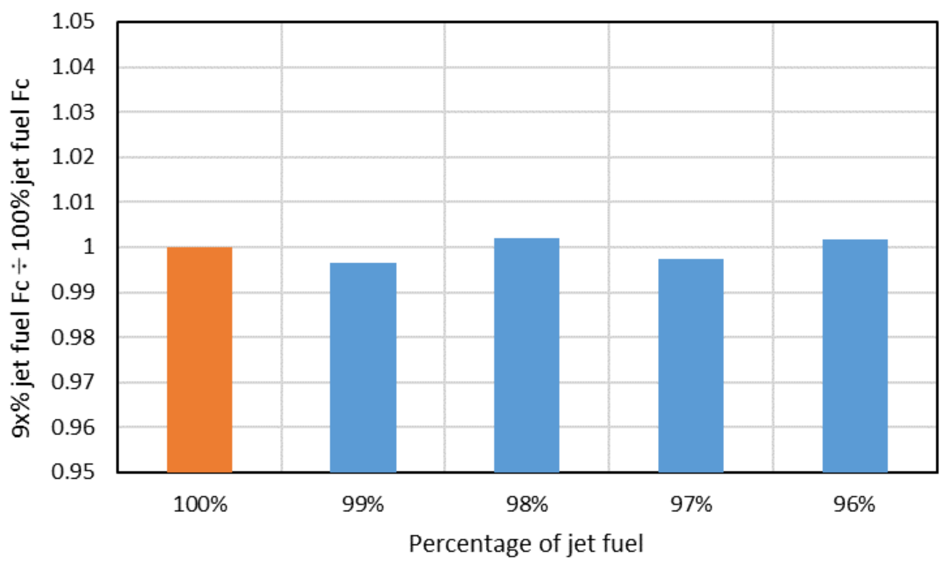

Fig.11 Comparison of corrected thrust F_c relative to 100% jet fuel

The corrected thrust difference is less than 0.3%, which is considered to be a measurement error. Therefore, it is considered that there is little thrust difference between emulsified fuel and 100% jet fuel at full power 152,000rpm.

5.3 Fuel mass flow rate

Fig. 12 is a graph comparing the corrected fuel mass flow rate of the emulsified fuel at each rotation speed, and Fig. 13 shows the difference in the fuel flow rate of the emulsified fuel at the rated rotation rate with the corrected fuel mass flow rate of 100% jet fuel as the reference value 1. The corrected fuel mass flow rate is obtained from the following equation.

Corrected fuel mass flow rate : $m_{fc} = \frac{m_f}{\delta\sqrt{\theta}}$ (4)

