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Application of high-power plasma gun for thermal cycle testing of refractory foams

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Abstract

A high-power hollow-cathode plasma-gun was utilized to perform durability tests of advanced silicon carbide (SiC) foam materials under extreme thermal cyclic loading conditions. SiC-foam is a primary candidate for in-cylinder thermal regenerators in diesel engines. The SiC regenerator would be exposed to rapid thermal cycling by alternating hot ($\sim 700^\circ$C) and cold ($\sim 50^\circ$C) gases with cycling rates ranging between 3 and 50 Hz and with flow rates of 0.1–0.3 l/cycle at gas pressures between 1 and 2 atm. Simulation of these conditions outside a combustion engine would require an elaborate experimental setup capable of alternating flow between hot and cold gas reservoirs. Furthermore, a high-temperature rapid gas flow switching system would have to be developed. Instead, a high power plasma gun was used to deliver the required hot working gas at a flow rate of 60 l/min and at a pressure of ~ 2 atm. Instead of an elaborate gas flow switching system an electrically driven open flathead engine was used to alternate between the cold and hot gases at frequencies of up to 5 Hz. The plasma gun was found to be a highly economical system for delivering hot argon gases at necessary flow rates of 0.25 l/cycle. A description of the experimental setup using the high-power plasma gun is given and representative results of the SiC-foam thermal cycling performance are reported.

Keywords: High-power plasma torch; Ceramic foam; SiC-foam; Regenerator; Thermal cycling

1. Introduction

Plasma torch have been used for many decades to deposit thermal barrier coatings (TBC) on a variety of substrates [1–3]. However, in recent years plasma torch have also become valuable and indispensable research tools when high-temperature gases are required. For example, plasma torch have been developed for the efficient decomposition of exhaust gases to reduce NO_x emission [4] or to treat CO_2 gases for reduction of greenhouse gases [5]. Recently, plasma source have been used for qualification of thermal protection materials for atmospheric reentry vehicles [6]. Plasmatrons have also been tested for hydrogen generation units to facilitate conversion of a wide range of hydrocarbons fuels into hydrogen-rich gases on board a vehicle [7].

In this paper we report on the application of a high power plasma jet for testing of thermo-mechanical properties of refractory foam structures, such as silicon carbide (SiC) or niobium foams.

Improvements in the cycle efficiency of diesel engines have been an active area of engineering

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investigations over the years, because of the enormous potential payoff. In this concept, nearly all of the working fluid is subjected to a regenerated cycle, which adds and removes the heat at near optimum conditions during the cycle. A newly developed ceramic foam-based thermal regenerator was selected as a candidate material for such a regenerator designs. The SiC-foam structure must survive high-rate cyclic thermal, inertial, and pressure loads (3–50 Hz). These cyclic loads are caused by combustion gases, which are forced through the open pores of the SiC-foam at high pressure ($\sim$2 atm) and at frequencies of $<$50 Hz. Typical combustion gas temperatures range between 500°C and 700°C, while the cold fuel–air mixture gases are introduced at about 50°C. The accumulation of fatigue damage due to alternating hot and cold gases may limit the maximum number of cycles or the maximum temperature drop across the foam.

The high-power vortex-stabilized plasma jet selected for testing SiC-foam was developed at the Osaka University for improved TBC [1]. Fig. 1 shows a schematic of the vortex-stabilized plasma torch. The plasma torch is a hollow cathode type, which allows the injection of powders along the centerline of the gun. The plasma gases enter the vortex-stabilized plasma torch, which can be operated at a maximum of 300 kW power, however, for these tests the maximum power used was 100 kW. The use of this high-power plasma jet for testing the effects of thermal cyclic loads on SiC-foams is reported here. The experimental apparatus is described and a sample SiC-foam test result is given. It is found that the resistance of SiC-foams to thermal cyclic loads is primarily a function of the gas temperature difference across the foam and not the cycling rate. Failure of SiC-foam occurred at top-bottom gas temperature differences above 400–500°C.

