Experimental Study on Thermal Decomposition of Several Kerosene Fuels

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Abstract

In the present study, experiments on thermal decomposition of several kerosene fuels (Jet A-1, indoor kerosene, YK-D80N) were performed. Three kerosene fuels have different aromatic and sulfur contents. Jet A-1 has largest sulfur content and YK-D80N has almost no sulfur. For thermal decomposition tests, the cooling specimens with inner copper alloy and outer stainless steel were designed and manufactured. Each kerosene fuel was heated above 670 K. For Jet A-1, coking did not occur at 600 K but took place at 670 K. For indoor kerosene and YK-D80N, coking phenomenon was not found at 670 K. Specially, YK-D80N was heated up to 720 K and was stable for one hour test. From the tests, it is confirmed that sulfur content is an important factor affecting coking limit temperature.

1. Introduction

Liquid rocket engine thrust chambers operate at high-temperature and high-pressure conditions, so very high heat transfer takes place inside the combustion chamber. To protect the combustion chamber from such high heat fluxes, cooling technologies such as regenerative cooling, film cooling, dump cooling, thermal barrier coatings (heat resistant ceramic coatings) have been used in combination [1]. The regenerative cooling channel of the combustion chamber is designed to satisfy with thermal/hydraulic side restriction conditions (regenerative cooling pressure drop, copper inner wall temperature) and structure/production side restriction conditions (minimum channel width, maximum channel width, copper alloy minimum rib width, stainless steel minimum rib width, copper alloy minimum wall thickness, stainless steel minimum wall thickness). The regenerative cooling pressure drop is determined in the engine system considering the discharge pressure of the turbopump, the pressure loss in the pipe and valve, the manifold/injector pressure loss, and the combustion chamber pressure. If the regenerative cooling pressure drop increases, that is, the cooling fluid velocity in the cooling channel increases, the cooling effect becomes better and the wall temperature of the copper alloy side becomes lower. However, the discharge pressure of the turbopump must rise at the engine system level [2].

Launchers using liquid oxygen/kerosene as propellants use RP-1, RP-2 (USA) and RG-1, T-1 (Russia) [3]. However, Korea Space launch vehicle-II will use general jet fuel (Jet A-1) instead of kerosene developed specially like US or Russia. According to several documents, Jet A-1 is vulnerable to coking problem around 650 K wall temperature inside the cooling channel. Therefore, the regenerative cooling channel is designed to be lower than 650 K considering the thermal decomposition characteristics of Jet A-1. The designed regenerative cooling combustor is firstly evaluated through an analytical method, and finally it is subjected to a feedback process which is verified and redesigned through water/combustion tests.

The Korea Aerospace Research Institute conducted coking tests of Jet A-1 simulating the regenerative cooling channel. Jet A-1 began to cause a coking phenomenon near 540 K of the surface temperature of the copper alloy, but revealed that the thermal flow rate changes due to the coking phenomenon were around 5% for 500 seconds. It is concluded that the development of regenerative cooling thrust chamber using Jet A-1 and copper alloy is possible based on these results [4]. In recent 15 years, research on the heat transfer characteristics and coking of kerosene fuels has been reported for use in liquid rocket engines and scramjet in China [5-7]. The United States has been studying the properties, heat transfer and coking of kerosene fuels for more than 50 years for use in liquid rocket engines and scramjet. In 2000,

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NASA and Air Force jointly established basic test data on the properties, heat transfer characteristics and combustion efficiency of various hydrocarbon fuels for advanced hydrocarbon fuel development [3, 8-9].

Regenerative cooling technology is essential to ensure the thermal durability of high-performance liquid rocket engine combustors, and kerosene-cooled combustion chambers should be designed so that kerosene pyrolysis does not occur, especially in areas where copper alloys are used. The occurrence of coking is known to be influenced by the kind of hydrocarbon fuel, heating temperature, residence time, cooling fluid velocity, wall material of cooling channel and roughness. In the heating environment simulating actual operating conditions, the impact of key parameters needs to be assessed. For this purpose, a fuel heating test system and simulating cooling specimen were designed and fabricated. Coking tests were conducted using Jet A-1, indoor kerosene, and YK-D80N (desulfurized kerosene) to investigate the effects of aromatic and sulfur contents.

