Flame Flow Analysis for HVOF/HVAF System by Two-Dimension Computational Fluid Dynamics Method

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Abstract
Based on the principle of the liquid-fueled rocket engine, a combustion model is proposed for the HVOF/HVAF system. The combustion gas components and temperature for different mixture fractions were analyzed. At lower oxygen content condition (under-stoechiometry), the combustion temperature is lower and the solid content carbon content is higher. The whole fluent flow mode was proposed for the supersonic spray, which consists in the gas combustion, the accelerating process, the cooling process and the decelerating process in the atmosphere. The velocity and temperature distributions were calculated according to this model; the results fitted well with experiments. The combustion gas parameter distributions are almost identical in the barrel, but differ significantly in the atmosphere. For HVOF system, the under-expanded gas will expand in the atmosphere, while HVAF system exhibits an opposite behavior. At the gun exit, the combustion gas reaches supersonic velocities both for the HVOF and HVAF condition.

Introduction
High velocity oxygen (air)-fuel (HVOF/HVAF) thermal spray systems and spray materials have been developed over the last two decades. As a result, the fields of application of the thermal spraying are expanding rapidly.

During spraying, the environment surrounding the particles is primarily determined by the gas dynamics of the jet. In the early thermal spray process, most researches on HVOF thermal spraying were focused on the development of advanced materials, and in the 90's of last century, Computational Fluid Dynamic (CFD) has been a major tool to develop HVOF systems [1-2].

However, commercial users and investigators of the HVOF/HVAF processes have realized that a better understanding of the gas dynamics of HVOF/HVAF sprays is needed to obtain the tighter process controls required for the reliable deposition of advanced coatings.

There are several techniques that can be used to model the gas flow of HVOF/HVAF systems. Recent analyses have used computational fluid dynamics to simulate this complex phenomenon. However the internal nozzle flow was treated as quasi-one-dimensional isentropic flow, and the flow in the inter- and outer-nozzle were separately [1-2]. The combustion gas was treated as a perfect gas or a semi-perfect gas, the chemical reactions of combustion in the combustion chamber considered ideal conditions so that the combustion gases are composed only of CO$_2$, H$_2$O(gas), excessive O$_2$, and carrier gas N$_2$ [4]. Nevertheless, the components can decompose at high temperatures and carbon could be obtained for higher fixture fraction. In the spray process, the combustion gas components and temperature will be different for different mixture fractions.

In this paper, a combustion model based on the liquid-fueled rocket engine is proposed. The combustion gas components and temperature for different mixture fractions were obtained for the KY-HVOF/HVAF system [5]. As a result, the components and temperature can be used to calculate the flame flow using two-dimension computational fluid dynamics method.
propulsion system, neither the thrust nor the weight of an HVOF or HVAF gun are key issues compared to coating quality. Nonetheless, the field of rocket propulsion includes much-developed technologies which can be readily transferred to HVOF/HVAF spray systems. At least, one can mention the gas dynamic behavior of a supersonic particle-laden nozzle flow.

The KY HVOF/HVAF system can be used in HVOF and HVAF system for different material and different process. The flame velocity and the temperature can be adjusted in the range 600-2300m/s and 600-3500K according to the oxygen, nitrogen and fuel flux [5].

In order to compute the combustion gas components and their temperature, the following assumptions were considered.

- the fuel in the combustion chamber is totally vaporized into gas, so that the combustion gas can be regarded as the semi perfect gas;
- since the chemical reactions occurring during the combustion process are complex and not easy to simulate, it is impossible to emphasize the reaction process. In such a way, the components were supposed [4];
- the possible components can be list, for example, CH₄, C, C(S), CO, CO₂, H, H₂, H₂O, O, O₂, OH, which can be decided by the combustion pressure.