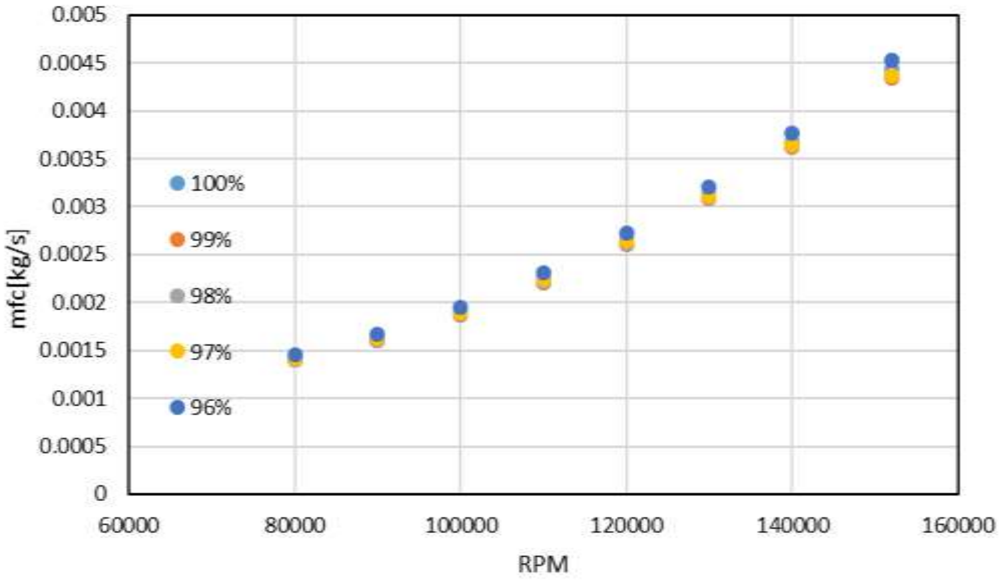

Fig.12 Comparison of corrected fuel mass flow rate

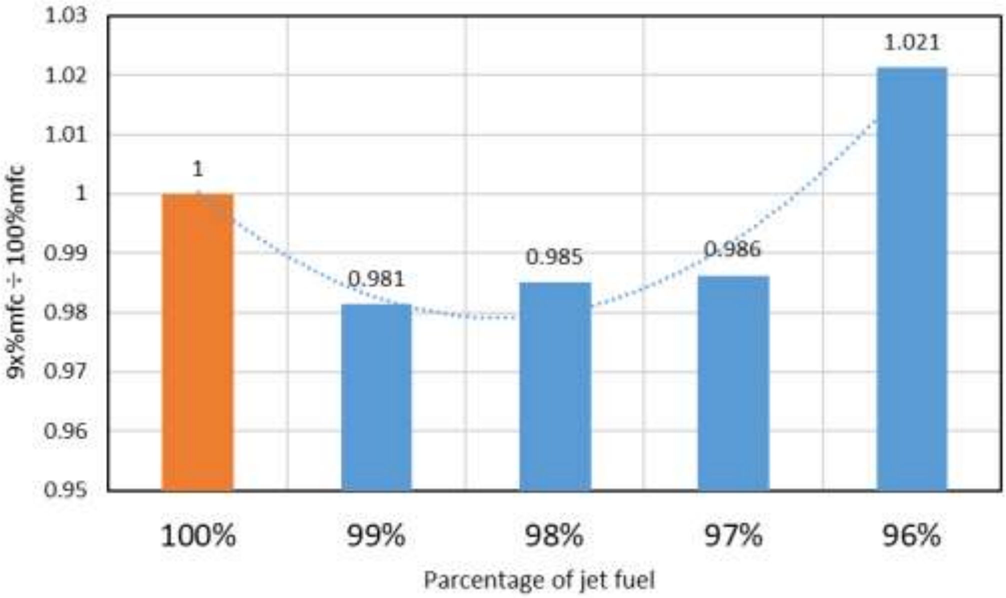

Fig.13 Comparison of corrected fuel mass flow rate relative to 100% jet fuel

In 99% to 97% cases fuel flow are are found to be lower than pure jet fuel by about 1% to 2%. No. 4, which contains 4.875% of water, showed an increase in fuel flow rate.

5.4 Specific Fuel Consumption (SFC)

The corrected specific fuel consumption rate is obtained from the following equation. m_f is fuel mass flow rate. As well as the correction thrust, Fig. 14 plots SFC_c of each fuel, and Fig.15 shows the difference in SFC_c at 152,000 rpm for each fuel relative to the 100% jet fuel as the reference value of 1.

$$\text{Corrected Specific Fuel Consumption : } SFC_c = \frac{SFC}{\sqrt{\theta}} = \frac{m_f/F}{\sqrt{\theta}} \qquad (5)$$