2. Experimental Method and Condition

2.1 Experimental Apparatus

Figure 1 shows the fuel heating test system which consists of rectifier, kerosene supply tank, kerosene drain tank, heat exchanger, channel specimen, flowmeter, temperature/pressure transducers, valves, and DAQ system. The rectifier (220 V, 3 phase) is capable of supplying DC power up to 10 V and maximum current of 5,000 A. The resistance is determined according to the design of the cooling channel specimen. In order to prevent leakage currents and malfunction of data measuring equipment caused by high currents, it is insulated. Most of the parts are made of stainless steel to prevent corrosion of the support table and the table, but the parts that come in contact with the simulating cooling channel and the busbar support are made of Teflon to prevent short circuit. Kerosene past the simulating cooling channel should be lower than the self-ignition temperature of the kerosene through appropriate heat exchange prior to discharge to the drain tank. The heat exchanger was manufactured at the downstream of the channel specimen. A 3/8 inch tube was bended inside the heat exchanger to allow the kerosene to cool through the cooling water.
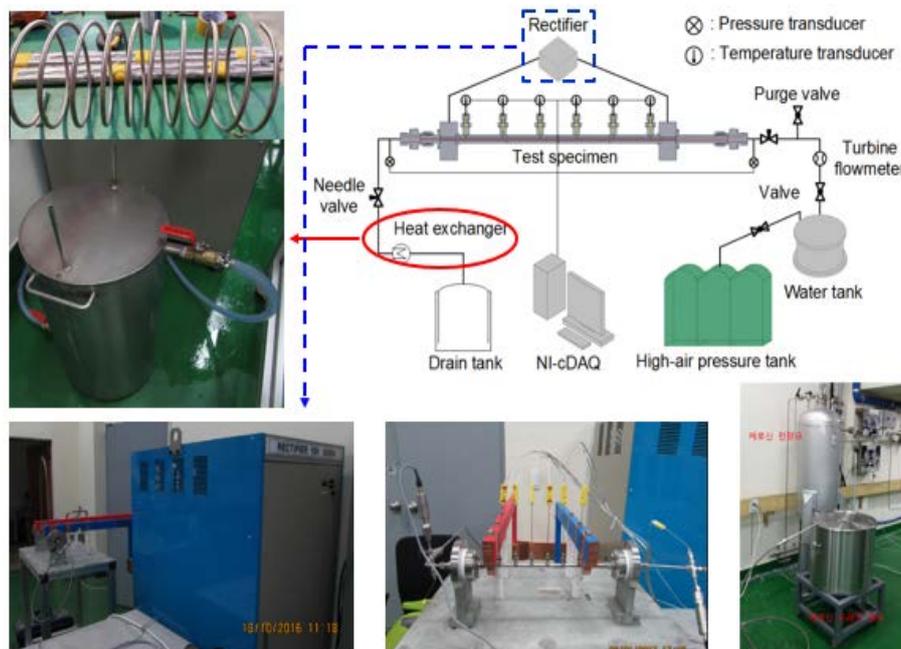

Figure 1: Fuel heating test system

Experiments were carried out with a high-pressure regulator pressurized to a kerosene tank at 80 bar for flow control. The flow rate was measured using a turbine flowmeter (Kometer, NK-250), and a pressure sensor (Sensys, PSH model) capable of measuring up to 100 barg was used before and after the specimen. In addition, K-type thermocouples were installed to measure the inlet temperature of the fluid because the kerosene property changes with temperature. Figure 2 is a photograph during the coking test. A total of six thermocouples were installed in the cooling channel specimen to measure the temperature of the copper outer wall in the longitudinal direction. The measured data was stored using NI-cDAQ at a sampling rate of 100 Hz. To reduce the risk of fire due to kerosene leaks, an acrylic cover was wrapped around the specimen and gaseous nitrogen was supplied into the cover.
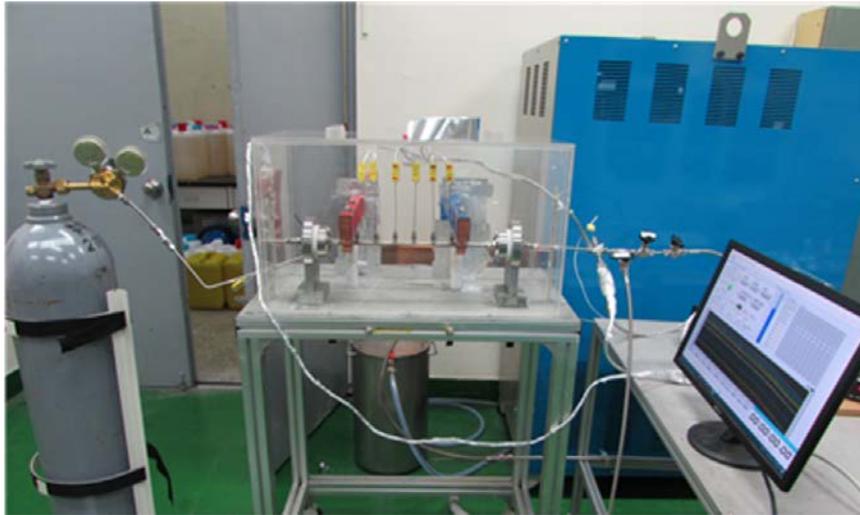
Figure 2: Photograph during the coking test

