Experimental Facility for Thermal Cycle Testing of Refractory Foams using Plasmatron Technology

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ABSTRACT

Refractory foam materials, such as silicon carbide, tungsten, or niobium are a new class of materials. Because testing tools and testing methodology for these foam materials have not yet been fully develop only few thermo-mechanical properties have been quantified. Here we report on the development of a high cycle thermo-mechanical fatigue testing apparatus using a plasmatron specifically designed for testing refractory foam materials. The facility was used to measure thermo-mechanical response of SiC foams to high cyclic thermal fatigue tests. It is found that SiC foams containing 130 ppi and a density of 30% are resistant to high cycle thermal fatigue damage as long as the temperature gradient across the foam structure does not exceed 1900^{o}C/in.

KEYWORDS: Silicon Carbide Foam, Refractory Foam, Thermal Cycling, Plasmatron.

1 INTRODUCTION

Increases in thermal efficiency of Diesel engines by as much as 20% have been estimated with the use of in-cylinder thermal regeneration [1]. Figure 1 depicts the schematic of the in-cylinder regenerator concept. The primary function of the regenerator is to absorb part of the exhaust thermal energy and then to release it by preheating the combustion gases, which results in combustion flames at higher compression ratios. The regenerator material is subjected to oscillating inertial loads, pressure, and temperature transients, which must tested for high reliability. Silicon carbide foam materials have been suggested as a primary candidate for in-cylinder regenerators. Figure 2 shows a solid model of a typical regenerator assembly with a cut in micrograph of refractory foam material.

These in-cylinder regenerators require extensive testing of thermo-mechanical response. A thermo-mechanical simulation facility was designed and constructed at the University of California Los Angeles (UCLA) with the collaboration of the Osaka University's Joining and Welding Research Institute to test the response of SiC foam materials to the rapid thermal cycling loads. The thermal cycle testing facility utilizes a high-power vortex-stabilized plasmatron and a 1951 Flathead 6-cylinder Ford engine.

Thermal cycling of the regenerator is associated with the accumulation of fatigue damage, which may limit the maximum number of cycles or the maximum temperature drop across the regenerator. The effects of thermal cyclic loads on the durability of sub-scale, in-cylinder thermal-regenerator assemblies were assessed experimentally and are described in this report. Details of the experimental set up given along with several SiC foam test results, which indicate that SiC foam can withstand high rate thermal cycling as long as the temperature drop across the SiC foam sample does not exceed 800^{o}C.

2 EXPERIMENTAL SETUP

A schematic of the experimental set up is given in Fig. 3 and Fig. 4 shows the UCLA/Osaka-JWRI testing facility. The test apparatus consists of four subsystems, which are the (1) test engine, (2) plasmatron, (3) electric drive motor, and (4) instrumented cylinder head.

2.1 Test Engine

The test engine is a 1951 Ford Flathead straight six. The Flathead valve arrangement simulates correctly the gas flow sequence of the regenerative Diesel engine. The Flathead engine serves as high speed switching mechanism for flowing alternating hot (<1000^{o}C) and cold gases through the regenerator foam. The engine is driven by a 7.5 hp electric motor. Figure 5 shows the schematic of the driven valve system for achieving high thermal fatigue loading conditions on the SiC foam disk. As the piston moves down during the combustion stroke, the piston pulls the hot plasma gases through the SiC foam. The hot gases are exhausted during the exhaust stroke, which is followed by the intake stroke, which fills the area underneath the SiC foam with cold air. During the compression stroke the cold air is pushed through the hot SiC foam. This maximum speed of the four stroke process was clocked at 1100 +/- 10 rpm, which translates to a maximum frequency of about 18 Hz.

