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Research Paper

Inverse identification of boundary conditions in a scramjet combustor with a regenerative cooling system

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HIGHLIGHTS

- Boundary condition of scramjet combustor is inversely identified for first time.
- The FEM in the ABAQUS software is employed to solve the direct problem.
- The identification is accurate, efficient, stable and robust.
- The identification methodology is promising in further practical applications.

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ABSTRACT

Accurately determining boundary conditions in a scramjet combustor is of great importance for modeling the coupled process of fuel burning, fluid flow and heat transfer in the scramjet combustor, and for design and optimization of the cooling system. In this paper, a new methodology is proposed for determining boundary conditions at inaccessible surfaces of a scramjet combustor with a regenerative cooling system, which are identified by solving a three-dimensional transient inverse heat conduction problem. The finite element method in the ABAQUS is employed to solve the direct heat conduction problem in the scramjet combustor with the regenerative cooling system. A gradient-based method is used to solve the inverse problem attributed to its high accuracy and efficiency, and temperatures at accessible positions provide additional information for the inverse analysis. Examples are given to examine the performances for identifying boundary conditions in a scramjet combustor with a regenerative cooling system.

1. Introduction

Scramjets are commonly employed in hypersonic vehicles, in which the temperature could reach more than 3000 K [1], and the thermal protection system [2] is of great importance for the safety of scramjets. Passive thermal protection technique [2] could not meet the demand of the flight time varying from minutes to hours of hypersonic vehicles. Therefore, an active thermal protection technique is necessary and the regenerative cooling technique [3] is generally regarded as the most prospective. For the regenerative cooling system of a scramjet, accurately determining the boundary conditions in the scramjet combustor is a key issue for design and optimization of the cooling system, which has been studied in some papers [4–6]. However, it is usually difficult involving complex fuel burning, fluid flow and heat transfer modeling [7–14], or not very reliable due to empirical formula, or partly carried out in experiments, which are disadvantageous for design and optimization of the cooling system for a scramjet combustor.

In the present work, a new methodology is proposed to determine the boundary conditions in a scramjet combustor. Boundary conditions at inaccessible surfaces of a scramjet combustor will be identified by solving a three-dimensional transient inverse heat conduction problem, by utilizing temperatures at measurable/accessible positions. While determination of boundary conditions by solving an inverse heat conduction problem has been reported [15], it is the first time to inversely estimate boundary conditions for a scramjet combustor with the regenerative cooling system to the best of the authors' knowledge. Moreover, the present work has great application values for both design and optimization of the regenerative cooling system.

To inversely identify boundary conditions in a scramjet combustor, solutions to both direct and inverse problems are important. To solve direct heat conduction problems, the finite difference method (FDM) [16], the finite element method (FEM) [17], the boundary element

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Nomenclature

c	specific heat, J/(kg·K)
E_{rel}	relative error between the identified and the exact/real values, %
h	heat convective coefficient, W/(m^2·K)
J	sensitivity matrix
M	total number of measurement
N	total number of identified parameters
P	iteration number
q	heat flux, W/m^2
S	objective function
T	temperature, K
t	time, s
x	x-coordinate, m
y	y-coordinate, m
z	z-coordinate, m
$\boldsymbol{q}$	inverted parameter vector

Greek

δ	updated vector of recovered/inverted parameters
ζ	random measurement error
η	random number
λ	thermal conductivity, W/(m·K)
ξ	small positive number
ρ	density, kg/m^3

Subscripts

0	initial time
identified	identified value
exact	exact
f	fuel/coolant
i	the ith component of a vector
w	wall surface

