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# Thermal analysis of regenerative-cooled pylon in multi-mode rocket based combined cycle engine

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ABSTRACT

Combining pylon injector with rocket is an effective method to achieve efficient mixing and combustion in the RBCC engine. This study designs a fuel pylon with active cooling structure, and numerically investigates the coupled heat transfer between active cooling process in the pylon and combustion in the combustor in different modes. Effect of the chemical reaction of the fuel on the flow, heat transfer and physical characteristics is also discussed. The numerical results present a good agreement with the experimental data. Results indicate that drastic supplementary combustion caused by rocket gas and secondary combustion caused by the fuel injection from the pylon result in severe thermal load on the pylon. Although regenerative cooling without cracking can reduce pylon's temperature below the allowable limit, a high-temperature area appears in the middle and nail section of the pylon due to the coolant's insufficient convective heat transfer coefficient. Comparatively, endothermic cracking can provide extra chemical heat sink for the coolant and low velocity contributes to prolong the reaction time to increase the heat absorption from chemical reaction, which further lowers and unifies the pylon surface temperature.

## 1. Introduction

Low-cost and reusable vehicles have received more attention with the increasing outer space activities. In order to broaden the operation range of a single propulsion, a rocket-based combined cycle (RBCC) engine integrates multi-mode in one same channel and presents the characteristics of high thrust to weight ratio of the rocket and specific impulse of the ramjet engine [1,2]. As dynamic pressure of intake air increases, it is difficult for traditional wall injection to achieve sufficient penetration and effective mixing throughout the whole flight. Thus, pylon injector is developed to increase the fuel turbulence intensity and jet momentum [3,4]. This implies that the pylon injector is located in the core reaction zone, and tends to suffer severe thermal load [5,6]. In order to guarantee reliable fuel injection and combustion, effective thermal protections receive significantly essential attention and are investigated by many researchers.

Markus [7] carried out a series of experiments on the ceramic strut with active cooling method. The results showed that transpiration cooling exhibited significantly lowered temperatures levels compared to other designs, whereas the pylon needed to be manufactured on ceramic matrix material. To save manufacture cost, Allan [8] developed a heat shield on the Nickel pylon and indicated that the thermally-insulated method achieved more uniform temperature distribution. Bouchez [9] conducted the numerical simulation on the active cooling performance in the pylon and achieved excellent protection on the leading edge through impingement cooling. The wall temperature was reduced below 900 K. However, the pylon must be fabricated by tungsten, molybdenum or other refractory material, which added extra load on the engine. Hou [10] also carried out active cooling numerical analysis in the scramjet mode and revealed impingement made great contribution to the increases in the cooling efficiency.

With regard to the coolant, endothermic hydrocarbon fuel behaves similar heat sink compared to hydrogen fuel and is widely used in the hypersonic vehicle [11]. Zhou [12] conducted heating tests and showed that when the initial temperature was approximately 770 K, cracking reaction of hydrocarbon fuel would occur. Fan [13] discussed the heat transfer characteristics of the cracking components and revealed that although heat sink of the products had reached 3.4 MJ/kg at a fuel temperature of 1050 K, the cracked component was extremely complicated. In order to settle this issue, Ward [14] carried out ground test to obtain effective alternatives and they firstly brought out the product proportional distribution model for the cracking reaction. Based on this model, Zhang [15] analyzed the effect of aspect ratio on the thermal behavior in the cracking reaction zone. Results indicated that the conversion presented a similar distribution in different channels and larger aspect ratio would cause more pressure drop.

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**Nomenclature**

| | |
|---|---|
| *Ch* | Cooling channel |
| $c_p$ | Specific heat, J/kg K |
| *ER* | Secondary fuel/intake air equivalence ratio (Dimensionless) |
| $h_f$ | Convective heat transfer coefficient, W/(m$^2$ K) |
| *L* | Height of the Ch.0 in the *y* direction, mm |
| *Ma* | Flight Mach number |
| *m* | Mass flow rate, kg/s |
| *O/F* | Oxygen/fuel mass ratio in the rocket (Dimensionless) |
| *Q* | Heat sink, J/kg |
| *r* | Radius, mm |
| *T* | Temperature, K |
| $T_t$ | Total temperature, K |
| *t* | Time, s |
| *v* | Velocity of the coolant, m/s |
| △ | Parameters change in the cooling process |

*Greek symbols*

| | |
|---|---|
| $\sigma$ | Distance between channel and pylon wall, mm |
| $\lambda$ | Thermal conductivity, W/m K |
| $\rho$ | Density, kg/m$^3$ |

*Subscripts*

| | |
|---|---|
| *bp* | Boiling point |
| *c* | Coolant |
| *chem* | Chemical |
| *d* | Droplet |
| *m* | Component *m* after reactions |
| *phy* | Physical |
| *res* | Unreacted fuel in the coolant |
| *total* | Total value |
| *vap* | Evaporation point |
| *w* | Pylon wall |

In the present study, the pylon with internal active-cooled structure is designed. An integrated numerical model is developed for the cooling performance inside the pylon, and subsequent secondary combustion of injected fuel from pylon and primary jet from ejection rocket, which functioned for the fuel ignition. Firstly, we analyze the rocket heating effect on the thermal environment around pylon in different modes. Then, the active cooling performances with the fuel cracking behaviour are discussed.

