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Performance evaluation of power generation system with fuel vapor turbine onboard hydrocarbon fueled scramjets

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ABSTRACT

In order to evaluate the performance of a new power generation system in which the generator is driven by the fuel vapor turbine, the pyrolysis characteristics and the compositions of pyrolyzed fuel mixture are experimentally studied. An algorithm is developed for the calculation of isentropic enthalpy drop of fuel vapor using a real gas model based on the SRK (Soave–Redlich–Kwong) equation of state. Fuel vapor is a variable mixture of fuel and its cracking products at different temperatures and pressures, making its physical properties variable. The working capacity of fuel vapor is dramatically enhanced in the pyrolysis reaction process. Benefiting from the high enough working capacity, the fuel vapor turbine still has enough power to drive a generator in addition to a fuel pump. The low-grade heat energy absorbed by fuel is transformed into high-grade mechanical/electrical energy by this system to achieve better energy utilization. Evaluation results indicate that this thermodynamic power generation system can be operated in a wide range of temperature to support the off-design operation of a scramjet.

1. Introduction

Energy recovery has been a hot issue in all kinds of engines in recent years. One primary approach is to establish a bottoming Rankine cycle for the recovery of waste heat of engine at low/medium temperatures. Yu et al. [1] indicated an improvement of 6.1% in thermal efficiency of a diesel by ORC (organic Rankine cycle). Gao et al. [2] developed a Rankine cycle with a reciprocating piston expander to increase the engine power by 12% on a turbocharged 80 kW/2590 r/min diesel engine. Boretti [3] considered applying the Rankine cycle on a hybrid car powered by gasoline engine and predicted a total increase of 8.2% in fuel conversion efficiency with the ORC system fitted on both the exhaust and the coolant. Carcasci et al. [4] proposed an ORC for waste heat recovery from gas turbines and pointed out that different working fluid should be used for different source temperature. Overall, there are plenty of studies on energy recovery from different engines at ground and they indicate encouraging prospect in energy conservation.

For flight vehicles especially hypersonic aircrafts and missiles powered by scramjet, an extremely high temperature is encountered in the combustor [5], making energy recovery more necessary to keep high efficiency of the engine. Meanwhile, a practical problem is that a large amount of power is desperately needed by the auxiliary systems for fuel feeding, environment control and radar. The flight ranges will be greatly limited by the capacity of onboard battery if there is no other onboard power generation system. It is therefore of great significance to build an energy recovery system with power generation for practical operation on hypersonic vehicles.

Scramjets are usually regeneratively cooled by fuel for safe sustained-operation [6]. Energy recovery is achieved in the shape of heat recovery by fuel injection after cooling the engine. However, the heat recovered by fuel is not transformed into mechanical/electrical energy. Based on regenerative cooling, Sforza [7] considered a semi-closed Rankine cycle for power generation using fuel as the working fluid. A dedicated turbine is used to extract power from the fluid to drive a generator. Although the generating capacity is huge, the mass penalty introduced by the semi-closed cycle is obvious and it is of little realistic meaning. Qin et al. [8] developed an open cooling cycle, which contained a turbine in the flowpath to transfer enthalpy from fuel to mechanical work. Bao et al. [9] extended the open cooling cycle to hydrocarbon fueled scramjet and pointed out that both increased heat sink and power output by the turbine are obtained by this recooling cycle. Although the recooling cycle is capable of power output, it is not designed and optimized for the purpose of power generation and it is still difficult for a short term application. Some attention has been paid

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Nomenclature

a, b, α	parameters in the SRK equation of state
C_p	constant pressure specific heat capacity, J kg^{-1} K^{-1}
C_v	constant volume specific heat capacity, J kg^{-1} K^{-1}
$C_{p,0}$	constant pressure specific heat capacity for ideal gas, J kg^{-1} K^{-1}
$C_{v,0}$	constant volume specific heat capacity for ideal gas, J kg^{-1} K^{-1}
dh	enthalpy drop of a discrete process, J kg^{-1}
dp	pressure drop of a discrete process, Pa
f	mole fraction of gas product
k	mole fraction of liquid product
k'_{dec}	mass fraction of n-decane in liquid product
M	molecular weight, kg mol^{-1}
M_w	molecular weight of fluid mixture, kg mol^{-1}
m	total mass flow rate, kg s^{-1}
m_g	mass flow rate of gas product, kg s^{-1}
m_l	mass flow rate of liquid product, kg s^{-1}
p	pressure, Pa
p_c	critical pressure, Pa
R_u	universal gas constant, J mol^{-1} K^{-1}
S	parameter function
T	temperature, K
T_c	critical temperature, K
T_r	reduced temperature
V	volume flow rate of gas components, L s^{-1}
v	specific volume, m^3 kg^{-1}
v_c	critical volume, cm^3 mol^{-1}
w	specific power, J kg^{-1}
x	mole fraction of species
z	fuel conversion rate
γ	specific heat ratio
Δh	enthalpy drop, J kg^{-1}
Δp	pressure head of pump, Pa
ε	binary interaction coefficient
η	work efficiency
κ	effective exponent for isentropic process
ρ	density, kg m^{-3}