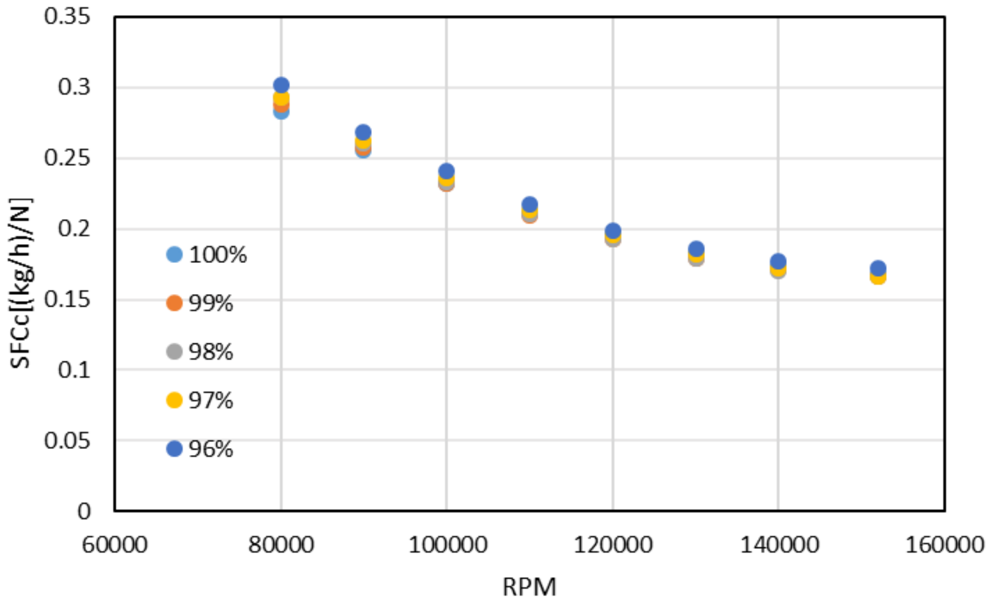

Fig.14 Comparison of SFC_c

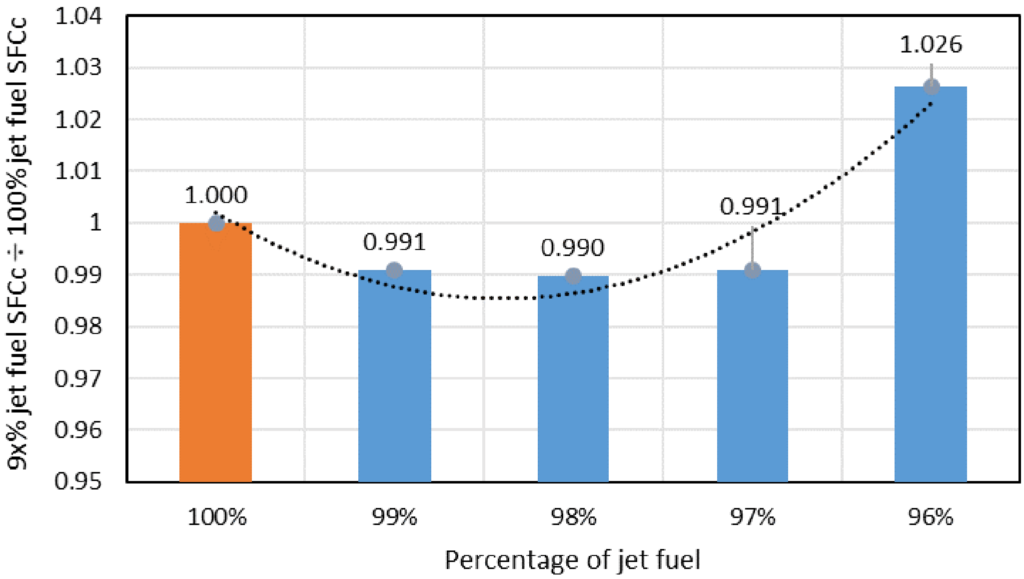

Fig.15 Comparison of SFC_c difference during rated rotation

Fig.16 plots SFC_c of each fuel, and Fig.17 shows the difference in SFC_c at 152,000 rpm for each fuel relative to the 100% jet fuel as the reference value of 1.

