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Set up of an experimental protocol for the investigation of graphite combustion in supersonic flow

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ABSTRACT

The paper reports on the set up of an experimental protocol for the investigation of high temperature ($1200\,^{\circ}C < T < 2200\,^{\circ}C$) graphite combustion in supersonic flow conditions. Cylindrical graphite specimens (3 mm D, 100 mm L) are exposed to supersonic flow of nitrogen/oxygen mixtures in a small Planetary Entry Simulator, equipped with a plasma torch. The impact of the gas flow on the specimen determines a very sharp temperature rise. A fast IR camera allows to realize two-dimensional maps of the specimen temperature throughout the experiment. IR thermal images can also be of help to rebuild the consumption of the graphite rod. Results are checked against the sample weight loss and used to estimate the rate of carbon combustion as a function of temperature and reaction time.

1. Introduction

High temperature combustion of graphite has been the subject of extensive investigation. Graphite represents to some extent a reference "surrogate" material for the characterization of oxidation chemistry of a broader class of carbon materials (coals, cokes) relevant to energy conversion. In a different context, coupling between high temperature ablation/oxidation and supersonic flow is brought about by the assessment of graphite and carbon–carbon composites performance as heat shields in aerospace applications [1]. The complexity of the heterogeneous reactions of carbon with oxygen at very high temperature is combined here with the understanding of chemical reactions in the gas-phase and the description of the fluid dynamics of supersonic flows.

Despite extensive research work has been carried out in this field over several decades, there are still many unresolved (or poorly understood) aspects of the heterogeneous oxidation of graphite in supersonic flows. As far as the chemical pathway of carbon oxidation is concerned, aspects deserving investigation are:

(a) The detailed chemical mechanism underlying heterogeneous oxidation of carbon. In particular, the relative importance of reactions involving molecular vs. atomic oxygen, and the coupling of this aspect with the nature of active sites, of surface complexes, of gaseous products of desorption. Moreover, the role of carbon nitridation deserves investigation. The whole subject has been extensively surveyed by Park [2].
(b) The role of gas-phase chemistry and more specifically of CO oxidation in the boundary layer and the establishment of detached or attached flames. This subject has been extensively investigated and surveyed by Makino and coworkers [3,4].
(c) The role of temperature-induced solid-state transformations of carbon (thermal annealing) and their relevance to carbon oxyreactivity. This issue was first highlighted by Nagle and Strickland-Constable [5] who demonstrated the "negative temperature coefficient". This aspect has recently risen to renewed interest for its relevance to the development of coal gasification and low-NOx combustion technologies [6–9].
(d) The occurrence of carbon fragmentation as a result of uneven heterogeneous combustion [10], thermal shock [11,12] and/or of percolative collapse of the carbon structure [13,14].
(e) The assessment of transport phenomena, relevant to diffusion-controlled combustion (typically associated with temperatures $900\,^{\circ}C < T < 2200\,^{\circ}C$ [15]).

The present paper presents the preliminary results obtained by the joint activity of two research groups, committed respectively to solid fuel combustion and to aerospace engineering. The activity aimed at developing and testing an experimental protocol for the investigation of graphite combustion in supersonic flows of nitrogen/oxygen mixtures.

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Nomenclature

α_I	mass fraction of species i	$\dot{m}_w$	water mass flow rate (kg/s) (t: torch; n: nozzle)
C_p	specific heat value (J/kg K) (g: gas; w: water)	M	Mach number
ΔT_n	temperature difference of the nozzle cooling system	p_{ne}	static pressure at the exit section of the nozzle
ΔT_t	temperature difference of the torch cooling system	p_{ts}	pressure in the test chamber
$\overline{H}_0$	mean total specific enthalpy at the nozzle exit (MJ/kg)	P_I	impact pressure
H_w	enthalpy at the specimen wall (J/kg)	q	heat transfer rate (W/m$^{(2)}$)
I	electric current (A)	T	water cooling of the torch and supersonic nozzle
$\dot{m}_g$	gas mass flow rate (g/s)	V	voltage (V)

