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Investigation of heat sink of endothermic hydrocarbon fuels*

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Abstract: Endothermic hydrocarbon fuels are advanced coolants for high-temperature structures of spacecraft. No data of tested-cooling-ability of endothermic fuels have been broadly discussed in literature. In this work a high-temperature flow calorimeter was designed, and the cooling capacity of six different hydrocarbon fuels were measured. Experimental results showed that these hydrocarbon fuels have capacity for cooling high-temperature structures, and that the cooling capacity of fuel N-1 can reach 3.15 MJ/kg, which can nearly satisfy the requirement of thermal management for a Mach 3 cruise aircraft, whose heat sink requirement is about 3.5 MJ/kg. The endothermic velocity of hydrocarbon fuels was also measured by the calorimeter.

Key words: Endothermic hydrocarbon fuels, Heat sink, Thermal management, Cooling capacity
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INTRODUCTION

Technology advances and requirements for increased aircraft performance are causing increase in aircraft subsystem and engine heat loads, which require the fuel to accomplish a variety of non-combustion related tasks. For example, the fuel is the primary coolant for aircraft hydraulic and environmental control subsystems and is also the primary coolant for the aircraft engine. And therefore, the endothermic hydrocarbon fuel is put forward (Edwards *et al.*, 1992; Petley *et al.*, 1990).

Endothermic hydrocarbon fuel decomposes at high temperature and generates light gases. This heat absorption process can be used as coolant on board of a hypersonic aircraft (Jackson *et al.*, 1995; Korabelnikov and Kuranov, 1999; Edwards, 1993). The heat absorption can be used for direct cooling of combustion chambers, nozzles, and front wing edges. The gaseous products of the decomposed fuels can be used as working medium for the drive of the engine. The efficiency of the engine can be improved by taking advantage of the increased cooling capacity which results in a higher heat of combustion and higher specific gas constant.

Thermal decomposition of hydrocarbon fuels is a complex process, comprising a great number of parallel and following chemical reactions with formation of a great number of smaller molecular mass products, which makes it very difficult to predict theoretically the heat sink of hydrocarbon fuels.

In the present work, a high-temperature flow calorimeter was designed and constructed for hydrocarbon fuels cooling capacity measurement (Fang *et al.*, 1998; Jiang *et al.*, 2002; Li *et al.*, 1998). *iso*-octane and six different hydrocarbon fuels were tested on the apparatus. Results showed that these hydrocarbon fuels can provide higher cooling capacity than *iso*-octane, and that some of them can even provide cooling capacity of about 3.15 MJ/kg almost satisfying the requirement of thermal management for a Mach 3 cruise aircraft, whose fuel must provide heat sink of around 3.5 MJ/kg.

MATERIALS AND METHODS

Hydrocarbon fuel samples

Six different fuels were chosen as testing sam-

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ples with characteristics shown in Table 1.

Equipments

Experimental investigations of the fuel chemical decomposition processes were carried out in laboratory installations. A schematic of the flow apparatus is shown in Fig.1. The apparatus consists of a single-pass fuel flow system that heats the fuel in a quartz tube.

After the reaction pipe is purged by N_2, the testing fuel is pumped into the preheater. And then the fuel enters into the calorimetric reactor, where the fuel cracks and absorbs considerable amount of heat, with formation of hydrogen and light hydrocarbon gases, when it comes out from the reactor. The smaller molecular products are analyzed by gas chromatograph.

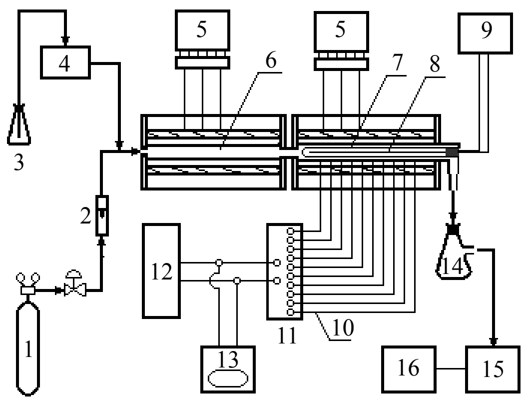

Fig.1 High-temperature calorimeter of heat conduction
1: Carrier; 2: Gas flow meter; 3: Fuel sample; 4.Micro-pump; 5: Temperature-controlling system; 6: Preheater-reactor; 7: Reactor; 8: Electric heater; 9: Direct current electrical source; 10: Thermocouple; 11: On-off switch; 12: Recorder; 13: Multifunction digital meter; 14: Buffer; 15: Gas chromatograph; 16: Digital processing system

RESULTS AND DISCUSSION

Determination of the heat sink for *iso*-octane

The *iso*-octane was introduced at a flow rate of 1 ml/min. The testing section and the preheater is maintained at 700 °C and 300 °C respectively. The heat absorption causes a signal change on the thermal-voltage value, which is a parameter in the function of the heat sink. The change of the signal is detected by thermocouples and is shown by a digital voltage meter. The smaller molecular products from cracking of the fuel are analyzed by gas chromatography, and are listed in Table 2.

