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Heat transfer characteristics and limitations analysis of heat-pipe-cooled thermal protection structure

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HIGHLIGHTS

- Numerical methods for the heat-pipe-cooled thermal protection structure are studied.
- Three-dimensional simulation model considering sonic limit of heat pipe is proposed.
- The frozen startup process of the embedded heat pipe can be predicted exactly.
- Heat transfer characteristics of TPS and limitations of heat pipe are discussed.

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ABSTRACT

The theories of heat transfer, thermodynamics and fluid dynamics are employed to develop the coupled heat transfer analytical methods for the heat-pipe-cooled thermal protection structure (HPC TPS), and a three-dimensional numerical method considering the sonic limit of heat pipe is proposed. To verify the calculation correctness, computations are carried out for a typical heat pipe and the results agree well with experimental data. Then, the heat transfer characteristics and limitations of HPC TPS are mainly studied. The studies indicate that the use of heat pipe can reduce the temperature at high heat flux region of structure efficiently. However, there is a frozen startup period before the heat pipe reaching a steady operating state, and the sonic limit will be a restriction on the heat transfer capability. Thus, the effects of frozen startup must be considered for the design of HPC TPS. The simulation model and numerical method proposed in this paper can predict the heat transfer characteristics of HPC TPS quickly and exactly, and the results will provide important references for the design or performance evaluation of HPC TPS.

1. Introduction

With the development of hypersonic vehicles, the design of thermal protection system to keep the high lift-to-drag aerodynamic configuration and ensure the thermal structural safety during sustained severe aerodynamic heating, particularly at wing leading edge, has been one of the critical skill shortfalls. Early in 1970's, the studies of Silverstein [1] indicated that the problems mentioned above could be alleviated by heat pipes which are passive isothermal devices capable of transporting large quantities of heat over long distances. To verify the applications of heat pipes for various hypersonic vehicles, a number of analytical and numerical studies, laboratory and wind-tunnel tests have been carried out by McDonnell Douglas Corporation and NASA Langley Research Center [2–6]. Since the working fluid of heat pipes will be initially in the frozen state during the reentry process, the frozen startup problem must be an important design consideration. Some one-dimensional and two-dimensional numerical models have been proposed and developed by Colwell, Chang, Tournier, Cao and Faghri [7–10]. A more recent study of Steeves [11] used an isothermal approximation to predict the behavior of a planar leading edge heat pipe, and Xiao [12] proposed a frozen startup model based on conductance capacitance network. However, it is still difficult to simulate the entire operating conditions of heat pipe, since the heat transfer limitations are neglected. The thermal protective mechanisms and coupled heat transfer characteristics of HPC TPS also need to be studied further.

In this paper, the heat transfer properties of the typical HPC TPS with the vapor-phase, solid-phase and liquid-phase coexistence inside are studied, and the numerical method of the three-dimensional

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heat transfer is proposed. Especially, the simulation approach considering the sonic limit of heat pipe is developed to analysis the whole process from startup state to steady state. Based on the proposed numerical method, the heat transfer characteristics of TPS and limitations of heat pipe are mainly studied, which are very important for the design and thermal safety prediction of the HPC TPS.

2. Operation of HPC TPS

Fig. 1 shows the physical and three-dimensional CAD model of typical HPC TPS [6], which is composed of three major parts: C/C Structure, wall and wick of heat pipe. As a hypersonic vehicle travels through the Earth's atmosphere, the high local heat through the outer structures at wing leading edges is absorbed within the heat pipe by melt (occurs in the early stage of frozen startup) and evaporation of the working fluid. The evaporation results in an internal differential pressure that causes the vapor to flow from the evaporator region to the condenser region, where heat is given up by condensation and rejected by radiation. The liquid condensate flows back to the evaporator section by the capillary of a wick, and the cycle is completed. Thus, the typical heat transfer of the HPC TPS is a complex process of coupled heat transfer, including surface radiation, heat conduction and convection, melt of working fluid, evaporation and condensation.

To describe the process of heat transfer exactly, it could be divided into four main stages based on the working state of heat pipe as shown in Fig. 2, which are the initial heating stage, the working fluid melting stage, the rarefied–continuum flow transition stage and the frozen startup of heat pipe complete stage.

In this research, the thermal resistance of vapor flow is ignored for the low vapor density, and the coupled methods (on the exterior surface of structure, in the porous wick and at the liquid–vapor interface of working fluid) referred to four response stages are proposed respectively. Therefore, the simulation of the structure heat transfer is simplified into a problem of unsteady heat conduction with complex boundary conditions as shown in Fig. 3.