2.2 Cooling channel specimen

The cooling channel specimen design drawing and the manufactured specimen are presented in Figure 3 and Figure 4, respectively. The cooling channel consists of inner copper and outer stainless steel. Three different designs were applied to the inner copper wall (UNS C10100): ① inner diameter 1.6 mm, thickness 1.2 mm, ② inner diameter 2.0 mm, thickness 1.0 mm, ③ inner diameter 2.4 mm, thickness 0.8 mm. The outer stainless steel jacket (UNS S31603) has the same design: inner diameter 4.0 mm and thickness 3.0 mm. If the inner copper thickness increases too much, the required power can't be sufficiently generated because the resistance is reduced. Therefore, the inner thickness should be as small as possible and the outer jacket is designed to have a sufficient thickness to withstand this pressure, since the pressure in the simulating cooling channel is more than 30 bar. To measure the temperature of the copper outer wall, the outer shell was machined and the port was welded so as to install six temperature sensors in the longitudinal direction. The six temperature sensors were set to T1, T2, T3, T4, T5 and T6 from the direction of the cooling fluid inlet to the outlet.
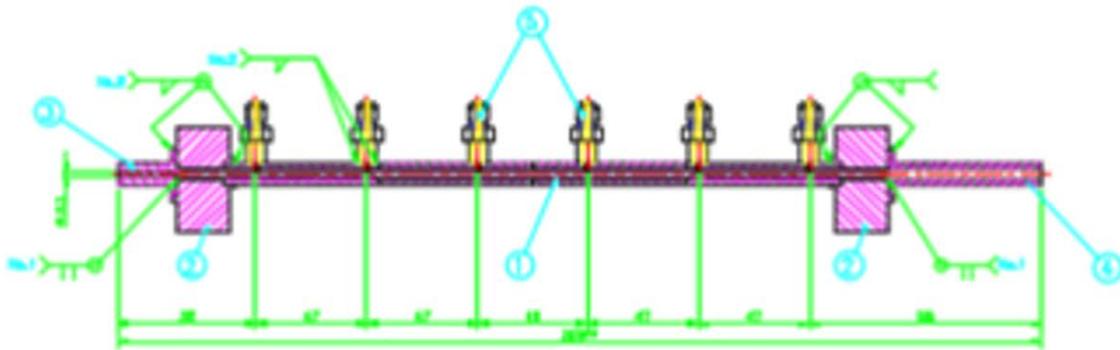

Figure 3: Cooling channel specimen design drawing

Figure 4: Photograph of the manufactured specimen

2.3 Experimental Condition

Using ANSYS CFX program, heat transfer analysis was performed for Jet A-1 according to shape, current, and flow rate. Figure 5 is a graph for predicting the temperature change of the inner copper outer surface in the cooling channel specimen according to the rectifier current. Using the numerical simulation data, the experimental condition is determined and is summarized in Table 1. In test numbers, the number after "PI" indicates the diameter of the inner copper, and the number after "N" indicates the specimen number. To prevent the boiling of kerosene, the kerosene pressure in the cooling channel was maintained to be greater than the critical pressure of kerosene.
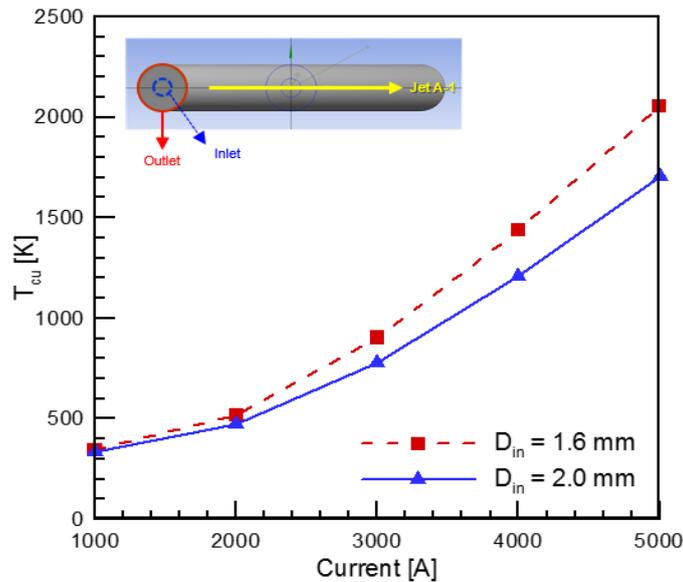

Figure 5: Temperature change of the inner copper outer surface as a function of the rectifier current

Table 1: Experimental condition

Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2				2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4				2440	10~18	700
PI16-N2		Jet A-1		2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4		YK-D80N		2600	10~30	720
PI16-N5		kerosene		2600	10~30	720