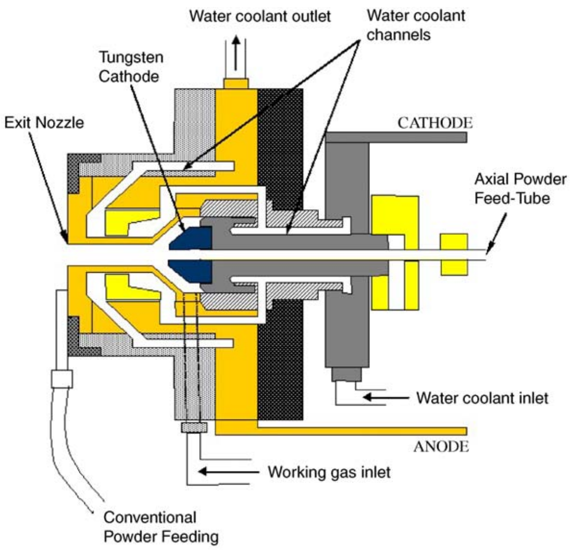

Fig. 1. Cross-sectional view of the hollow-cathode plasma torch [2].

2. Experimental setup

Testing of the SiC-foam-based regenerator (Fig. 2) requires (1) a large reservoir of hot gases ($\sim$700°C) at high pressures ($\sim$2 atm) and (2) a gas delivery system capable of switching between hot and cold gases at high frequencies. Such a system would be very costly, because the entire hot gas reservoir, the delivery system, and the switching

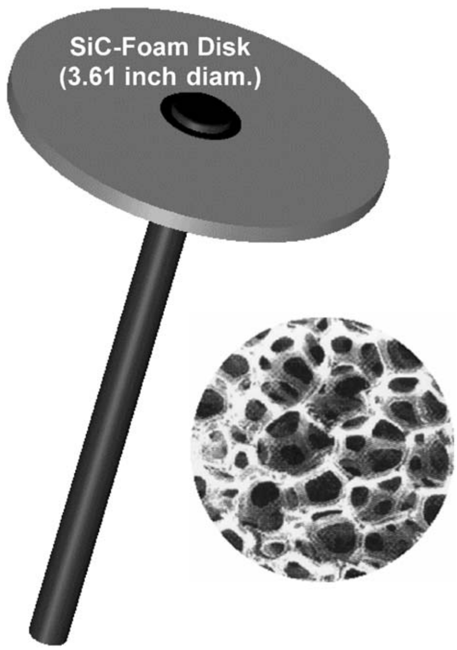

Fig. 2. SiC regenerator assembly.

mechanism would have to withstand operating temperatures of above 700°C at high pressures.

Instead, using a high-power plasma torch a unique test apparatus was designed and developed at the Mechanical and Aerospace Engineering Department of University of California Los Angeles in collaboration with the Joining and Welding Research Institute of Osaka University. Fig. 3 shows the schematic of the thermal cycling apparatus for testing SiC-foam-based regenerators. The SiC-foam sample is placed inside an open graphite cylinder head of a 1951 Flathead Ford 4 stroke engine. The plasma torch is positioned above the SiC-foam sample. The engine is driven by an electric motor. As the engine rotates, the piston sucks hot plasma gases through the SiC-foam during the first stroke. When the piston moves up the valves will close during the second stroke. The hot gases inside the cylinder are exhausted and replaced with cold air during the third stroke. The fourth stroke then pushed the cold air upwards through the SiC-foam, thus hot and cold gases are alternately forced through the SiC-foam sample. The temperature of the hot gas entering the test sample can be controlled by adjusting the distance between the plasma torch exhaust nozzle and the SiC-foam disk.