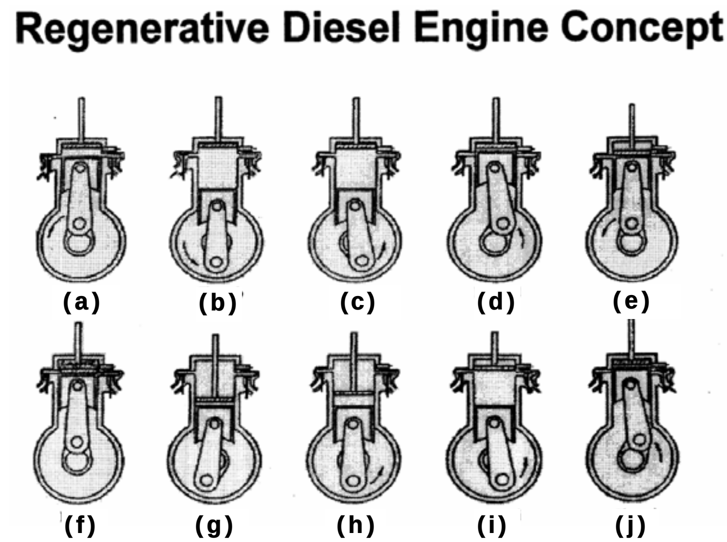

Figure 1: Schematic of the Regenerator Diesel Engine concept; (a) start of intake stroke (regenerator is at top of cylinder bore), (b) end of intake stroke, (c) beginning of compression stroke, (d) end of compression stroke, (e) beginning of combustion stroke, (f) regenerator travels downward with piston, transferring stored thermal energy into compressed air charge, fuel injection and initiation of combustion, (g) combustion stroke (piston and regenerator travel at same downward rate during combustion stroke - regenerator travels near piston crown and ahead of flame front), (h) completion of combustion stroke (regenerator begins upward travel through hot exhaust gas capturing and storing part of its thermal energy), (i) start of exhaust stroke, (j) completion of exhaust stroke (regenerator stationary at top of cylinder ready for next cycle).

2.2 High Power Plasmatron

The high-power plasmatron [2] is a two stage system, consisting of (1) a DC-Hallow Cathode plasma gun and (2) a high-power (300 kW) vortex-stabilized plasma (VSP) generator (see Fig.7). The plasma flame exiting the gun/ vortex is aimed directly at the regenerator with an adjustable plasma fame guide (Fig. 6). Previous experiments have shown that the maximum gas temperature is about 1,700 Celsius at about 15 cm from the plasmatron exit nozzle. By adjusting the height of the guide the amount of cold air entrained into the plasma flame can be varied, which changes the average temperature of the gas being pulled through the regenerator. During operation the hot argon and the cold air are alternately pulled/pushed through the regenerator.

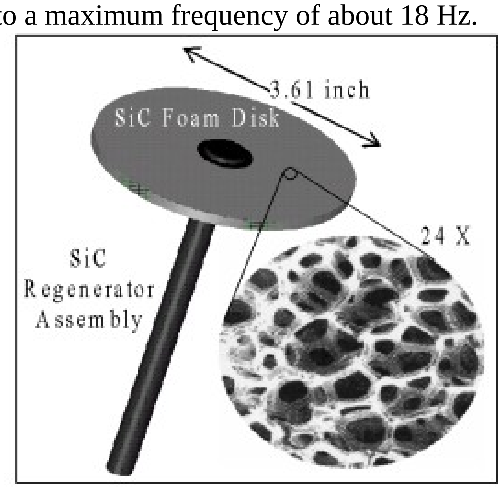

Figure 2: SiC regenerator assembly and SEM of refractory foam.

2.3 Cylinder Head

The original steel cylinder head was replaced with an instrumented cylinder head. The cylinder head is made of graphite to provide strength and temperature tolerance for the anticipated regime of the test program. A protective anti-oxidation coating (SiC) is applied to the graphite to prolong the lifetime of the cylinder head (Fig. 4). CNC equipment was utilized to machine the graphite to specifications.

