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Combustion characteristics of hydrogen and cracked kerosene in a DLR scramjet combustor using hybrid RANS/LES method

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ABSTRACT

This paper applies a zonal hybrid RANS/LES framework to analyze supersonic combustion in a model scramjet combustor. The geometries and boundary conditions of model scramjet combustor are based on an experiment conducted at DLR, German Aerospace Center. This model scramjet combustor was designed to achieve free flight Mach number of 5.5 and total air temperature of 1500 K. Hydrogen at subcritical conditions and thermal/catalytic cracked kerosene at supercritical conditions are injected as fuel. A surrogate of thermal/catalytic cracked kerosene is composed of ethylene and methane in supercritical conditions. To remain consistent with the hydrogen-fueled case, the total equivalence ratio is set to 0.034 for both cases. The total equivalence ratio is quite small, so it is not induced flow separation in the combustor duct. The thermodynamic and transport properties of the supercritical thermal/catalytic cracked kerosene are calculated using the Redlich–Kwong Peng–Robinson cubic equation of state and Chung's model for viscosity and conductivity. This paper focuses on comparisons of the subcritical hydrogen-fueled and supercritical cracked kerosene-fueled scramjet combustors in terms of intrinsic flow and combustion features. The analysis is demonstrated via a reacting regime diagram in nonpremixed turbulent combustion, flame index contours and scatter plots of the flamelet structure. It is found that the cracked kerosene surrogate flame is more vulnerable to quenching than the hydrogen flame, and flame quenching occurs in the immediate vicinity of the injector.

1. Introduction

Scramjet engines have been studied for more than 50 years, but they have not yet reached a stage of development suitable for practical applications. Researchers interested in air-breathing engines are confronted with a number of fundamental difficulties, including the low degree of fuel–air mixing, complications with respect to supersonic combustion mechanisms and the high heat loads on the combustor wall during scramjet operation. Within the scope of thermal structures, the active cooling system using the endothermic decomposition of hydrocarbon fuels (particularly kerosene) onto the combustor wall is required to alleviate the thermal loads and stress. For scramjet applications, the fuel may be used to regeneratively cool down internal engine walls. This indicates that fuel can be utilized as a heat sink source, and it can then be injected into the combustor containing higher enthalpy. For hydrocarbon fuels, the temperature at the end of the cooling channel is typically between 640 to 670 degrees Kelvin, but as the temperature increases above 750 K, the fuel is thermally and catalytically cracked. An aircraft's fuel pressurization system can generally pressurize up to 2–3 MPa, which exceeds kerosene's critical pressure value because of the need to maintain high pressure in the combustor and prevent the fuel from boiling in the cooling channel. The characteristics of the decomposition phenomenon of kerosene under highly pressurized conditions are very complicated, and this topic has also received attention in recent years. The thermal cracking of hydrocarbon aviation fuels was thoroughly reviewed by Edwards [1]. One of the challenging tasks is the choice of surrogates for thermal/catalytic cracked kerosene. Various studies have looked at the thermal/catalytic cracking of kerosene under supercritical conditions. Zhong et al. [2] experimentally investigated the thermal cracking and endothermicity of China No. 3 aviation kerosene and found that the main gaseous products were methane, hydrogen, ethane and ethylene under 3.0–4.5 MPa and 780–1050 K conditions. More intensive research on the thermal cracking phenomenon in regenerative cooling channels was conducted by Jiang et al. [3]. They carried out experiments concerning the detailed species concentration and heat transfer along the cooling channel under supercritical conditions (5 MPa, 950–970 K). They also constructed an analytical model to study the thermal