Superscripts

0	initial guess
*	measured

method (BEM) [18], the meshless method (MLM) [19], and the finite volume method (FVM) [20] are frequently used. Each method has both advantages and disadvantages, and the FEM is the most suitable to solve multidimensional heat conduction problems in complex structures or in engineering applications and there are some available commercial software, such as ANSYS, ABAQUS, NASTRAN and so on. Therefore, the three-dimensional transient heat conduction problem is to be solved by using the FEM in the ABAQUS in the present work. To solve inverse heat transfer problems, a lot of methods were innovatively proposed, such as the conjugate gradient method [21–25], the Levenberg–Marquardt method [26–28], the krill herd algorithm [29], the Fourier transform [30], the genetic algorithm [31,32] and fundamental solutions [33], the Kalman filter method [34,35], a domain decomposition Method [36], the particle swarm optimization algorithm [37], and the singular value decomposition [38], which were partly reviewed in Refs. [39,40]. These methods could be divided into two groups: the stochastic and the gradient ones [40]. The former could search a global optimal solution, but they may require many iteration numbers. While the latter are more suitable to be adopted if one could estimate the range of the inverted parameters, attributed to sufficient accuracy and efficiency [41–47]; boundary conditions or thermo-physical properties have been estimated. In the present work, a gradient method, i.e., the Least-squares method [41], will be employed to solve the inverse heat conduction problem.

In the present work, two challenges are encountered by using the FEM in the ABAQUS and the Least-squares method for identifying boundary conditions in a scramjet combustor with the regenerative cooling system. First, the complex-variable-differentiation method (CVDM) [48], which has been employed for accurately calculating sensitivity coefficients in the previous work [40–42], cannot be used in the present work, because the complex-variable-differentiation method is unavailable in the ABAQUS. Second, data exchange has to be automatically carried out between intermediate results and input/output files of the ABAQUS. Some specific data in the input file have to be automatically revised, and some results have to be automatically extracted from the strings in the output file of the ABAQUS. To solve the first problem, an alternative method is adopted to calculate sensitivity coefficients without the CVDM. To deal with the second issue, program codes are developed, which could automatically extract temperatures at measurement points from the output file of the ABAQUS, and automatically revise specific data in the input file for the ABAQUS as well.

The remainder of this paper is as follows. In Section 2, the three-dimensional transient heat conduction problem is described. Section 3 briefly reviews the Least-squares method, in which additional program codes are also introduced. The new methodology is validated by using

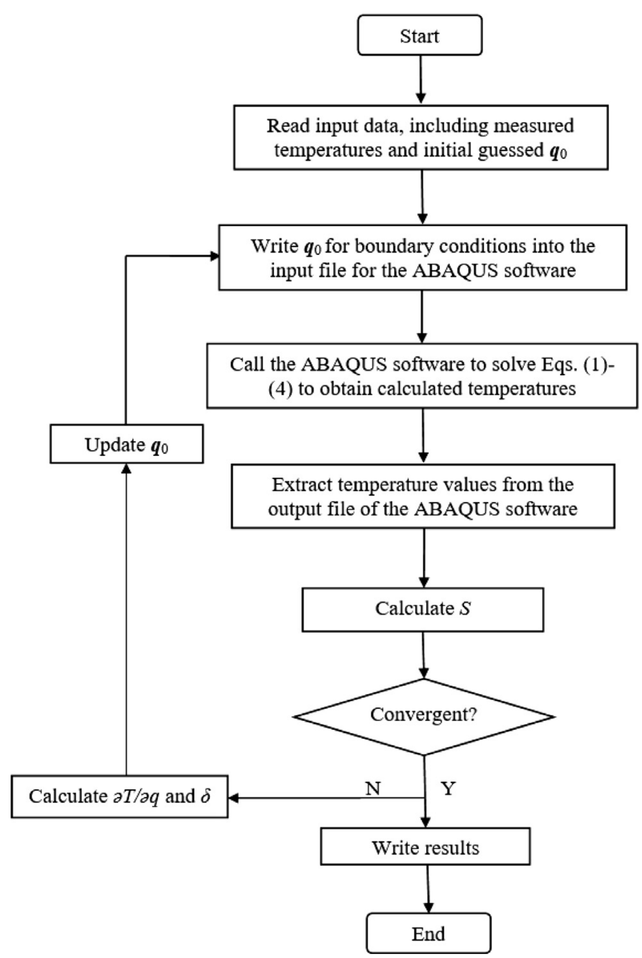

Fig. 1. Flowchart for identifying boundary conditions in a scramjet combustor with the cooling system.