As shown in Table 1, experiments on thermal decomposition of several kerosene fuels (Jet A-1, indoor kerosene, YK-D80N) were performed. A total of 7 coking tests were carried out based on the temperature of the inner copper outer surface from 600 K to 720 K. Three kerosene fuels have different aromatic and sulfur contents. The results of the component analysis of kerosene are shown in Table 2. Jet A-1 has largest aromatic/sulfur contents and YK-D80N has almost no aromatic/sulfur contents. Indoor kerosene has similar aromatic content and much low sulfur content compared to Jet A-1.
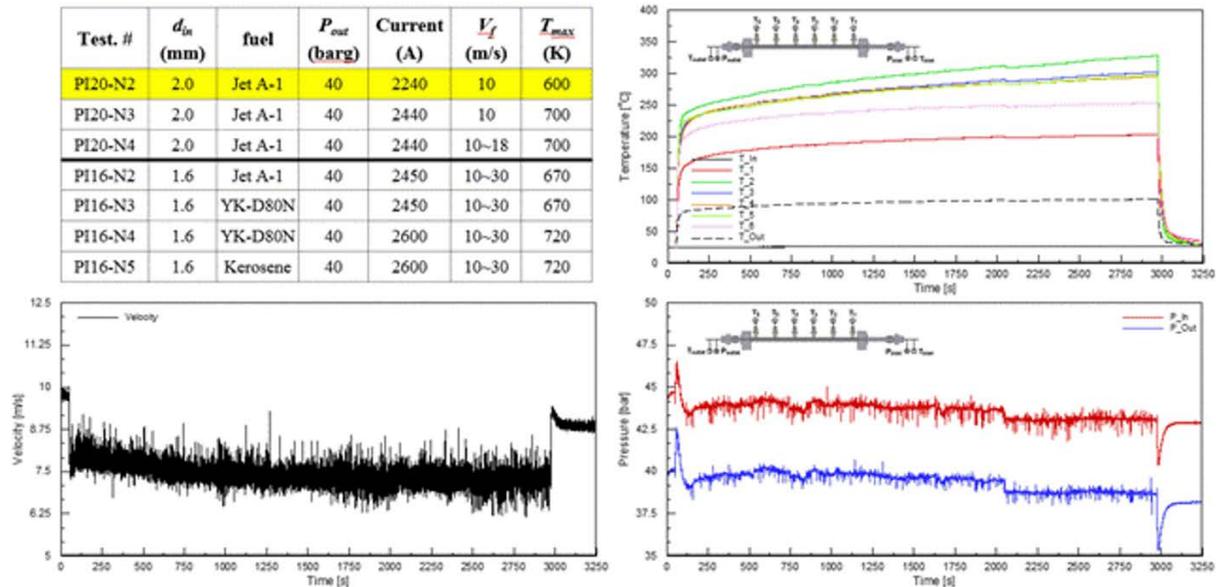
Table 2: Component analysis of present kerosene fuels

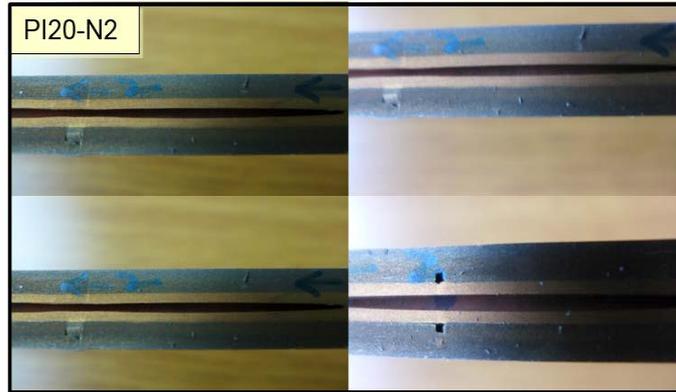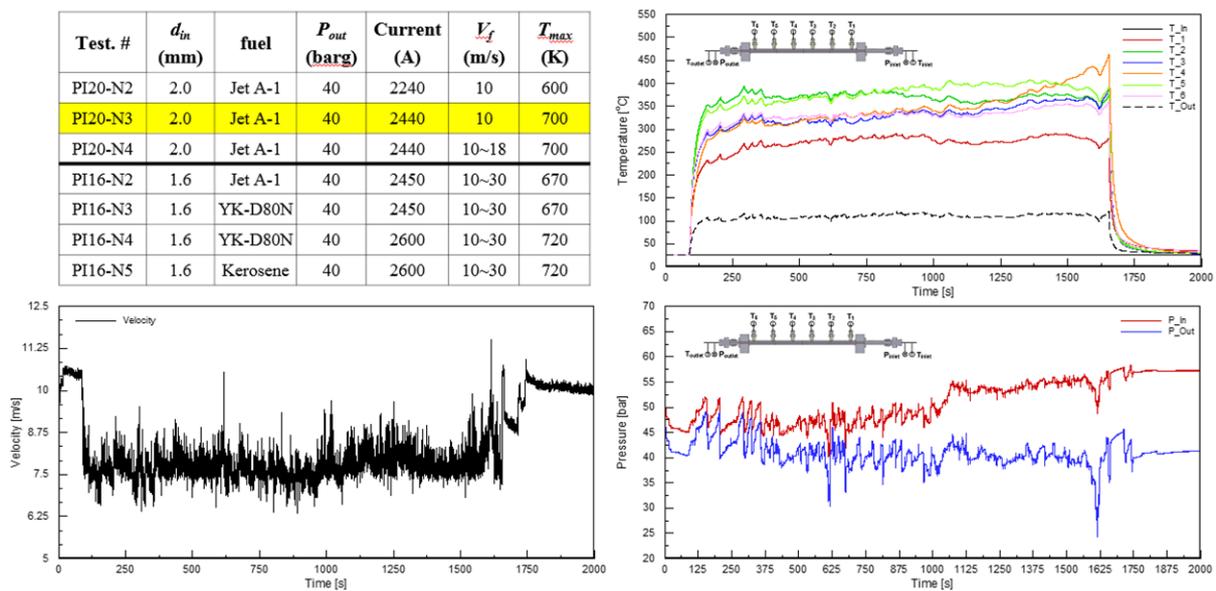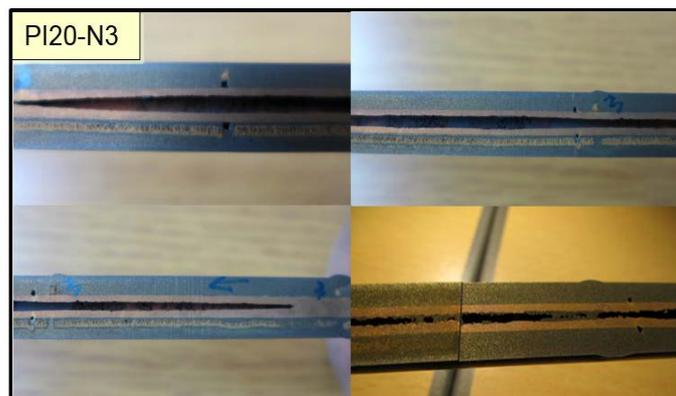|	**Jet A-1**	**Indoor kerosene**	**YK-D80N**
Aromatic (vol %)	20	17.6	0.1
Sulfur (wt %)	0.2		
Sulfur (mg/kg)		9	< 1
Density (kg/m^3 at 15℃)	793	800	825