Table 2 The thermal decomposition products of *iso*-octane at 700 °C

Components	v_2	$\Delta_f H_{700}$ (kJ/mol)	$v_i \Delta_f H_{700}$ (kJ/mol)
Methane	0.1791	−89.5774	−16.0433
Ethane	0.0283	−105.6704	−2.9905
Ethylene	0.0484	38.4769	1.8623
Propane	0.0018	−129.1620	−0.2325
Propylene	0.1833	0.1254	0.0229
2-methylpropane	0.0013	−187.9746	−0.2444
Butane	0.0001	−155.7468	−0.0156
trans-2-butene	0.0021	−36.4916	−0.0766
2-methylpropene	0.0139	−41.0476	−0.5706
cis-2-butene	0.4677	−35.3210	−16.5196
Cyclopentane	0.0008	−112.4838	−0.0899
Pentane	0.0002	−180.6178	−0.0361
Cyclopentene	0.0045	2.5916	0.0117
2-methylpentane	0.0039	−210.2540	−0.8199
Hexane	0.0032	−205.9486	−0.6590
Heptane	0.0289	−230.3180	−6.6562
iso-octane	0.5888	−260.8320	−153.5779
Hydrogen	0.1451	0	0

Nitrogen flow: V=0.1 m^3/h

Table 1 The characteristics of the six fuel samples

Samples	Density ρ_{20} (g/cm^3)	Viscosity υ_{20} (mm^2/s)	Boiling point T_b (°C)	Flash point T_f (°C)	Hydrogen content (%)
N-1	0.8108	2.122	222.82	47.0	13.77
N-2	0.7603	1.071	162.50	33.0	14.51
N-3	0.7820	1.411	187.49	47.5	14.62
N-4	0.7959	1.871	212.53	64.0	15.00
N-5	0.8148	2.780	237.48	90.5	14.69
N-6	0.8268	3.903	262.50	108.0	14.50

From these analysis results, the effect of the endothermic reaction can be estimated, and the complex thermal decomposition process may be predicted which is very useful for studying the thermal decomposition process of hydrocarbon fuels. What is more, these results can also be used for calculating the theoretical heat sink for *iso*-octane. The calculated heat sink value of *iso*-octane at 700 °C is 1.89 MJ/kg, which is about equal to the experimental value 1.84 MJ/kg. This result indicated that the equipment is reliable.

Determination of heat sink for hydrocarbon fuels

The fuels were processed by distillation and refined on base of the base oil, and additives such as antioxidants, coke-inhibitor was added to reduce the coke formation in the process of decomposition of the fuels and to increase the thermal stability of the fuel. Pure N_2 was used to carry the fuels through the calorimetric section at different rates.

Table 3 lists the heat sinks of the six different fuels changing with flow rates. Five flow rates for each fuel sample were tested: 0.8 ml/min, 1.0 ml/min, 1.2 ml/min, 1.5 ml/min, and 2.0 ml/min. The preheating-section and the calorimetric reactor were kept at 300 °C and 700 °C respectively.

Table 3 Measured results of endothermic hydrocarbon fuels heat sink

No.	Fuel flow (ml/min)	Heat sink (MJ/kg)					
		N-1	N-2	N-3	N-4	N-5	N-6
1	0.8	3.05	3.10	2.75	2.80	3.12	2.65
2	1.0	3.15	2.83	2.68	2.86	3.01	2.70
3	1.2	2.99	2.73	2.65	2.97	3.09	2.79
4	1.5	3.09	2.74	2.72	3.06	3.00	2.68
5	2.0	3.02	3.09	2.74	2.89	2.87	2.72

Nitrogen flow: V=0.1 m^3/h

Compared with *iso*-octane, the six hydrocarbon fuels have higher cooling capacity. At different flow rates, the average heat sink for fuel sample N-1 was the highest one, and could reach to about 3.15 MJ/kg, almost meeting the demand of the thermal management for a Mach 3 cruise aircraft.

In the high Mach number region of the flight, the ramjet becomes more efficient and provides increasing thrust. At the same time, aerodynamic heating becomes an increasing problem for the aircraft. The added heat has to be removed from such high-temperature structures as the plane's engine for conventional structural materials to survive. The endothermic hydrocarbon fuel must not only provide necessary heat sink for the cooling system, but must also have perfect endothermic velocities. Fig.2 is a plot of six hydrocarbon fuels endothermic velocities, versus the flow rate.