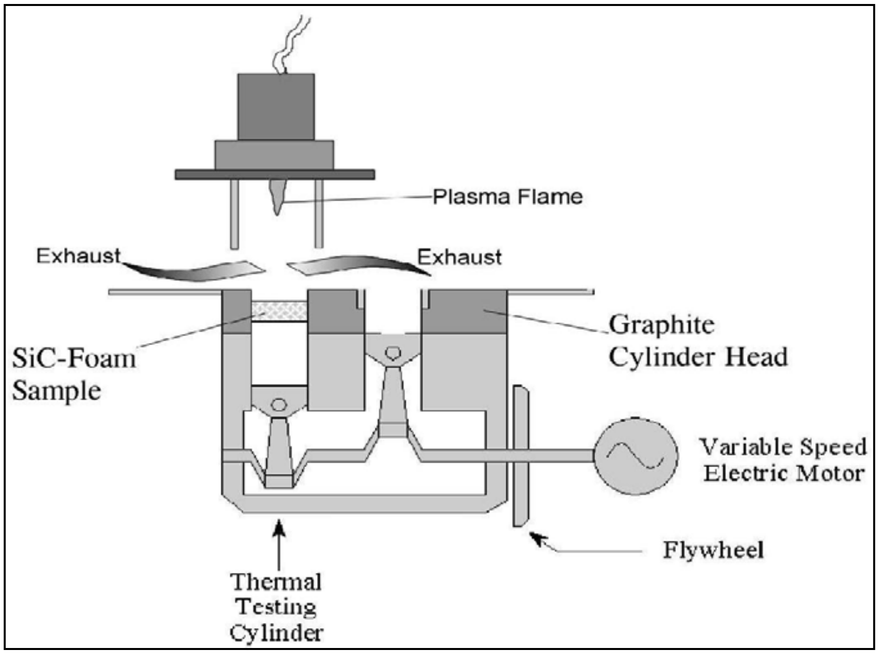

Figure 3: Schematic of foam thermal fatigue apparatus (valve system not show).

2.4 Test Matrix

A total of 8 SiC-foam disks were tested making a total of 23 runs. The disks were ground from the same batch and all had a relative density of 30% and a pore density of 130 ppi (pores per inch). Each of the disks was tested until failure (see Table 1).

Table 1: Matrix of SiC-Foam Disks for Thermal Cycle Testing

Disk	Pores Per Inch (ppi)	Relative Density (%)	Thickness (in)	Number of Test Runs
T1	130	30	0.274	6
T2	130	30	0.295	1
R1	130	30	0.261	1
R2	130	30	0.284	2
R3	130	30	0.289	3
R4	130	30	0.273	4
R5	130	30	0.290	3
R6	130	30	0.295	3

3 SiC Foam Thermal Fatigue Test Results

The instrumented cylinder head contains a number of thermocouples for measuring gas temperatures directly above and below the SiC foam samples. Typical measurements are shown in Fig. 8 with the temperature of the gas impinging on the disk reaching almost 1200^{o}C within 5 seconds of turning on the plasma gun. Contrary to the previous runs, the temperature below the disk starts to rise before the engine is switched on, because the hot gas is pushed through the disk and gradually heats up the gas inside the cylinder. As soon as the engine is switched on (see Fig. 8), the temperature of the gas above the disk drops, while that below the disk keeps rising. Steady state temperatures are reached within about 7 seconds of turning on the engine, and they are: 855^{o}C and 214^{o}C. The temperature drop across the SiC foam is ~560^{o}C, which is the largest temperature drop that did not result in fracture of the SiC foam disk.

Figure 9 shows the measurements of a test, which resulted in the failure of the SiC foam disk. The SiC-foam disk failed rather quickly once it reached maximum temperature drop of 840°C. At failure, the gas at the top of the SiC foam temperature was 981°C and below it was measured to be 141°C. The disk failed by splitting into two halves.

Except for the first sample, which was first exposed to flow of hot gases parallel to the disk, all other samples failed at a temperature gradient of around 1918°C/in. Based on the average maximum temperature gradient of 1900°C/in, we estimate the maximum allowable thermal stress for these samples to be between 0.06 ksi and 0.17 ksi. The two values are estimated using two Young's Modula, E1 for the initial and E2 for the secondary modulus [3]. The thermal stress limit for SiC-foam is about 1 order of magnitude lower than the crush strength, which was measured between 1 and 3 ksi. Therefore, our test results indicate that thermal stresses are the limiting factor for SiC foam regenerators, when compared with inertial load induced stresses.