3. Results

3.1 1st test data

As shown in Table 2, the first kerosene coking test was performed using a PI20 specimen and Jet A-1 fuel. The flow rate in the channel was 10 m/s and the pressure at the downstream of the cooling channel was maintained at 40 bar. The rectifier current was set at 2240 A, so that the copper wall temperature was around 600 K. Figure 6 shows the data of kerosene velocity in the specimen, kerosene pressures at the upstream and downstream of the specimen, and temperatures at the outer surfaces of the inner copper wall. After one test, the specimen was cut into several parts with the wire cutting. Figure 6 is a cut-off photograph of the specimen after the test, showing only a slight tanning of the copper surface, but no precipitate was found. The test was run for 50 minutes and it was concluded that no coking occurred at 600 K for Jet A-1 fuel.

Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2	2.0	Jet A-1	40	2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4	2.0	Jet A-1	40	2440	10~18	700
PI16-N2	1.6	Jet A-1	40	2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4	1.6	YK-D80N	40	2600	10~30	720
PI16-N5	1.6	Kerosene	40	2600	10~30	720

Figure 6: Graphs of the data during 1st coking test

3.2 2nd test data

The second coking test was performed with a PI20 specimen. The fuel was jet A-1, the flow rate in the channel was 10 m/s, and the pressure after the cooling channel was maintained at 40 bar. The rectifier current increased to 2440 A and the copper wall temperature was targeted at 700 K. Figure 8 shows test summary results. During the test, there was a problem that the flow rate decreased due to an increased pressure drop in the specimen. Also, the T4 copper surface temperature was steadily increased so that the test was stopped. Figure 9 is a cut-off photograph of the specimen after the test, showing significant coke material.

Figure 7: Cut-off photograph of the specimen after 1st coking test

Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2	2.0	Jet A-1	40	2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4	2.0	Jet A-1	40	2440	10~18	700
PI16-N2	1.6	Jet A-1	40	2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4	1.6	YK-D80N	40	2600	10~30	720
PI16-N5	1.6	Kerosene	40	2600	10~30	720

Figure 8: Graphs of the data during 2nd coking test

Figure 9: Cut-off photograph of the specimen after 2nd coking test

3.3 3rd and 4th test data

The third test was performed under the same conditions as the second test. The decrease in flow rate with time was not great, but the flow rate was increased by adjusting the needle valve so that the temperature maintained around at 700 K. At 10 m/s of flow velocity, the pressure drop between the specimen increased from 2.3 bar to 5.6 bar after the end

of the test. The coke material was separated from the cut specimen and analyzed for constituents. Generally, the sulfur content in kerosene is less than 0.3%, but as shown in Figure 10, 11.7% of the coke component was analyzed as sulfur. Therefore, it was concluded that the occurrence of coking may be more likely to occur as the sulfur content is higher.

