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Thermal Shock Resistance of Multilayered Silicon Carbide Receiver Tubes for 720 ^{o}C Molten Salt Concentrating Solar Power Application

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1. Introduction

Silicon Carbide (SiC) ceramic matrix composites (CMC) are a high-temperature class of materials that have been gaining interest as a lower-cost alternative to high-temperature metallic alloys. SiC CMC materials are made up of ceramic fibers that lie in a ceramic matrix phase. Here a SiC/SiC composite is made by having a SiC matrix phase and a fiber phase incorporated together through novel processing methodologies to facilitate a strong, high-temperature bond. Additionally, these CMC tubes can be combined with an inner layer of high density monolithic SiC to assure full containment, with zero leakage, of the heat transfer fluid, whether it be high temperature molten salt, or a high temperature gas. Finally, the matrix composition and texture on the surface of the tubes can be tailored to assure very high absorptivity and low emissivity of solar radiation. These materials exhibit outstanding properties which include high thermal, mechanical and chemical stability while also providing a high strength to weight ratio, which is attractive for high-temperature concentrating solar power (CSP) receiver applications that can reach heat transfer fluid (HTF) temperatures as high as 720 °C. These CSP systems with thermal energy storage have the potential to produce emissions-free electricity for commercial grid delivery at competitive prices. The high temperature capability leads to improvement in the overall solar to electric conversion efficiency which in turn leads to competitive prices. For this investigation, Sandia National Laboratories (SNL) investigated a series of materials tests on small sections of these multilayered tubes manufactured by Ceramic Tubular Products to determine their suitability as CSP receiver tubes. Experiments included: 1. chemical compatibility with molten chloride salt at 800 °C, 2. solar absorption and emission properties, 3. mechanical shock resistance afforded by the graceful failure mode of CMC's and 4. resistance to thermal shock that will occur during weather related episodes at a CSP facility.

Testing was performed at SNL Solar Furnace facility using a dynamic stage and thermal shock tube test setup. The tubes that were placed under incident solar heat flux were heated to 800°C (or higher) and then quenched with simulated rain. The tubes were then cooled and subjected to hoop stress analysis using an Instron device to assess their subsequent mechanical strength. The preliminary results indicate an average 24.2% higher hoop stress for the CMC tubes than those composed of monolithic SiC.

2. Thermal Shock Experimental Setup

The experimental test system comprised a horizontal tube holder with a SS316 mesh basket to capture all pieces of the tubes that shattered under incident high-flux. The tube holder assembly comprised several thermocouples that were positioned within each respective tested tube to measure axial thermal distributions along each tube. The initial shake-down tests with an Al_2O_3 tube determined the optimal height above the coupon needed to provide enough uniform water coverage during quenching. Initial shake-down tests helped to determine the optimal ramp and quenching rates.

An IR camera was used to assess thermal distributions across the sample for use in post-test stress analysis. Before and after each respective test, sub-millimeter scale geometrical measurements, as well as optical measurements, were taken to assess thermal-mechanical deformation. After all post-test analyses were completed a final test was conducted to determine the maximum pressure required to induce failure. A polyethylene plug test approach [3] was used to evaluate tubes that survive thermal shock testing to understand how the thermal shock may have impacted its strength. The experimental test system comprised a single VeeJet 80100 nozzle, which was selected based on simulated rain tests by previous investigators who simulated raindrops with a diameter of approximately 2-4 mm [1,2]. The orifice diameter for this nozzle is 5.51 mm and the operating pressure was approximately 6 psi. The initial shake-down tests with an Al_2O_3 tube helped determine the optimal height above the coupon as needed to provide enough uniform water coverage during quenching. Initial shake-down tests comprised tests at varying flux and simulated rain pressure levels to determine the optimal ramp and quenching rates.

