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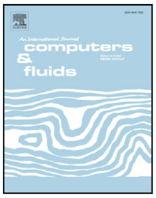

Chemically reacting hypersonic flows over 3D cavities: Flowfield structure characterisation

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ABSTRACT

In this paper, a computational investigation of hypersonic rarefied gas flows in the transitional flow regime over 3D cavities is carried out by using the direct simulation Monte Carlo method. Such cavities give rise to geometric discontinuities that are often present at the surface of reentry vehicles. This work is focused on the flowfield structure characterisation under a rarefied environment and in the presence of chemical reactions. The cavities are investigated with different length-to-depth ratios, and the different flow structures are studied. In particular, for length-to-depth ratios of 1 and 2, a single recirculation is observed inside the cavities and the main flow is not able to enter the cavity due to the recirculation structure and high particle density. In the case of length-to-depth ratio 3, the flow is able to partially enter the cavity resulting in an elongated recirculation and the beginning of a secondary recirculation core is noticed. For the case of values 4 and 5, the main flow is able to penetrate deeper into the cavities and two recirculation zones are observed; however, for the length-to-depth ratio 5 the flow impinges directly on the bottom surface, which is a behaviour that is only observed in the continuum regime with a cavity length-to-depth ratio greater than 14.

1. Introduction

Space vehicles reentering the Earth's atmosphere may achieve speeds of tens of km/s. In order to slow down and reach landing speed, the spacecraft experiences atmospheric friction effects which produce external surface temperatures as high as 1700 K, well above the melting point of steel. Although such hypersonic vehicles are built with advanced materials and methods, the airframe is constructed using lightweight aluminium and can only withstand temperatures ranging from 750 to 900 K without annealing or softening. In this scenario, reliable heat shields are required to protect the vehicle's surface and its crew from the extremely hostile re-entry environment [1,2].

External insulation materials such as Reinforced Carbon-Carbon (RCC), Low- and High-Temperature Reusable Surface Insulation tiles (LRSI and HRSI, respectively), and Felt Reusable Surface Insulation (FRSI) blankets have been developed for such applications [3]. These materials are bonded to a substrate, either directly to the airframe or to a supporting structure. For the Space Shuttle's development flights, more than 32,000 individual thermal protections system (TPS) tiles were used to cover the lower and upper surfaces. The tiles were arranged in a staggered or aligned pattern on the spacecraft surface and this can create numerous panel-to-panel joints. As such, cavities, gaps, and steps are often present on the surface of the aerospace vehicle. The implications for engineering and design requirements include the ability to account for thermal expansion and contraction of non-similar materials. In addition, gaps may be introduced by sensor installations, retro-propulsion systems, parachute and landing gears bays, or may be caused by the impact of orbiting debris or near field experiments [4–7]. These discontinuities at the TPS can lead to the appearance of stagnation points, hot spots, flow separation and attachment or it may induce an early boundary layer transition from a laminar to turbulent conditions [8,9] (see Fig. 1).

Many experimental and numerical studies have been carried out to define and develop new materials for reusable thermal protections system that could withstand the harsh reentry environment and to accurately predict the required spacing between the TPS tiles [10–28]. Based on the available literature [19–21,25,29], high speed flows over cavities may be classified into four types. These four types, as shown in Fig. 2, appear to be primarily a function of the cavity length-to-depth ratio as briefly described below:

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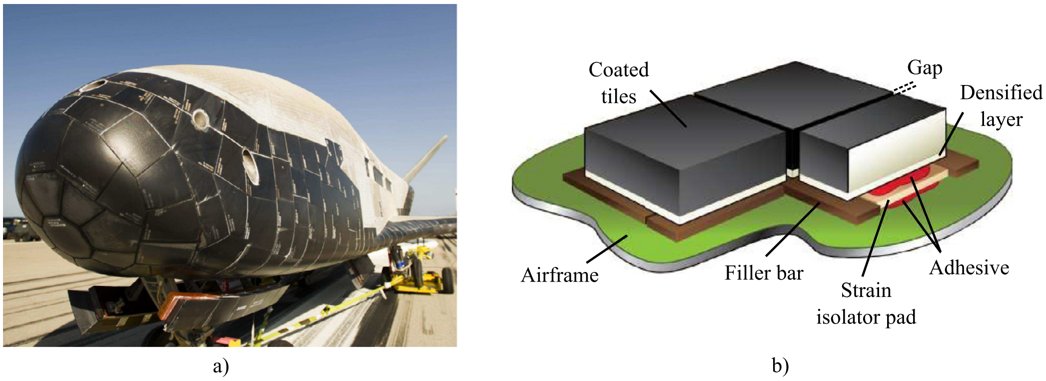
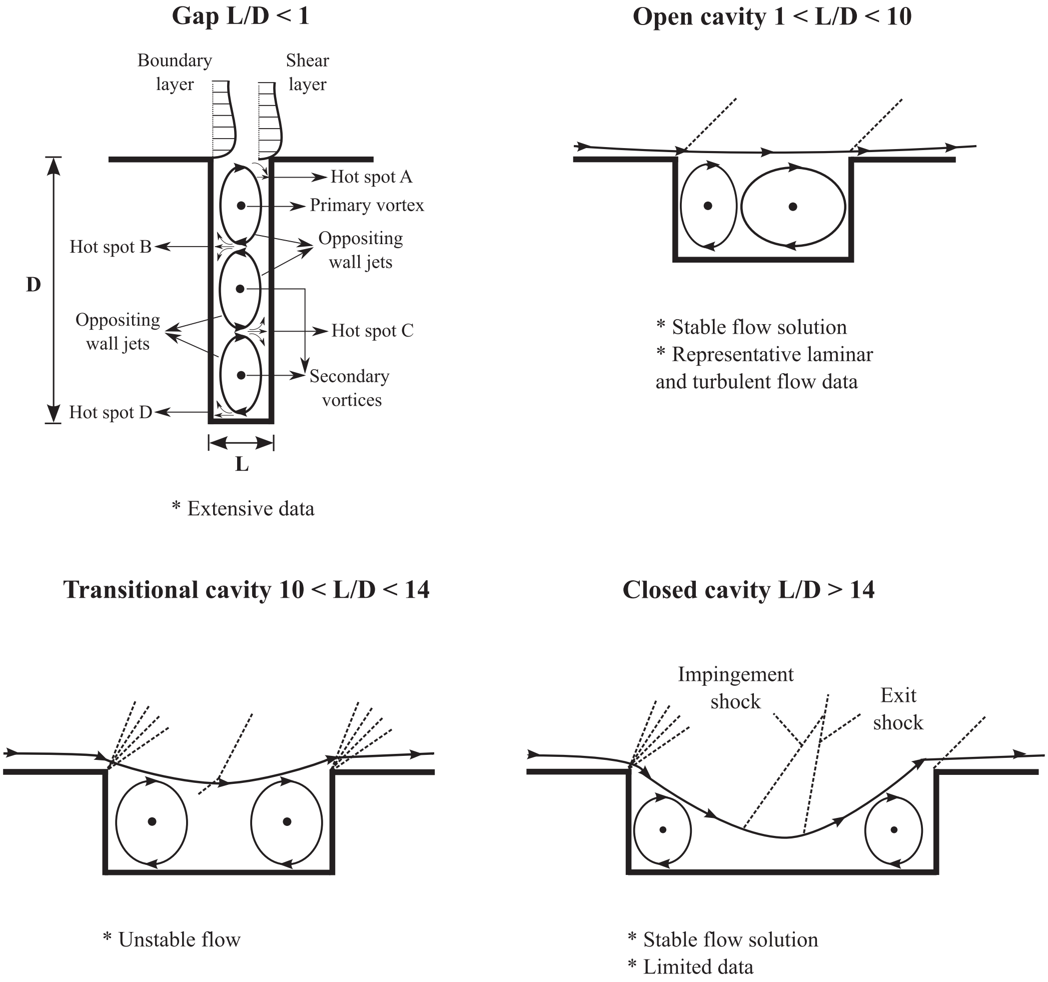


a) b)

Fig. 1. (a) X-37B space plane, (b) thermal protection system airframe (images credit: NASA).


Gap L/D < 1

Open cavity 1 < L/D < 10

Transitional cavity 10 < L/D < 14

Closed cavity L/D > 14

Fig. 2. Cavity flowfield structure in the continuum regime [25].

- Gap ($L/D < 1$): The first flow type occurs for very short or deep cavities. The induced shearing provokes the main flow to develop a column of counter rotating vortices inside the gap and hot spots occur when the vortices directionally align and impinge on the sidewall.
- Open cavity ($1 < L/D < 10$): The mainstream flow does not enter the cavity directly and the high pressures ahead of the rear face and low pressure region downstream of the front face cause the shear layer to flow over or bridge the cavity. A weak shock wave may be formed near the downstream lip as a result of the flow being compressed by the shear layer and heat fluxes slowly increase at this region. The pressure coefficients over the cavity floor are slightly positive and relatively uniform with a small adverse gradient occurring ahead of the rear face due the shear layer reattachment on the outer edge of this face.
- Transitional cavity ($10 < L/D < 14$): Typically characterised by unsteady flow behaviour since it alternates between an open and closed cavity. In this case, the shear layer turns through an angle to exit from the cavity coincident with the impingement shock and the exit shock collapsing into a single wave. A pressure plateau is observed in the reattachment region and a uniform pressure increase from the low values in the region aft of the front face with peak values on the rear face.
- Close cavity ($L/D > 14$): In this case, the shear layer separates from the upstream cavity lip, reattaches at some point on the cavity floor, and then separates again before reaching the cav-