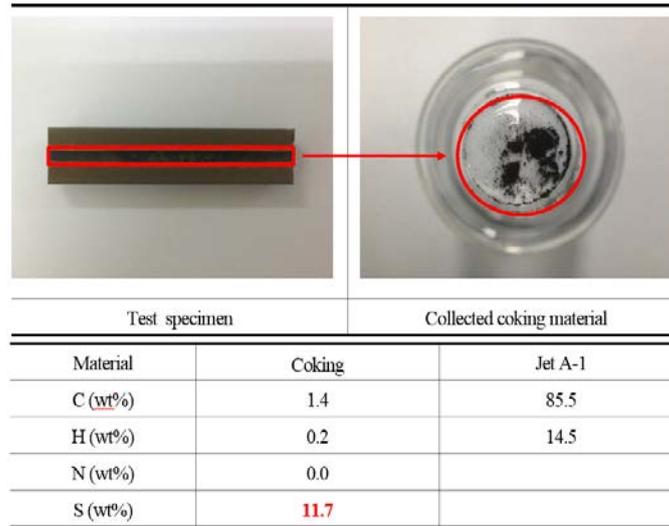| Material	Coking	Jet A-1
C (wt%)	1.4	85.5
H (wt%)	0.2	14.5
N (wt%)	0.0	
S (wt%)	11.7	

Figure 10: Analysis report of coke components after the 3rd coking test

The fourth coking test was performed with a PI16 specimen. The fuel was jet A-1 and the copper wall temperature was targeted at 670 K. Figure 11 shows test summary results. The temperature of the T5 sensor rose steadily, and the flow rate was continuously increased from 10 m/s to reach the target temperature of 670 K, and the flow rate before the completion was 30 m/s. The temperature of the sensors other than the T5 sensor showed a tendency to decrease compared with the initial value due to the increase of the flow rate. It was judged that local temperature rise occurred due to the occurrence of coking around the T5 sensor, resulting in lowered heat transfer.
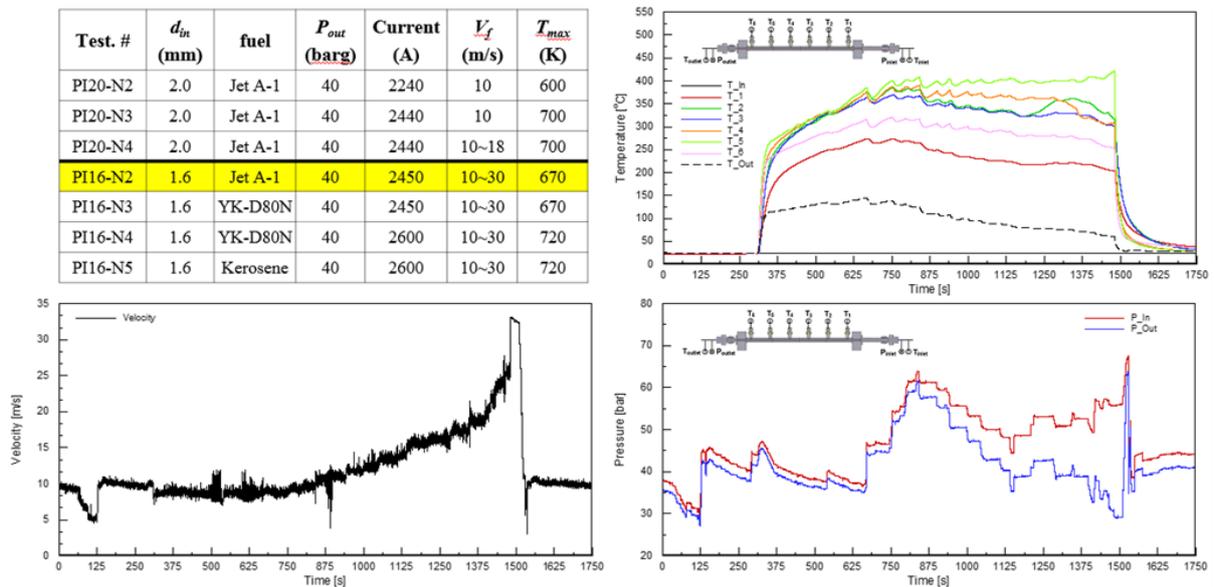
Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2	2.0	Jet A-1	40	2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4	2.0	Jet A-1	40	2440	10~18	700
PI16-N2	1.6	Jet A-1	40	2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4	1.6	YK-D80N	40	2600	10~30	720
PI16-N5	1.6	Kerosene	40	2600	10~30	720

Figure 11: Graphs of the data during 4th coking test

3.4 5th and 6th test data

The fifth and sixth coking tests were performed using PI16 specimens and YK-D80N kerosene. The flow rate in the channel was 10 m/s, the rectifier current was set to 2450 A, and the maximum copper wall temperature was at 670 K. Unlike the fourth coking test, no rapid change in temperature was observed during 47 minutes heating time. It is

confirmed that the change in the pressure loss was very small as compared with the Jet A-1 fuel. When the inside of the specimen was visually confirmed after the test, it was very clean and no coke material was observed.