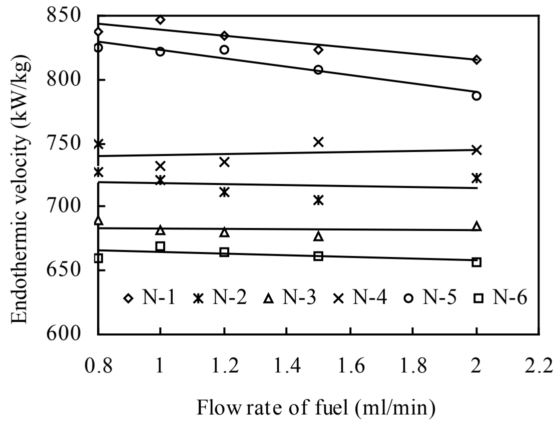

Fig.2 The endothermic velocities of endothermic hydrocarbon fuels

Fig.2 shows that the endothermic velocity of fuel N-1 is the highest one. Endothermic velocity is one of the most important characteristics of endothermic hydrocarbon fuels and is directly related to the ability of an aircraft's high-temperature parts to be cooled down in time. Higher endothermic velocity is favorable for thermal management of aircraft.

Thermal signals axial length distribution in the calorimetric reactor

N_2 was used to carry hydrocarbon fuel N-1 as test sample through the test section at flow rate of 1.0 ml/min. The calorimetric reactor was heated and maintained at 700 °C. After entering the reactor, the fuel removed much heat from it. At the same time, the fuel temperature increased rapidly with the thermal exchanging process until temperature high enough for the hydrocarbon fuel's thermal decomposition, which is a very complex process. Along the reactor axial distance, the heat exchange between fuel and reactor was different at different test position, which was reflected in the changes of thermocouple signals.

Fig.3 is a plot of thermal signals, versus the axial length of the test section.

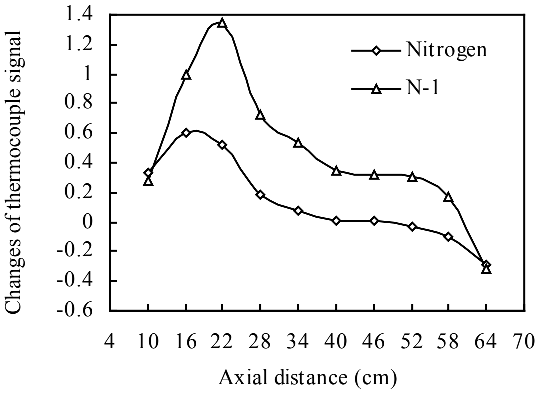

Fig.3 The axial length distribution of thermocouple signal in the reactor

At the entrance, the fuel's physical cooling capacity removed heat. The fuel flow inside the reactor causes fuel temperature to become high enough for thermal decomposition to occur. Fig.3 shows that the fuel had the highest chemical heat capacity; it was 22 cm from the entrance. With absorbing considerable amounts of heat, thermal decomposition produced a great number of small molecular mass products which can polymerize at high temperature and release heat (Ianovski *et al.*, 1996; Pan *et al.*, 2001). That is the reason why the thermocouple signals at the second half reactor reduced.

CONCLUSION

The high-temperature calorimeter in the present work is reliable for determination of the heat sink for hydrocarbon fuel. Six different fuel samples and *iso*-octane were tested on the apparatus. Results showed that fuel N-1 has highest cooling capacity and that the samples' endothermic rate almost met the requirement of thermal management for a Mach 3 cruise aircraft.

References

Edwards, T., 1993. USAF supercritical hydrocarbon fuels interests. *AIAA 93*, **0807**:1-9.

Edwards, T., Anderson, S.D., Pearce, J.A., Harrison, W.E., 1992. High temperature thermally stable JP fuels–An overview. *AIAA 92*, **0683**:1-11.

Fang, W.J., Yu, Q.S., Zong, H.X., Lin, R.S., 1998. Calorimetric determination of the vapor heat capacity of petroleum cuts. *Fuel*, **77**(8):895-899.

Ianovski, L., Sapgir, G., Baikov, A., 1996. Heat and mass transfer to hydrocarbon on fuels at thermal decomposition in channels of engines. *AIAA 96*, **2683**:1-11.

Jackson, K., Corporan, E., Buckley, P., Leingang, J., 1995. Test results of an endothermic fuel reactor. *AIAA 95*, **6028**:1-9.

Jiang, W., Guo, Y.S., Lei, Q.F., Lin, R.S., 2002. Study on heat sink of endothermic fuels. *Journal of Fuel Chemistry and Technology*, **30**(1):27-31.

Korabelnikov, A.V., Kuranov, A.L., 1999. Thermochemical conversion of hydrocarbon fuel for the AJAX concept. *AIAA 99*, **3537**:1-6.

Li, Z.G., Gao, H., Li, G., Lin, R.S., 1998. Determination of heat sink of endothermic hydrocarbon fuel. *Journal of Propulsion Technology*, **19**(2):96-99.

Pan, F.M., He, L., Lin, R.S., 2001. Studying on endothermic fuel's coke (II) evaluation on coking-inhibitors' functions. *Journal of Propulsion Technology*, **22**(3):241-244.

Petley, D.H., Virgina, H., Jones, S.C., 1990. Thermal management for a Mach 5 cruise aircraft using endothermic fuel. *AIAA 90*, **3284**:1-13.

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