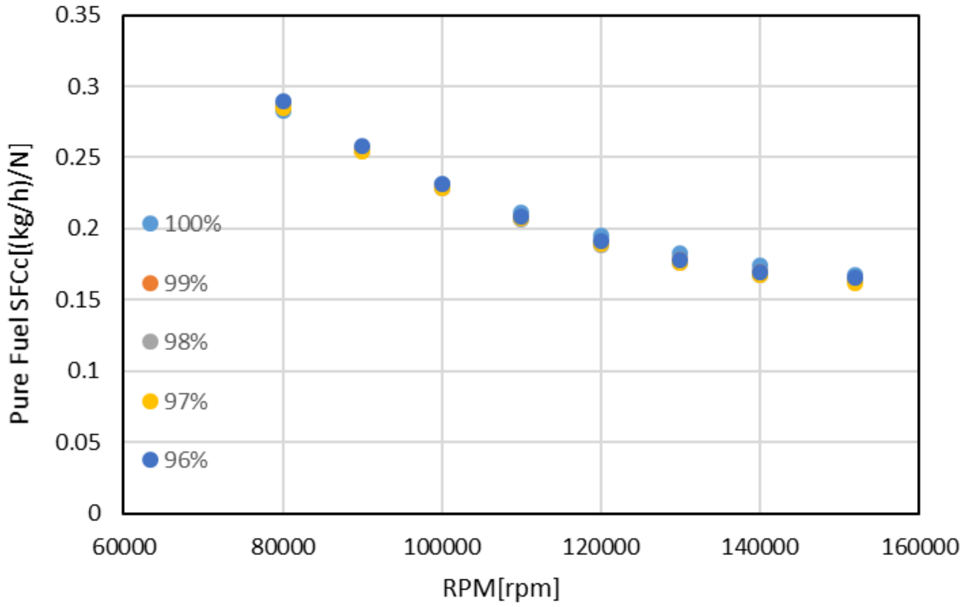

Fig.16 Comparison of pure fuel SFC_c

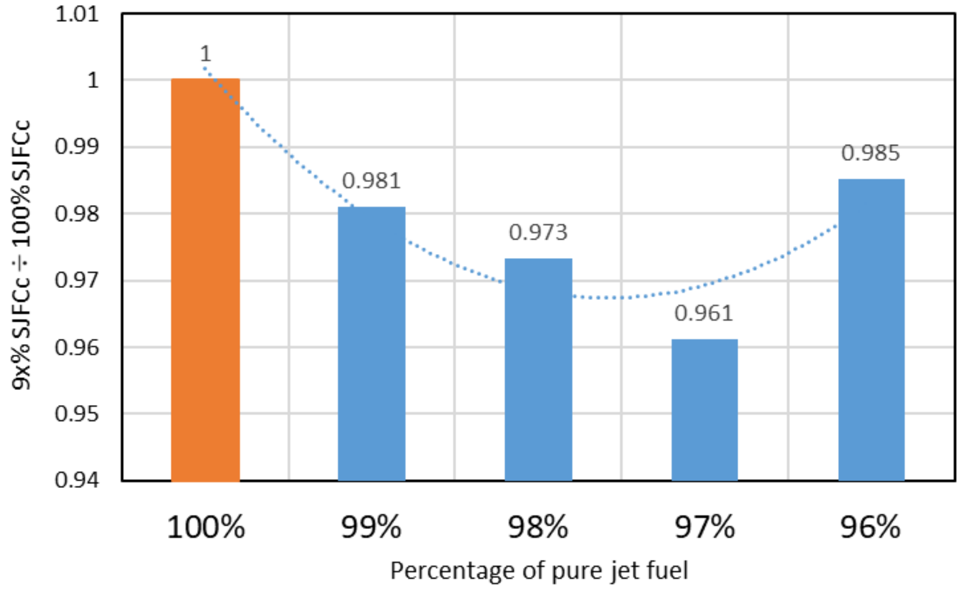

Fig.17 Comparison of pure fuel SFC_c difference during rated rotation

SFC_c decreases or improves by about 1% for 99%~97% emulsified fuel. It can also be seen that it increases or deteriorates by 2.6% in the case of 96% jet fuel. Also, it was found that the consumption rate of jet fuel contained in the fuel improved by 4%. This will lead to a 1% improvement in on-board fuel weight and a 4% improvement in fuel prices and CO2 emissions.

5.5 Combustion Efficiency

The combustion efficiency η_p is roughly estimated based on the following equation. Fig.8 shows the combustion efficiencies for each RPM, based on 100% jet fuel and compared to the respective emulsion fuel. Figure 9 shows the difference in combustion efficiency at 152,000 rpm, based on 100% jet fuel.

$$\text{Combustion efficiency : } \eta_p = \frac{(m_a+m_f)\times c_{pg}\times T3-m_a\times c_{pa}\times T2}{m_f\times Q_R} \tag{6}$$

m_a: Air mass flow rate [kg/s]
m_f: Fuel mass flow rate [kg/s]
C_{pg}: Specific heat of combustion gas at constant pressure [J/(kg·K)]
C_{pa}: specific heat of air at constant pressure [J/(kg·K)]
T2: Compressor outlet temperature [K]
T3: Turbine inlet temperature [K]
Q_R: Amount of heat generated per fuel 1kg [J/kg]

