A Coupled Heat Transfer Analysis with Effects of Thermal/Catalytic Cracking of Kerosene for Regenerative Cooled Supersonic Combustor

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Summary The objective of this work is to develop a one-dimensional heat transfer model that couples the supersonic combustor flow, the coolant flow and the solid wall for a regenerative cooling system of scramjet. The combustor flow was calculated by directly solving the flow equations with fuel/air mixing and combustion models. The flow and heat transfer properties of the coolant (hydrocarbon fuels) were solved with flow equations and at the same time, were coupled by calculating the heat conduction equation through the cooling wall. The uniqueness of the present model is that thermal/catalytic cracking of aviation kerosene at relatively high temperatures was included and the cracking effect on the cooling was discussed.

Introduction

For hypersonic fight applications, regenerative cooling using on-board fuels as the coolant is considered to be one of the most effective ways for thermal protection of vehicle and engines[1]. In a regenerative cooling system, before injected into combustor, the fuel flows through the cooling channels in the engine wall and takes away heat from wall via heat convection and endothermic pyrolysis. Regenerative cooling is a complicated gas/solid/fluid heat coupled system including the internal flow of combustor, the engine wall and the coolant flow. At temperatures exceeding certain values, hydrocarbon fuel would undergo decomposition process and for aviation kerosene, the cracking may be endothermic and extra heat sink capacity is obtained for the cooling [2]. To the authors' knowledge, the effect of cracking on the cooling has not been reported yet. Hence, the cracking effect is of the most interest of the present study.

The Coupled heat transfer analysis

A heat transfer analysis is developed to couple convective heat transfer of the combustor flow, heat conduction through the wall and heat convection and endothermic reaction of the coolant. Properties of the combustor internal flow such as static pressure and temperature, Mach number et.al, were obtained by solving a series of differential equations of the flow in terms of the conservation of mass, momentum and energy. The fuel/air mixing is modeled by the empirical relations proposed by Pulsonetti et.al [3]. A global reaction of $C_{11}H_{22} + 17(O_2+H_2O+3N_2) \rightarrow 11CO_2 + 29H_2O + 51N_2$ was used to simulate the combustion and the reaction rate is mixing-controlled due to the fact that ignition of the fuel is generally initiated with pilot hydrogen or other facilities. In addition, the shock/boundary-layer interaction was considered in the present analysis with a shock train model [4]. The wall heat flux and wall temperature of the combustor inner surface (so called "hot-wall") were determined with the heat transfer coupling and reference enthalpy method originally proposed by E. Eckert [5]. The fuel absorbs heat via heat convection and endothermic reaction and its thermophysical properties vary as the temperature increases. Details of heat transfer properties for aviation kerosene can be found in our previous study [6]. The flow parameters of the coolant are obtained by solving one-dimensional equations of mass, momentum and energy. The cracking effect was included in the analysis with a global reaction being used. According to the conservation of energy for a steady state, the total heat into the cooling wall should be equal to the total heat absorbed by the coolant, thus a heat coupling of the combustor flow and the coolant flow is developed.

Thermal/catalytic cracking model

It is necessary to consider the cracking effect on the flow and heat transfer since kerosene decomposes into small hydrocarbons at high temperatures and its thermophysical and heat transfer properties would change significantly. At a pressure rang of 3－5MPa, the starting temperature of China No.3 aviation kerosene is approximately 800K [2] for thermal cracking and approximately 750K for catalytic cracking with zeolite catalyst being coated on the channel walls [7]. The cracking process can be described with a global reaction [8]: *Kerosene* $\rightarrow$ v_g *gases* + v_r *residual* and the coefficients of the reaction as well as the reaction rate are determined by a theoretical analysis with experimental results [8]. Figure 1 plots the change of reaction rate *k* with temperatures for both thermal and catalytic cracking. It is obvious that the usage of catalyst decreases both the activation energy *Ea* and the starting temperature of the cracking. Figure 2 shows chemical heat sink of the cracking as a function of fuel conversion on mass basis. It is found that chemical heat sink of catalytic cracking is larger than that of thermal cracking, especially at large percentages of fuel conversion.