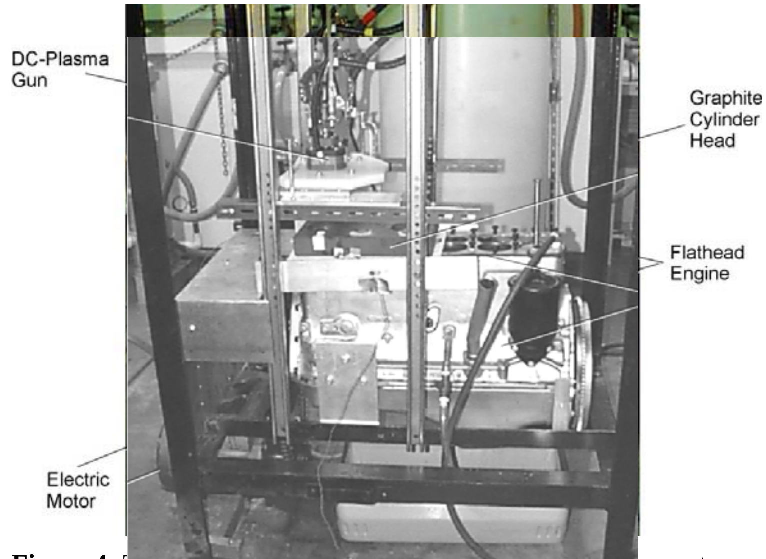

Figure 4: The UCLA/Osaka JWRI Thermal Cycle Test Apparatus.

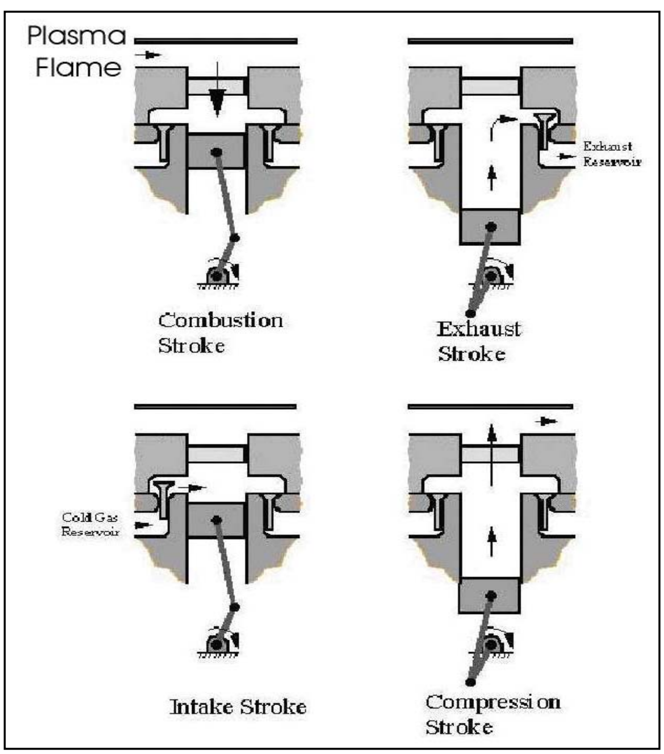

Figure 5: Schematic of the Four-Stroke Cycle alternating hot and cold gas flow through a stationary SiC foam regenerator disk.

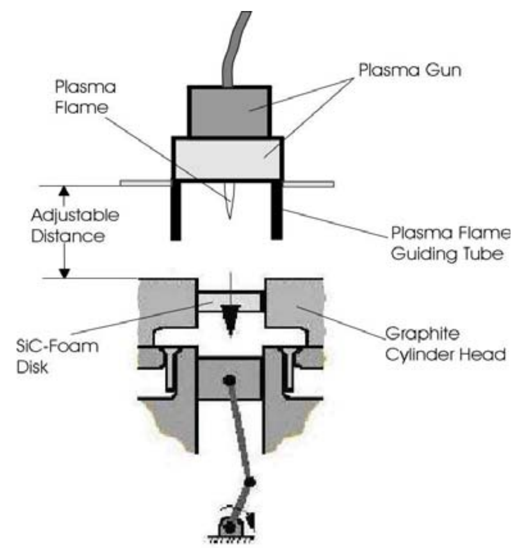

Figure 6: Schematic thermal fatigue cycle apparatus showing the plasmatron mounted above the regenerator (SiC foam) disk.

4 Conclusions

A high-power vortex stabilized plasmatron was successfully applied to thermal cyclic testing of SiC foam regenerator assemblies. The plasmatron was run at 100 A with a flow rate of 60 liter/min. Hot (300 – 1000°C) and cold (room) gases were alternated through the open pore SiC foam at a 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 3000°C/in. Failure of the SiC foams occurred at an average temperature gradient above 1900°C/in through the foam. These results indicate that plasmatrons can be readily utilized to test the thermal cycling behavior of open pore ceramic and refractory foam structures.