Subscripts

dec	n-decane
f	fluid
final	the final state
gen	generator
i,j	specific product number
initial	the initial state
pump	pump
s	isentropic process
T	isothermal process
turb	turbine

to MHD (magneto hydrodynamics) power generation for scramjets [10]. However, its potential application is hypersonic flight with a Mach number higher than 10, where hydrogen will be utilized as the propellant to provide enough cooling for effective operation of the superconducting magnets.

Another relevant topic is fuel feeding on scramjets. The fuel powered turbopump commonly used in a rocket engine has been considered for fuel feeding on a hydrogen fueled scramjet [11]. The concepts of fuel feeding cycles in liquid rocket, such as expander cycle, gas generator cycle, staged combustion cycle and coolant bleed cycle, have been developed to regeneratively cooled scramjet. Among these cycles, the expander cycle containing a fuel powered turbopump is relatively simple in structure, and it has the best performance in terms of specific impulse, and is called topping cycle in liquid rocket. A similar fuel feeding cycle in hydrocarbon fueled scramjet is also proposed in the SFSFC (Storable Fuel Scramjet Flowpath Concepts) Program, and it utilizes a hydrocarbon fuel powered turbopump for fuel feeding [12]. However, no more technical details are published further.

The key point of turbopump feeding systems is energy conversion from the heated propellant to mechanical power by the turbine. Therefore, if a fuel powered turbopump is connected with a generator, it has the potential to be a simple and efficient onboard power generation system capable of fuel feeding on scramjet as shown in Fig. 1. Fuel is pumped into the cooling jacket of a scramjet to cool the engine walls. The fuel pressure in the cooling jacket is usually higher than its critical pressure to avoid film boiling, which causes the deterioration of heat transfer [13]. After absorbing the heat transferred from the combustor, the fuel temperature rises rapidly in the cooling jacket. When it is higher than its critical temperature, the fuel becomes supercritical. At the outlet of the cooling passage, the turbine is driven by supercritical fuel and the shaft power of the turbine is delivered to the pump and the generator. Fuel is then injected into the combustor after it powers the turbine. In view of energy recovery, the low-grade heat energy dissipated from the combustor is absorbed by the coolant and then transformed into high-grade mechanic/electric energy by this system. Both energy recovery and power generation are achieved by this system onboard scramjets.

However, the regenerative cooling process of hydrocarbon fuels is much complex than that of hydrogen, which remains a pure substance in the whole cooling process. At a relatively high temperature, endothermic reactions take place and hydrocarbon fuels crack into small hydrocarbons (CH_4, C_2H_4, C_2H_6, etc.) to offer extra chemical heat sink, which is urgently needed for scramjets [14]. The fuel temperature and pressure in the cooling passages will change during the acceleration or off-design operation of scramjets, and their variations have great influence on the chemical reactions in the cooling passages and the compositions of final products in the turbines [15]. Therefore, the working fluid powering the turbine is fuel vapor, a variable mixture of hydrocarbon fuel and its cracking products.

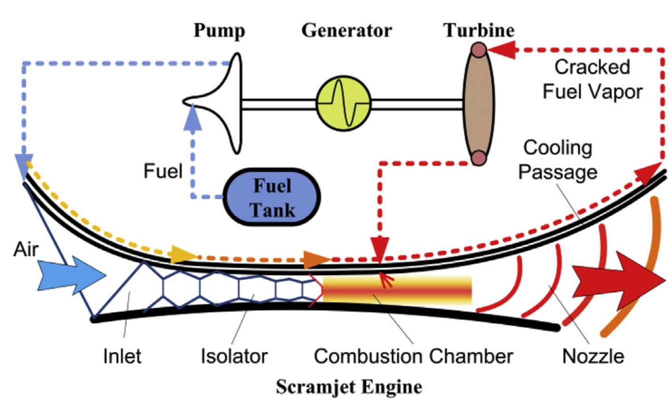

Fig. 1. Schematic diagram of onboard power generation with fuel vapor turbine.