Using the described technique, the operating condition of HPC TPS can be analyzed. However, in order to confirm whether the heat pipe operates satisfactorily, the heat transfer limitations must be evaluated to see if it exceeds the design condition. There are generally three operating limits on the heat pipe: sonic, capillary and boiling limits. Among these operating limits, the boiling limit is

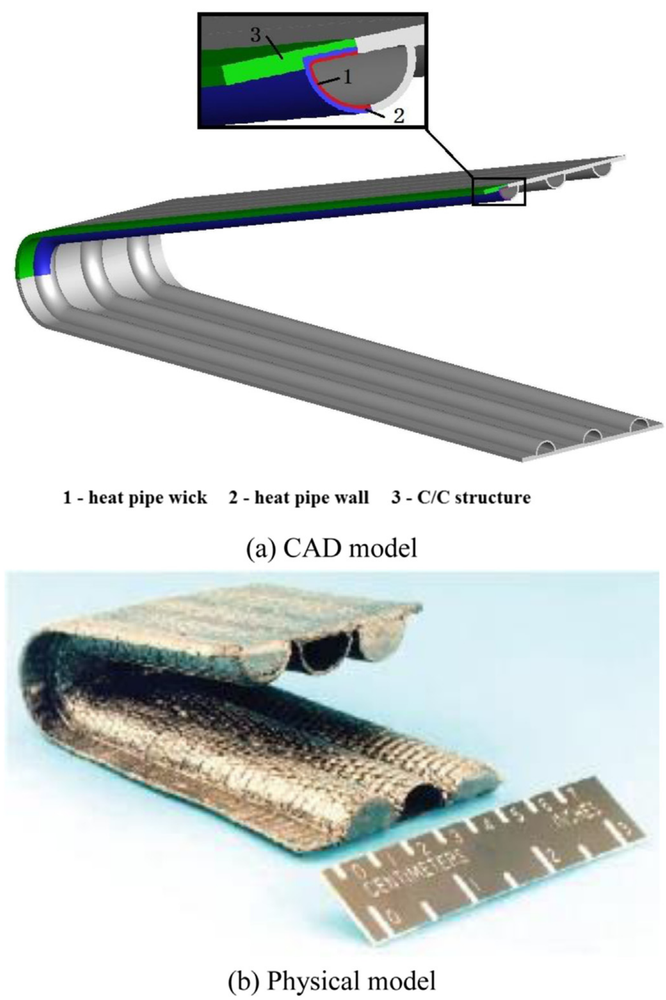

Fig. 1. The model of the HPC TPS.

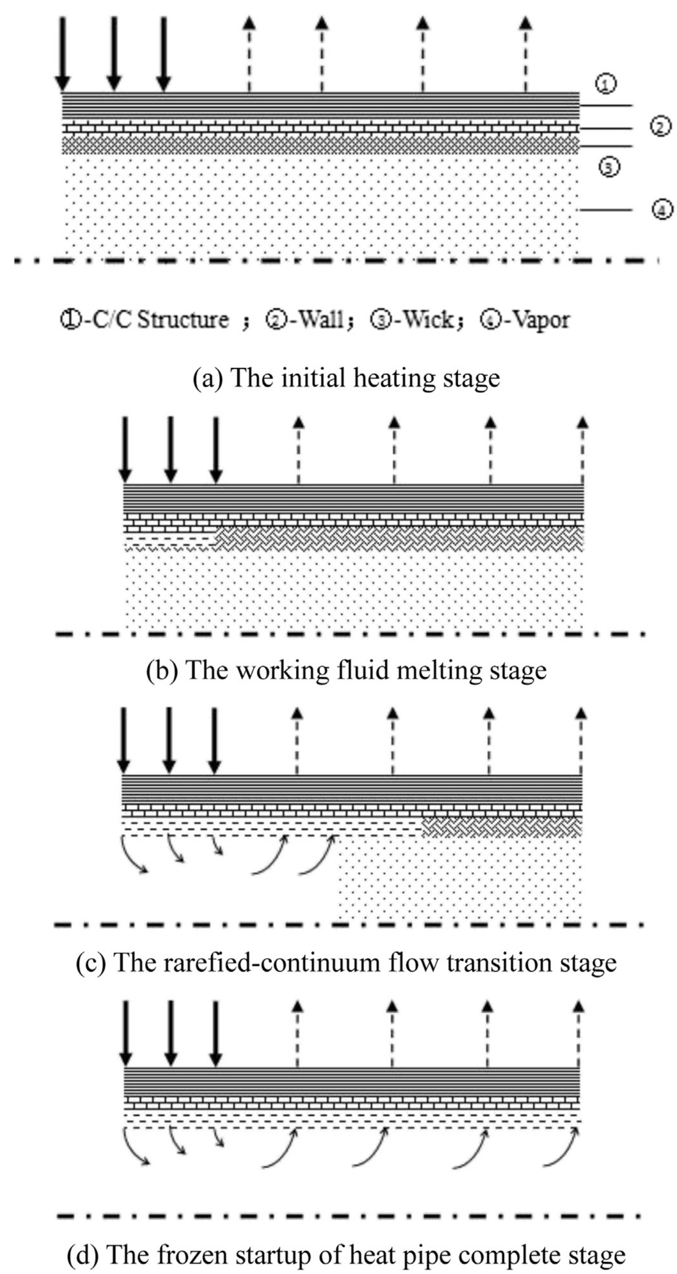

Fig. 2. The heat pipe startup process.