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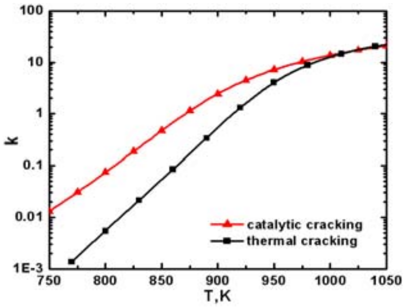

Fig.1 Reaction rates as function of temperature for thermal and catalytic cracking

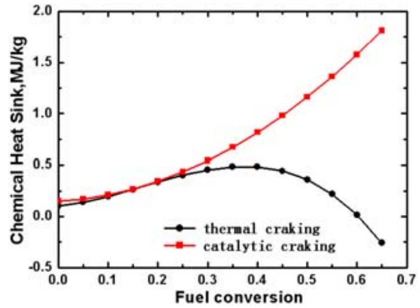

Fig.2 Chemical heat sink as function of fuel conversion for thermal and catalytic cracking

Results

The supersonic combustor consists of an isolator with a length of 50mm, two sections for combustion with lengths of 620mm and 400mm respectively, and a divergent nozzle. The fuel was injected at two downstream locations at a total fuel/air equivalence ratio of 1.16. The inlet total temperature of the combustor is 1600K, the mass flow rate is 1.74kg/s and the inlet Mach number is 2.5. The amount of fuel used as coolant is equal to that for combustion utility and the inlet pressure and temperature of the coolant are 5MPa and 373K.

Figure 3 compares the results of static pressure along the combustor predicted by the present model and measured in experiment. A good agreement between the model prediction and the experimental data is found. Figure 4 gives the distribution of hot-wall temperature and fuel temperature of the regenerative cooled combustor with/without cracking effects. As shown in the figure, the hot-wall temperature for the three cases is found to be different in the downstream part of the combustor. It can be explained by the fact that cracking occurs only at high temperatures. The catalytic cracking has the best cooling effect since the hot-wall temperature and the fuel temperature are lowest among the three cases. Figure 5 plots the wall heat along the combustor. The case with catalytic cracking gives the highest heat flux in the downstream part of the combustor since catalytic cracking provides the maximum heat sink.

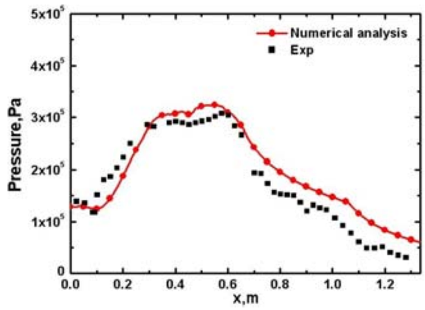

Fig.3 Comparison of the static pressure of the numerical analysis and experiments

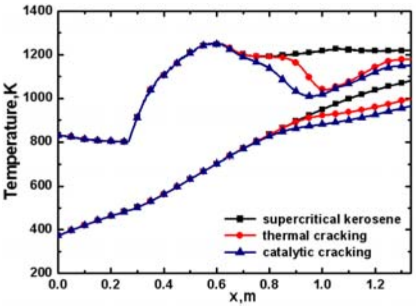

Fig.4 Distribution of the hot-wall temperature and fuel temperature with thermal or catalytic cracking and without cracking effect

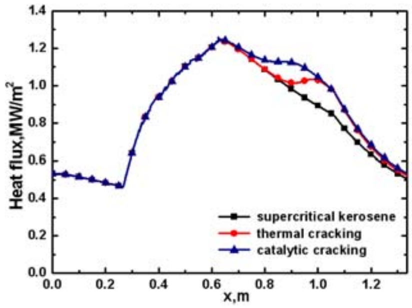

Fig.5 Heat flux distribution with thermal or catalytic cracking and without cracking effect

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