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Indirect measurement method of inner wall temperature of scramjet with a state observer

Cong Zhang, Jiang Qin *, Qingchun Yang, Silong Zhang, Juntao Chang, Wen Bao *

School of Energy Science and Engineering, Harbin Institute of Technology, Heilongjiang 150001, People's Republic of China

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ABSTRACT

A state observer-based method is developed for the indirect online measurement of the inner wall temperature using the out surface temperature and pressure of a scramjet combustor. A mathematical model is established to describe the heat transfer from gas to combustor wall and inside combustor wall as well. A proportional integral observer is developed using the mathematical model for establishing the relationship between the observed inner wall temperature and the experimentally measurable parameters, including the out surface temperature and pressure. Numerical simulations and ground experiments are carried out with a direct-connect hydrocarbon fueled scramjet combustor to prove the validity of the proportional integral observer. Test results indicate the proportional integral observer method could be used to measure the inner wall temperature of the scramjet combustor.

1. Introduction

The supersonic combustion ramjet (scramjet) engine is generally considered the most efficient propulsion system for a hypersonic flight regime [1–3]. Under the broad range of aero-thermodynamic conditions experienced and supersonic combustion heat release during hypersonic flight, thermal management is a critical issue for the application of a scramjet [4]. The inner wall temperature of a combustor is a key parameter for its thermal management system. And as a direct reflection of the thermal state of the inner wall of the combustor, it has a great impact on the calculation of heat flux and the design of a thermal protection system. The measurement or prediction of the inner wall temperature is therefore very important to maintain the safety, performance, and longevity of scramjet combustor.

Much work has been done the calculation and measurement of heat flux and inner wall temperature of a scramjet combustor in recent years. For example, Huang and his coworkers employed the conjugate gradient method to solve the inverse heat transfer problem in an irregular boundary [5,6]. Park and Jung [7] developed an efficient scheme based on Kalman filtering and Karhunen–Loève Galerkin procedure, to estimate the unsteady, spatially varying wall heat flux and temperature in a two-dimensional heat conduction system. Bialecki et al. [8] used the Levenberg–Marquardt method along with the boundary element method to calculate the time-dependent boundary heat flux and temperature. These methods provided theoretical and methodological bases for the calculation of inner wall temperature of a scramjet combustor. Meanwhile, sensors were also developed to measure the inner wall temperature of a scramjet combustor. For example, Li [9] developed an integrated water-cooled high temperature sensor for the measurement of the temperature and wall heat flux in the inner wall of a scramjet combustor.

* Corresponding authors.
E-mail addresses: freedom.zhangc@gmail.com (C. Zhang), qinjiang@hit.edu.cn (J. Qin), hcmsyang@163.com (Q. Yang), zslhrb@gmail.com (S. Zhang), changjuntao@hit.edu.cn (J. Chang), baowen@hit.edu.cn (W. Bao).

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Nomenclature

A	cross section area of the combustor, m^2
C_f	skin friction coefficient
C_p	constant-pressure specific heat, J/mol K
h	enthalpy, kJ/kg
k	ratio of specific heats
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
P_w	wetted perimeter of the duct, m
q	heat flux, W/m^2
Re	Reynolds number
S	surface of combustor wall
St	Stanton number
T	temperature, K
V_e	velocity of central gas flow, m/s
x	axial coordinate, m
y	axial coordinate, m
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3

Subscripts

air	air
aw	adiabatic wall
g	gas
in	inner wall of combustor
out	outer wall of combustor
w	wall

Embedded and coaxial thermocouples were used to measure the temperature at different axial locations in a heat-sink copper combustion chamber [10].

Huang et al. [11] developed a new numerically method to simulate the flow fields in a three-dimensional scramjet isolator. It can be seen that the leading edge of the shock wave train can move forward towards the entrance of the isolator due to the high back pressure. The combustion flow field of a hydrogen-fueled scramjet combustor with a cavity flameholder was simulated by Huang et al. [12]. The effects of geometric parameters on the cavity flameholder were investigated. Therefore, considering the high back pressure influence and the process of flame holding, the flow field properties and heat transfer process of the scramjet combustor are more complex. The wall temperature and heat flux have strong mutagenicity in the operation of the scramjet. The measurement of inner wall surface temperature still has the following limitations. There are only installation positions of a scramjet combustor for the new sensors, which leads to be difficult to locate peak inner wall temperature of a scramjet combustor. The size of a measuring device makes the temperature of an area instead of the temperature of a point in a scramjet. It is unable to obtain the accurate temperature distribution. So, these methods and measuring devices are not suitable for the measurement of inner wall temperature during hypersonic flight. Therefore, it is of great significance to develop a new method which can be convenient arrangement of measurement point to measure the inner wall temperature in a scramjet combustor.

In this research, particular attention is focused on the indirect measurement of inner wall temperature based on the easily measured information. A mathematical model is established to describe the heat transfer from the gas to combustor wall and in combustor wall as well. A proportional integral observer is developed using the mathematical model for measuring the inner wall temperature of a scramjet combustor based on the measured values. A series of numerical simulations and ground experiments are conducted to verify the effectiveness of the method.

2. Heat transfer model of scramjet combustor

2.1. Physical model

A typical heat transfer process of scramjet combustor wall is selected as a research object. As shown in Fig. 1, a variational core flow temperature (T_g) combined with the velocity (Ma) and pressure (P) of core flow, which together contribute a nonuniform heat flux (q_w) is applied to S_{in} surface. S_{in} is the inner wall of the combustor with temperature T_{in}. S_{out} is the outer surface which dissipates heat into the environment through the natural convection. The parameters that can be measured during the experiments of combustor are the pressure P of inner wall (measured by pressure sensors) and the temperature T_{out} (measured by infrared imager or thermocouples) of S_{out}.

As shown in Fig. 1, a mathematical model could be established to describe the heat transfer from gas to combustor wall and inside combustor wall as well. It can be divided into three parts: calculation of core gas flow parameters, heat convection from gas to combustor wall

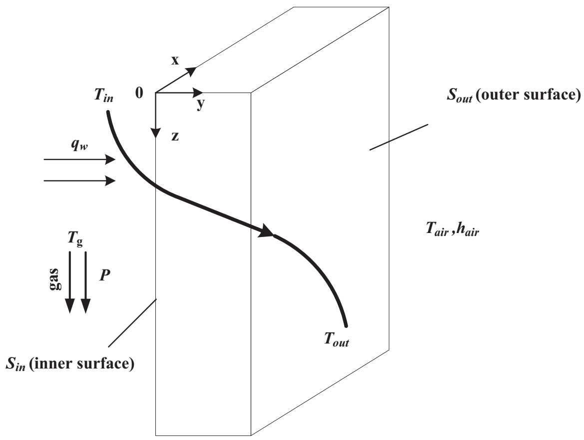

Fig. 1. Schematic diagram of heat transfer process of scramjet combustor wall.