2. 2. Experimental apparatus and procedure

2.1. Experimental apparatus

Experiments have been carried out in the small arc wind tunnel SPES (Fig. 1) at the Aerospace Laboratory of the Department of Industrial Engineering in Naples. SPES (Small Planetary Entry Simulator) is a continuous, open circuit arc-driven wind tunnel. Its main components are [16]:

1. An electric arc-heater (industrial plasma torch, Sulzer-Metco 9-MB, with arc swirl stabilization), operating with pure inert gases (argon, nitrogen, helium and their mixtures). Maximum power is 60 kW.
2. A mixing chamber, where the nitrogen plasma can be mixed with cold gases (oxygen, carbon dioxide and others) to simulate planetary atmospheres with different compositions.
3. Conical nozzles with different area ratio (4,20,56) for operations in supersonic and hypersonic regimes.
4. A cylindrical vacuum test chamber (minimum pressure of 50 Pa about).
5. A data acquisition and control system and a software for monitoring the tests on line, allowing remote operations in the test chamber.

This facility has been utilized for hypersonic aerodynamic studies and for aerothermodynamic characterization of different thermal protection materials, including new classes of Ultra High Temperature Ceramics [17–19].

For the present experimental campaign a sample holder in stainless steel with ceramic coating was purposely realized in order to hold a cylinder-shaped specimen in the middle of the supersonic jet, as shown in Fig. 2. Specimens used in the experiments were cylindrical rods of synthetic graphite with 3 mm diameter and 100 mm length.

The apparatus was further equipped with an Infratherm two colour Pyrometer and an IR Thermocamera. The FLIR Phoenix IR thermocamera with digital acquisition system and spectral sensitivity in the range 1.5–5 μm was employed to monitor the evolution of the graphite specimen, obtaining simultaneously its temperature profile, while eliminating the gas contribution.

2.2. Experimental procedure

During the tests the following parameters were continuously recorded:

- the mass flow rate of nitrogen and oxygen ($\dot{m}_g$ (g/s))
- the electric current (I (A)) and voltage (V (V)) at the arc
- the mass flow rate ($\dot{m}_w$ (kg/s)) and inlet and outlet temperatures (T (°C)) of the water cooling the torch and the supersonic nozzle
- the static pressure in the exit section of the nozzle (p_{ne}) and in the test chamber (p_{ts})
- temperature profiles within the graphite specimen

Before combustion, the rods were exposed to a supersonic flow in 100% nitrogen for 120 s to release any residual volatile matter. Then the gas was switched to 21% oxygen–79% nitrogen. The mass of the sample and its length were measured at given reaction time intervals, by retrieving the specimens from the reaction chamber.

3. Analysis of experimental results

3.1. Thermo-fluid dynamic parameters

For a given mass flow rate and electrical power to the arc, the flow is completely characterized by its averaged specific total enthalpy at the nozzle exit. It can be estimated by means of the energy balance between the energy supplied to the gas by the arc heater and the energy losses through the cooling system:

$$\overline{H}_0 = \frac{V * I + c_{pg} \cdot \left(T_{fg} - T_g^i\right) \cdot \dot{m}_g - c_{pw} \cdot \Delta T_t \cdot \dot{m}_{wt} - c_{pw} \cdot \Delta T_n \cdot \dot{m}_{wn}}{\dot{m}_g} \tag{1}$$

In Eq. (1) $\overline{H}_0$ is the average total specific enthalpy at the nozzle exit (MJ/kg), VI is the electric power supplied to the gas by the arc heater

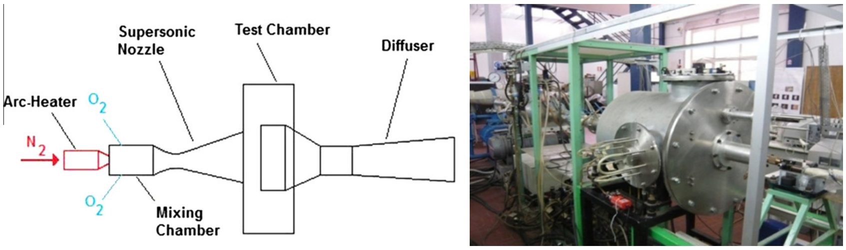

Fig. 1. Planetary entry simulator.