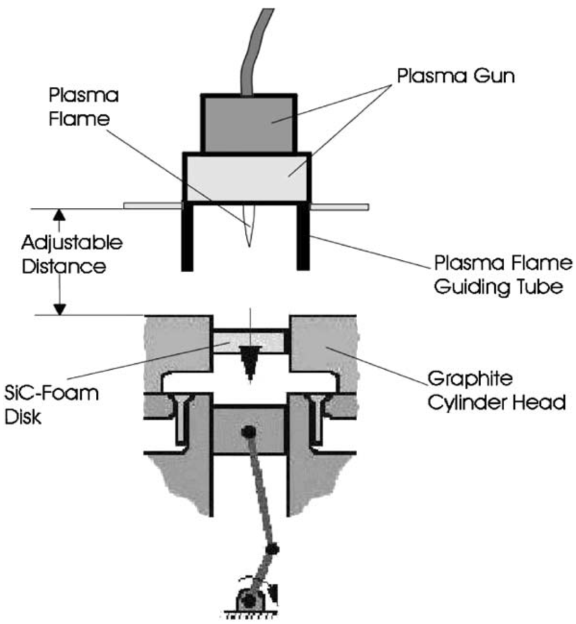

Fig. 3. Schematic of the thermal cycling apparatus for testing SiC-foam-based regenerators.

Several candidate hot and cold gas sources were investigated, and it was found that a high-power (100A) plasma jet could efficiently and continuously deliver high temperature (T_{max} $\sim$1200°C) gases at the required 1–2 atm pressures. Details of the high-power plasma torch are described elsewhere [1,8]. Furthermore, the plasma jet produced hot argon gas at a flow rate of $\sim$60 l/min, which sufficient for test a full-size regenerator disk instead of resorting to small SiC-foam samples. Thus, the plasma gun not only provided the necessary testing conditions outside a combustion engine, it facilitated testing of a full mock-up of the regenerator assembly. The high-power plasma gun serves as an efficient source of hot gas with room temperature air serving as the cold gas source. The gas delivery system consisted of an electrically powered flat-head Ford engine with the regenerator mounted inside an open cylinder of engine. The valve system of the flat-head engine served as the switching mechanism between hot and cold gases.

The thermal cycle test apparatus is shown in Fig. 4. It consists of a high-power plasma gun developed at Osaka University [1]; a 1951 Flathead Ford Engine driven by an electric motor (7.5 Hp;

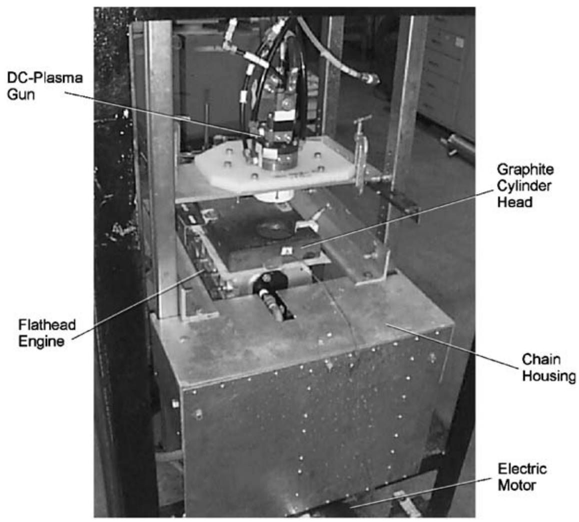

Fig. 4. Thermal cycle testing facility for high cycle testing of refractory open cell foam.

at 1000 ± 10 rpm), a graphite cylinder head and a data acquisition system to record temperatures. The original cylinder head was replaced by a low thermal-expansion coefficient graphite block, which houses the regenerator assembly. The graphite cylinder head was CVD coated with an oxidation resistant SiC layer. The motor was directly coupled to the crankshaft of the engine via a chain and sprocket. The four stroke engine forces alternating hot argon gas and cold room temperature air through the regenerator. Adjusting the distance between the plasmatron exhaust nozzle and the SiC-foam disk can control the temperature of the hot gas entering the test sample. Several thermo-couples were mounted to monitor the gas temperature above, below, and inside the SiC-foam.