Suppose that the fuel is CₙHₘ and that the combustion efficiency is η. The chemical reaction depicting the combustion can be expressed from a general point of view as follows:

\[ m_H C + m_O_2 + m_N_2 \rightarrow (1-\eta)m_H C + m_O_2 + m_N_2 + n CO + \eta CO + \eta CO_2 + \eta O_2 + \eta O + \eta C(S) + m_N_2 \]

The elementary equations are as follows:

\[ m_1 = (1-\eta) m_1 + n_1 + n_6 + n_9 \]
\[ m_2 = (1-\eta) m_2 + 2n_1 + 2n_5 + 4n_6 + n_7 + n_9 \]
\[ 2m_1 = 2n_1 + 2n_5 + n_7 + n_9 \]

The chemical balance constant equation is driven by the idiographic chemical reaction and each reaction presents a constant chemical balance as a function of the combustion chamber pressure and the internal temperature. If the pressure can be measured in the spray process, the chemical reaction constant will only be driven by the temperature. Nevertheless, the actual process will be different since different mixture fractions are considered. The equations are extensively displayed in [6].

The energy equation can be expressed as follows:

\[ (h_p)_i - (h_p)_f = \int_{T_i}^{T_f} C_p dT \]

Figure 1: Combustion components.
where \((h_p)_2\) and \((h_p)_1\) refer to the combustion gas enthalpy at the combustion temperature 2 and at the initial (i.e., "cold") temperature 1, respectively.

The main components resulting from combustion are \(H_2O\), \(CO_2\), \(CO\), \(O_2\), \(H_2\), a small quantity of \(CH_4\), \(OH\), \(O\) and \(H\). At higher temperature, the components are quite different from the ideal condition since some materials decomposed, and the temperature is lower than the theoretical condition due to a higher heat quantity consumed by the reaction.

In the thermal process, sometimes the black solid carbon caused by the decomposed \(CH_4\) may be deposited in the spray gun inner, which should be removed for a periodical time.

Since the KY-HVOF/HVAF system can be used under HVOF or HVAF conditions, the oxygen content influence was taken into account as displayed in Fig. 1a, 1b, 1c and 1d and Fig. 2, which consider different \(O_2\) contents (30%, 45%, 60%, 70%, respectively). At lower oxygen content condition, the combustion temperature is lower and the maximal point is close up to the lower mixture fraction and the solid content carbon content is increased.

The computational domain contains inside and outside of the spray gun, in the outside region, the rectangle region of 40d in the axial direction and 10d in the vertical direction was considered and \(d\) refers to the gun diameter. The standard K-\(\varepsilon\) turbulent model was used. Figures 3 and 4 illustrate the axial velocity, temperature in the whole region. The two course pulse may be easily seen, one course in the gun and the other outside the gun. The combustion gas parameter distributions are almost identical in the barrel, but differ significantly in the atmosphere. For HVOF system, the under-expanded gas will expand in the atmosphere, so the flame velocity will increase and temperature will decrease, while HVAF system exhibits an opposite behavior. At the gun exit, the combustion gas reaches supersonic velocities both for the HVOF and HVAF condition.

**Figure 2**: Combustion temperature.

**Flame Flow Analyses**

The overall rate of propagation of the flame is determined by both the laminar flame speed and the turbulent eddies. The laminar flame speed is determined by the rate that species and heat diffuse upstream into the reactants and burn. To capture the laminar flame speed, the internal flame structure would need to be resolved, as well as the detailed chemical kinetics and molecular diffusion processes.

The two-dimension computational fluid dynamics method can be used to calculate the flame characteristics in the full region.

**Figure 3**: Axial velocity distribution

**Figure 4**: Static temperature distribution.

**Conclusions**

Based on the principle of the liquid-fueled rocket engines, the combustion model for supersonic spray was proposed. The combustion gas components and temperature for different...
mixture fractions were obtained for a KY-HVOF/HVAF system:

- at lower oxygen content condition, the combustion temperature is lower and the solid content carbon content is higher. The maximal point is close up to the lower mixture fraction with the oxygen content increase;
- the two-dimension computational fluid dynamics method can be used to calculate the flame characteristics in the full region;
- the combustion gas parameters distributions are almost the same as HVOF and HVAF system in the gun. For HVOF, the under-expanded gas will expand in the atmosphere, while HVAF system is quite the contrary. The supersonic condition can be obtained from the two different systems, and the velocity and temperature become adjustable between HVOF and HVAF system.

References