The total thermal shock test assembly was placed on top of a movable stage at the NSTTF Solar Furnace Facility which could be translated in three axes and equipped with a LabVIEW data acquisition (DAQ) system for monitoring temperatures, flux profiles and flow rates. The facility also encompassed a high-speed attenuator system to control the level of incident heat flux on to the samples, as well as a flux gauge to calibrate the flux level. The facility has a peak flux of up to 600 W/cm^2, where for these tests flux levels were only tested up to approximately 500 W/cm^2, which is characteristic of average maximum NSTTF TMY (Typical Meteorological Year) periods. For this investigation, a

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variety of thermal shock tests were performed with the tube materials listed below where geometrical and surface cracking analysis was performed before and after each respective test:

1. Aluminum Oxide – used as practice tubes during experimental setup development shake-down tests.
2. Haynes 230 – Being strongly considered for Generation 3 solar receivers.
3. Monolithic SiC Hexoloy^{TM} – used as the primary test tubes for investigation. These tests were conducted immediately following success of the shake-down experiments.
4. Composite Type 1: Nicalon CG fiber + Lancer SiOC matrix – these tubes tested as part of the primary thermal shock tests.
5. Composite Type 2: Nicalon CG fiber + Starfire SiOC matrix – these tubes tested as part of the primary thermal shock tests.

3. Thermal Shock Results & Discussion

During the thermal shock tests on-sun, all tested tubes were thermally ramped up to prescribed max temperature of 800 ºC for two minutes. This ramp time was determined from preliminary empirical tests for ensuring all tubes tested would not shatter prematurely before quenching. The preliminary results indicate that all multilayered SiC and Al_2O_3 tubes did not shatter while all monolithic SiC tubes, as well as black Al_2O_3 tubes did. As shown in Fig. 1, Composite 1 tubes were able to withstand an average 24.2% higher hoop stress than the Composite 2 tubes. Representative thermal results, indicate that although the front inner surface temperature was higher, the temperature gradients were found to be larger radially between front and back surfaces versus axially along the tubes. For each experiment, a high-temperature pyrometer (capable of temperatures of up to 975 °C) was employed for measuring temperature on the front side of the tube. Although the measured temperatures were not factored into the post-processing analysis due to rounded front surface that wasn't geometrically adequate for an accurate reading with the equipment, the results qualitatively indicated potentially very high front side temperatures, where for one of the composite tubes, extrapolated values were found to be as high as approximately 1280 °C. The flat portion of this measurement was due to temperature saturation limitations for the thermocouple device.

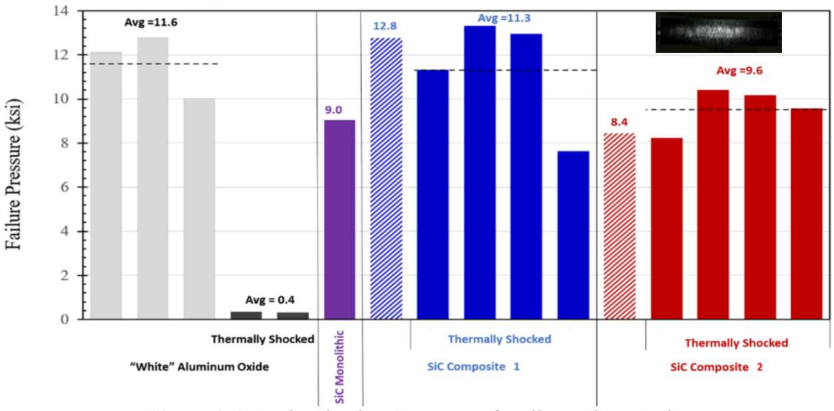

Figure 1. Data showing burst pressures for all samples tested.

4. Conclusion

A rigorous analysis was performed with monolithic, CMC and other tube materials for the development of a high-temperature CSP receiver. Results from tested thermally-shocked tubes revealed a relative difference in strength between the two sets of composite tubes. Here, the maximum compressive stress, or failure pressure, was measured with respect to the maximum induced compressive load by the Intron system. The results also indicated very low values of stress with the Al_2O_3 tubes that were painted black as compared to the white Al_2O_3 tubes. Although all of the Hexoloy^{TM}, monolithic SiC tubes that were tested on sun were destroyed during the thermal shock process, there was one pristine sample that was not put through the thermal shock process which was tested with the Instron tester. This sample exhibited remarkable strength compared to both sets of composite tubes, where its measured stress of 9.04 was found to be 20.1% and 5.8% lower than the average values of set 1 and set 2 respectively.

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