For the sixth coking test, the flow rate in the channel was 10 m/s, the rectifier current was set at 2600 A, and the copper wall temperature was aimed at 720 K. The test lasted for 60 minutes without stopping. Figure 12 shows the sixth test summary results and Figure 13 is a cut-off photograph of the specimen after the sixth test. Compared with the results of the Jet A-1 coking test, the YK-D80N fuel showed no coking even at 720 K, suggesting that the sulfur content may cause a significant increase in coking. However, the YK-D80N fuel has a lower sulfur content, but the fuel itself has different characteristics compared to Jet A-1, so more research is needed to determine whether sulfur content alone is the root cause.
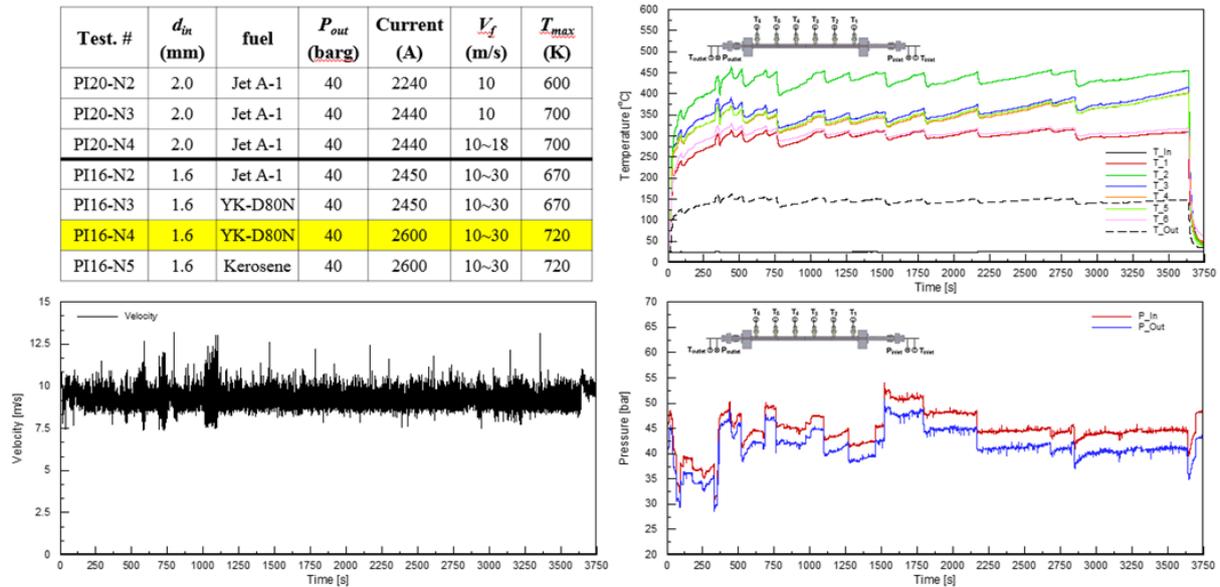
Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2	2.0	Jet A-1	40	2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4	2.0	Jet A-1	40	2440	10~18	700
PI16-N2	1.6	Jet A-1	40	2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4	1.6	YK-D80N	40	2600	10~30	720
PI16-N5	1.6	Kerosene	40	2600	10~30	720

Figure 12: Graphs of the data during 6th coking test

Figure 13: Cut-off photograph of the specimen after 6th coking test

3.5 7th test data

The seventh coking test was performed with a PI16 specimen and indoor kerosene. Indoor kerosene has 9 times more sulfur than YK-D80N kerosene, but less than 1/300 of that of Jet A-1. As with the 5th coking test, the test conditions were as follows: the flow rate in the channel was 10 m/s, the rectifier current was 2450 A, and the copper wall temperature was 670 K. Figure 14 shows test summary results and Figure 15 is a cut-off photograph of the specimen after the test, showing no coke material. Unlike the fourth coking test, no rapid change in temperature was observed for 60 minutes of heating time, and the temperature of the T2 sensor at the maximum temperature of 720 K was continuously maintained. Compared with the results of coking tests of Jet A-1, indoor kerosene fuel did not cause