5 ACKNOWLEDGEMENTS

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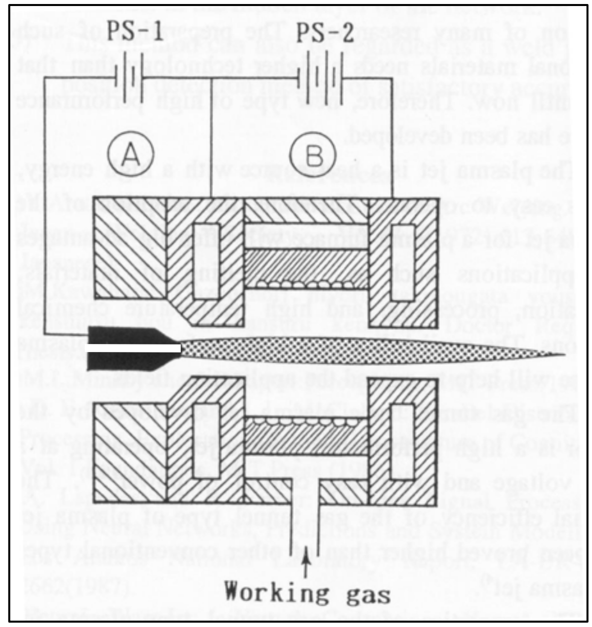

Fig. 7: Schematic diagram of the vortex-stabilized plasmatron, (A) conventional plasmatron, (B) Vortex-stabilized plasmatron. PS-1& PS-2: power supplies[2].

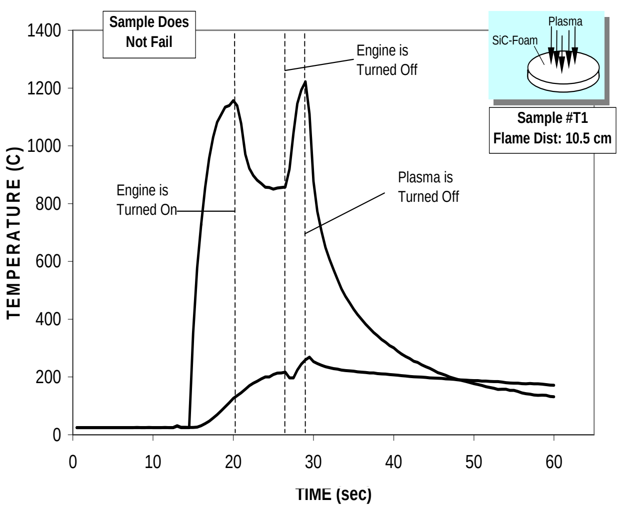

Figure 8: Measurement of gas temperatures directly above and below of the SiC-foam disk as a function of time (SiC Foam disk did not fail).

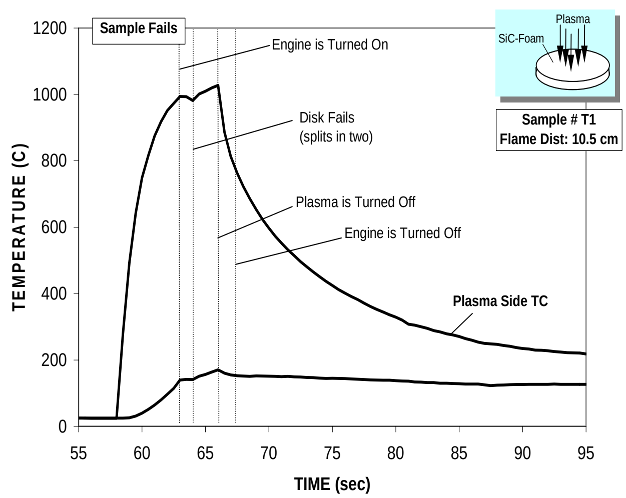

Figure 9: Measurement of gas temperatures directly above and below to the SiC-foam disk as a function of time (the SiC Foam sample failed within 15 sec).

6 REFERENCES:

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