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Nomenclature

a_{ij}	Cholesky decomposition of Reynolds stress tensor
$a_c,\ b_c$	attraction and repulsive factor
c_p	specific heat at constant pressure of mixture
c_χ	model constant
d	function of critical compressibility factor
E	total energy
f_σ	shape function
k	turbulent kinetic energy
k_c	function of critical compressibility factor
h	specific enthalpy of mixture
M_w	molecular weight of mixture
N	number of SEM eddies
p_c	critical pressure
p	static pressure
R_{ij}	Reynolds stress tensor
R_u	universal gas constant
T	static temperature
T_c	critical temperature
T_r	reference temperature
t	time
u	velocity
u'	velocity fluctuation
V_B	box of eddies
x	streamwise coordinate
x^l	position of lth SEM eddy
y	spanwise coordinate
y_c	function of critical compressibility factor
Y_k	mass fraction of species k
Z	mixture fraction
Z_c	critical compressibility factor
Z''^2	transversal coordinate
z	variance of the mixture fraction
Z_{st}	stoichiometric mixture fraction
α	function for cubic equation of state
ΔZ	diffusion thickness in mixture fraction space
$\delta_1,\ \delta_2$	functions of critical compressibility factor
ε^l	intensity of lth SEM eddy
λ	heat conduction coefficient
μ	molecular viscosity
μ_t	eddy viscosity
ρ	density
σ	control parameter of turbulent structure size
σ_k	coefficient for two-equation model
τ	molecular stress tensor
τ'	Reynolds stress tensor
χ	scalar dissipation rate
χ_{st}	stoichiometric scalar dissipation rate
χ_q	quenching scalar dissipation rate
ω	specific dissipation rate
ω_c	acentric factor

Subscript

$i,\ j$	spatial coordinate index

Superscript

$\overline{()}$	Reynolds averaged
$\widetilde{()}$	Favre averaged

cracking of hydrocarbon aviation fuels, and they compared their results with experimental values. They determined that the largest portions of gaseous products were propylene, ethylene and ethane. In addition, liquid products such as alkenes, cycloalkenes and aromatics were observed. Vaden et al. [4] conducted experiments on fuel versus air systems for hydrocarbon fuels using an oscillatory-input opposed jet burner at atmospheric pressure. They identified a simple surrogate with a composition of 64% ethylene and 36% methane by molar fraction. They determined that this was a viable surrogate for cracked JP-7 kerosene for Hypersonic International Flight Research Experimentation Program (HIFiRE) scramjets in terms of flame strength, ignition characteristics and flameout limit. Denman et al. [5] demonstrated a Mach 7.3 scramjet engine (rather than only a combustor) fueled by hydrogen and hydrocarbon fuels (methane and ethylene) in order to investigate ignition and combustion characteristics with various fuels. By means of their enthusiastic efforts, innovative methodologies and technologies were made available for research on hypersonic propulsion systems.

In the present study, the two-species surrogate proposed by Vaden et al. is applied to secure numerical simplicity and reasonable flame dynamics. If fuel is placed under high pressure and injected into a combustor just below the pressurization pressure, it may be below or above the critical pressure. In addition, the temperature will be high because the fuel will be exposed to the heat transfer in the micro cooling channel. Thus, it will generally rise above the critical temperature of the matter. Thus, in the immediate vicinity of the injector, a small part of the fuel is placed in a gray area of supercritical and subcritical conditions even though the combustor is atmospheric. This paper considers thermodynamic and transport properties under supercritical conditions using the Redlich–Kwong Peng–Robinson (RK–PR) equation of state (EOS) [6] and Chung's method, respectively [7].

In the present contribution, we tackle a fundamental question – namely, how does a kerosene-fueled scramjet combustor differ from a hydrogen-fueled scramjet combustor in terms of the entire flowfield and the manner of their turbulent combustion? The DLR model scramjet combustor [8] is selected to explore these differences. Accordingly, the thermal/catalytic cracked kerosene surrogate under supercritical conditions is injected into the scramjet combustor. To maintain consistency with respect to the hydrogen combustion, the kerosene fueling calculation has an air–fuel equivalence ratio identical to that of the hydrogen. The computational domain is divided into RANS and LES regions. In the RANS region, the k–ω shear stress transport (SST) model and high-order upwind convective flux discretization method are applied. On the contrary, the LES region employs a low-dissipative convective flux discretization method and improved delayed detached eddy simulation (IDDES). A synthetic eddy method (SEM) is used to connect the RANS and LES regions. The SEM provides synthesized unsteady velocity fluctuations to the LES region using statistically calculated turbulent kinetic energy based on the flow conditions of the RANS region. The predictions of hydrogen-fueled scramjet combustor are compared with available experimental data, and then the comparisons of hydrogen-fueled and cracked kerosene-fueled scramjet combustors are carried out in terms of flow and combustion characteristics.

2. Methodology

2.1. Governing equations

Favre averaged compressible Navier–Stokes equations for mass, momentum and total energy conservation are

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