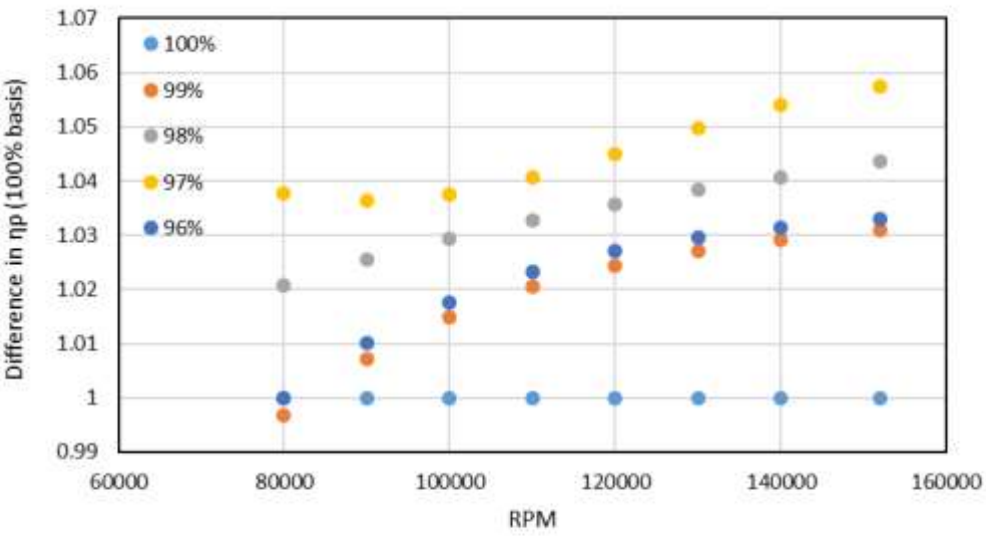

Fig.8 Comparison of η_p, as 100% jet fuel reference of 1

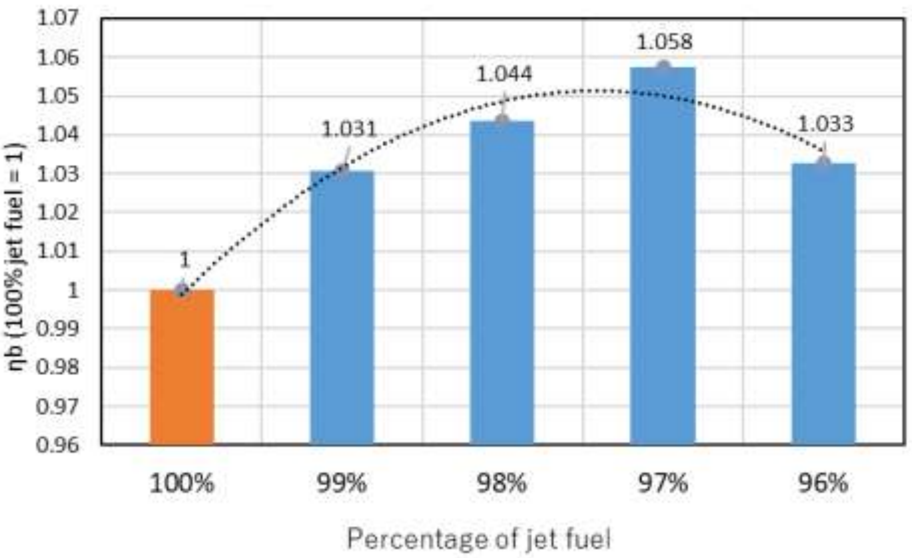

Fig.9 Comparison of η_p at 152,000rpm, as 100% jet fuel reference of 1

The combustion efficiency improves as added water increased, but peaks out beyond 97%. The maximum combustion efficiency is 5.8% obtained at 97% emulsified fuel.

6 Conclusion

The following three things are inferred from the experimental results. First of all, little difference in thrust by emulsified fuel was observed in this experiment. Secondly, the fuel consumption rate decreased by about 1% at 99% to 97% of jet fuel, and 2.6% for jet fuel 96%. This indicates a 1% reduction in fuel capacity in the range of 99% to 97%, and that the effect of emulsified fuel will be peaked out around 97%. Thirdly, combustion efficiency is improved by 5.8% at 97% jet fuel. It is considered to be the effect of the micro explosion.

We are planning more detailed experiment and evaluation including NOx emission in the near future.

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