**Table 1**
Different operating modes.

| Mode | Flight Ma | Rocket flow rate (kg/s) | Pylon injection (ER) |
|---|---|---|---|
| Ejection | Ma = 0–3.0 | 0.8 to 0.1 | off |
| Ramjet | Ma = 3.0–5.5 | 0.1 to off | 0.2 to 0.5 |
| Scramjet | Ma > 6.0 | off | 0.8 to 1.0 |

## 2. Model

The physical model for numerical simulation comprises a flow channel and an embedded rocket engine (Fig. 1). Table 1 presents the operating description of the RBCC engine in various modes. In the ejection mode, the rockets locates in the center of the flowpath and operates at a large flow rate condition (0.8 kg/s) to provide thrust and accelerate at low Mach flight conditions. As the flight Mach number increases, inlet (before the isolator) starts to capture air, which further mixes with the secondary injected fuel. In order to ensure impulse, the rocket operates at a low flow rate (0.1 kg/s) and the equivalence ratio on the pylon increases to enhance combustion efficiency at high Mach flight conditions. It can be found that intensive heating effect of rocket and combustion will cause high thermal load on the following pylon injector and this effect is more severe in the ejection mode and scramjet mode, so that the cooling analysis in the present study is carried out at Ma = 0 and Ma = 6 conditions. Since rocket should operate to ensure ignition in the scramjet mode under some extreme conditions, analysis under the Ma = 6 condition with rocket operating is also discussed.

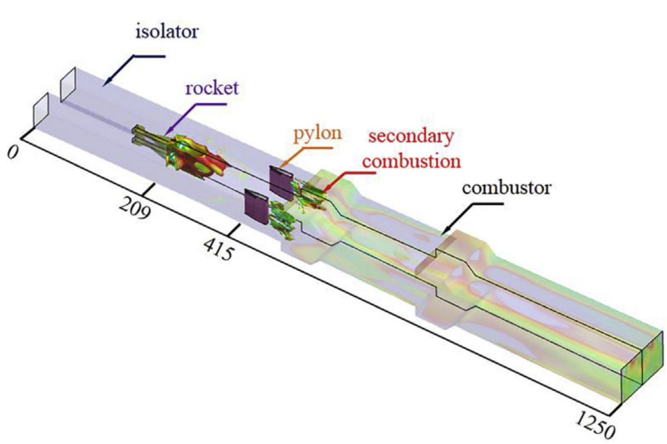


**Fig. 1.** Physical model diagram.

Fig. 2 describes the pylon that integrates the active cooling scheme. In the cooling process, coolant flows into Chs.0–2 and Chs.4–9, and then converges in the manifold at the bottom [Fig. 2 (a)]. By this means, heat on the side wall and bottom are both absorbed. Owing to large sectional area of the Ch.3, it is employed as the exit after cooling process, so that the total mass flux from the other channels can ensure enough velocity and heat transfer coefficient in this channel. Specific channel geometric parameters are given in the top view, as described in Fig. 2 (b).

## 3. Governing equations and solution methods

In this paper, n-Decane ($C_{10}H_{22}$) is chosen as a fuel compound for the present study because it is a typical pure liquid hydrocarbon fuel with 10 carbon atoms in its molecule. The carbon number and properties is also similar to those of liquid hydrocarbon fuel commonly used in aerospace applications.

### 3.1. Chemical reaction model

Coupling simulating the cracking behaviour and real thermal environment is very difficult to accomplish. Zhong conducted many experimental researches [16] and found that when the equivalence ratio increases over 0.8, fuel cracking has no effect on combustion temperature. Thus, we suppose that the coolant (fuel) flows to the tank after active cooling and the fuel is injected in the combustor through the form of discrete phase. The effect of coupling process on the pylon thermal environment is neglected.

For the cracking simulation, pyrolysis products of n-Decane (PPD) model brought by Ward [14] is widely used in the active cooling analysis [15]. It provides more accurate results with the experimental data [17]. The reaction model is shown in Table 2. As the products and their distribution are unchanged under the pressure and the temperature change in present study [15], this model is employed.

With considerations to computing cost and speed, a simplified 9-