coking even at 670 K. Since the aromatic contents of jet A-1 and indoor kerosene are similar, it can be inferred that the content of sulfur component causes a large amount of coking.
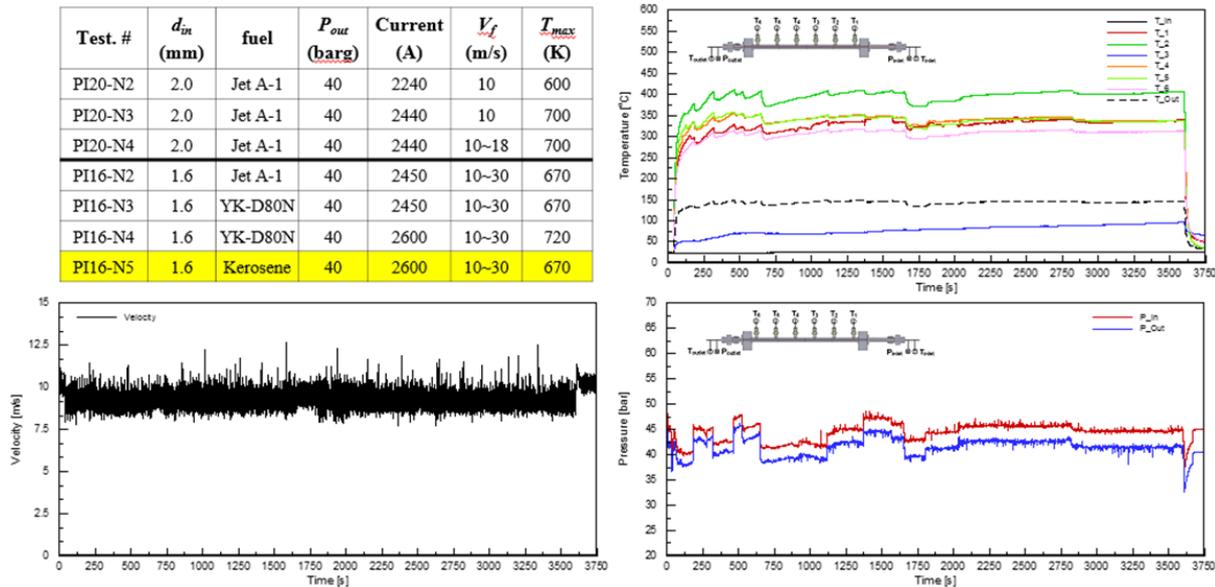
Test. #	d_{in} (mm)	fuel	P_{out} (barg)	Current (A)	V_f (m/s)	T_{max} (K)
PI20-N2	2.0	Jet A-1	40	2240	10	600
PI20-N3	2.0	Jet A-1	40	2440	10	700
PI20-N4	2.0	Jet A-1	40	2440	10~18	700
PI16-N2	1.6	Jet A-1	40	2450	10~30	670
PI16-N3	1.6	YK-D80N	40	2450	10~30	670
PI16-N4	1.6	YK-D80N	40	2600	10~30	720
PI16-N5	1.6	Kerosene	40	2600	10~30	670

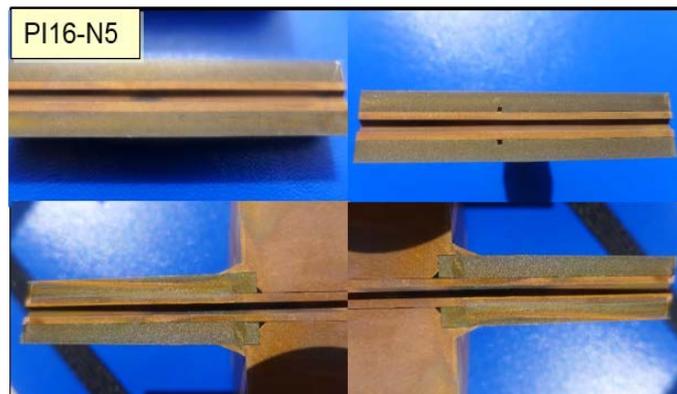Figure 14: Graphs of the data during 7th coking test

Figure 15: Cut-off photograph of the specimen after 7th coking test

4. Conclusion

An experimental work was carried out to study the coking characteristics of three kinds of kerosene fuels. Jet A-1, indoor kerosene, and YK-D80N (desulfurized kerosene) with different aromatic and sulfur contents were used to investigate their effects on thermal decomposition. Total seven coking tests (four for Jet A-1, two for YK-D80N kerosene, and one test for indoor kerosene) were performed from 600 K to 720 K based on the inner copper surface wall. The simulating cooling channel consists of the inner copper wall and the outer stainless steel jacket.

For Jet A-1, coking phenomenon did not occur at 600 K, but occurred above 670 K. For indoor kerosene, coking was not found at 670 K. For YK-D80N kerosene, the specimen was heated up to 720 K and was stable for one-hour test. When coking was encountered for Jet A-1, 11.7% of the coke material was sulfur. From the results, it is confirmed that sulfur content is the most important factor affecting coking limit temperature.

The present results are the result of preliminary experiments. In the future, a quantitative database will be built according to the flow rate in the channel, the channel diameter, and the same test iteration.

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