3. SiC foam test results

Fig. 5 shows a typical temperature history during thermal cycling of a SiC-foam disk with 100 ppi (pores per inch), a density of 30%, and a thickness of 0.394 in. The plasma torch exit nozzle was moved to 14.5 cm above the SiC-foam surface. The plasmatron was turned on at 25 s into the experiment, which resulted in a rapid increase of the plasmatron exhaust centerline above the SiC-foam from room temperature to an average high temperature of 525°C.

Up until about 47 s into the experiment no cycling of cold and hot gases has commenced. Therefore, the SiC-foam bottom surface temperature starts to rise slowly to a height of about 170°C at 47 s. The flat-head engine is now turned on ($t = 47$ s, cycle frequency 4 Hz) and the cycling of cold air and hot argon begins. The plasmatron exhaust temperature on the SiC-foam surface starts to drop immediately, because of mixing of cold air with the hot plasma flame to about 470°C. Simultaneously, the bottom surface of the foam starts to heat up because the hot argon gas is sucked through the SiC-foam. Once the bottom SiC-foam surface reached 210°C the flat-head engine is turned off and the surface of the SiC-foam starts to heat up rapidly, because cooling by the room temperature air has been cut off. The plasmatron is then turned off as soon as the SiC-foam surface temperature exceeds 560°C, and both

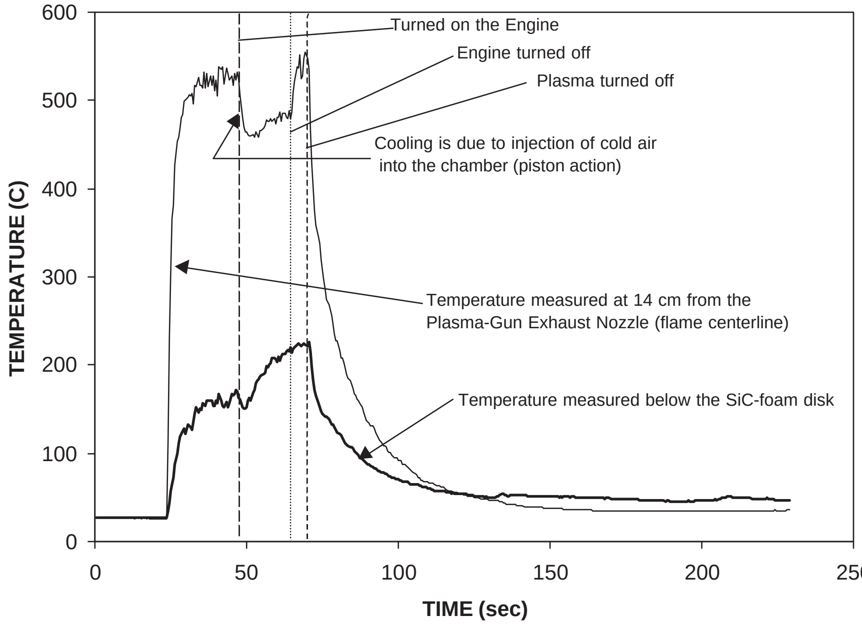

Fig. 5. Gas temperature directly above and below the SiC-foam disk during thermal fatigue cycling operation.

the front and the back of the SiC-foam cool down to almost room temperature at 150 s. SiC-foam disks, which experienced temperature gradients above 805°C/cm failed catastrophically, while all other foam samples survived similar thermal cycling loads.

By varying the plasma torch distance the gas temperature above the SiC-foam disk was modified between 300°C and 1000°C. Table 1 summarizes the results of the 21 thermal cycling runs. Temperature gradients across the SiC-foam ranged between 142°C/cm and 1217°C/cm at a maximum cyclic rate of 4 Hz.

Fig. 6 summarizes the measured temperature drops across the SiC-foam disks at failure. Based on the average temperature gradient of failure of 1918°C/in (755°C/cm), the order of maximum allowable thermal stress can be estimated using a simplified thermal stress formulation ($\sigma_{th} = E\alpha\Delta T$; where E is the Young's modulus, α is the thermal expansion coefficient, and ΔT is the through-the-thickness temperature drop). The key parameters are the Young's modulus and the expansion coefficient. The Young's modulus of SiC-foam was shown to have two distinct regions: a pre-damaged ($E1$) and a damaged ($E2$) Young's modulus [9]. The reason is that ceramic foams tend to undergo a significant initial amount of damage (ligament failure) at the onset of loads above that

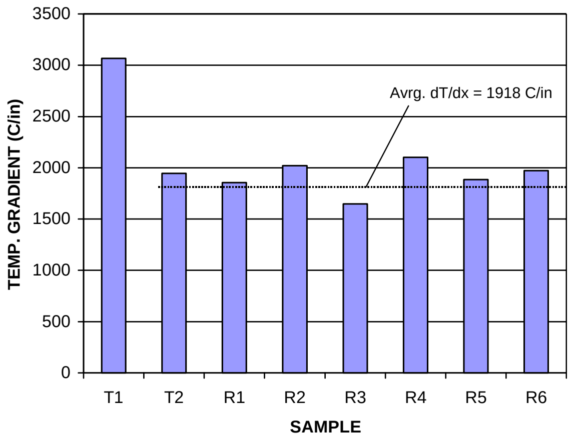

Fig. 6. Measured temperature drop across the SiC-foam disk samples at failure.

Table 1
Summary of SiC-foam thermal cycle test measurements

Run #	Sample #	Sample failure	Delta temp. (°C)	Temp. above SiC-foam (°C)	Temp. below SiC-foam (°C)
1	T1	No	98	199	101
2	T1	No	—	—	—
3	T1	No	—	—	—
4	T1	No	164	232	68
5	T1	No	641	854	213
6	T1	Yes	840	981	141
7	T2	Yes	574	651	77
8	R1	Yes	484	599	115
9	R2	Yes	574	651	77
10	R3	No	477	684	207
11	R3	Yes	476	683	207
12	R4	No	225	383	158
13	R4	No	231	390	159
14	R4	No	386	598	212
15	R4	Yes	574	765	191
16	R5	No	198	348	151
17	R5	No	261	447	185
18	R5	Yes	546	695	149
19	R6	No	160	513	353
20	R6	No	210	686	477
21	R6	Yes	582	939	358

of individual ligament strength. The damaged ligaments create a network of failed but interlocking ligaments, which increases the Young's modulus from the pre-damaged 50 ksi to about 200 ksi for the damaged SiC-foam [9]. Although the Young's modulus measurements were made at room temperature it is assumed that they hold at elevated temperatures ($<1500^\circ$C). Taking a thermal expansion coefficient equal to that of CVD SiC ($4.5 \times 10^{-6}/^\circ$C) the pre-damaged thermal stress of SiC-foam (100 ppi; 30% dense) is estimated to be of the order of 0.17 ksi and that of a "damaged" SiC-foam is of the order of 0.679 ksi.

The estimated thermal stress limits for SiC-foam are about 1 order of magnitude lower than the crush strength, which was measured between 1 and 3 ksi [9]. These test results indicate that thermal stresses are the limiting factor for SiC-foam regenerators, when compared with inertial load induced stresses.

4. Conclusions

A high-power vortex stabilized plasma jet was successfully applied to thermal cyclic testing of SiC-foam regenerator assemblies. The plasma gun was run at 100 A with a flow rate of 60 l/m of argon. Hot (300–1000°C argon) and cold (room temperature air) gases were alternated (pulled and pushed) through the open pore SiC-foam at a cycling rate of 4 Hz using a motor-driven 1951 Ford Flathead engine. Temperature measurements indicate that the SiC-foam was subject to alternating temperature gradients as large as 1217°C/cm. Failure of the SiC-foams occurred at an average temperature gradient above 755°C/cm through the foam. This experiment identified the plasmatron to be a viable source for high-temperature gases for conducting high rate thermal cycling behavior of open pore ceramic and refractory foam structures.

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