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ENHANCED HEAT TRANSFER FOR THERMIONIC POWER MODULES

TOPICAL REPORT

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INTRODUCTION

The thermionic power module is capable of operating at very high heat fluxes, which in turn serve to reduce capital costs. The most efficient operation also requires uniform heat fluxes. The development of enhanced heat transfer systems is required to meet the demand for high heat fluxes ($>20 \text{ w/cm}^2$) at high temperatures ($>1500\text{K}$) which advanced thermionic power modules place upon combustion systems.

Energy transfer from the hot combustion gases may take place by convection, radiation, or a combination of radiation and convection. Enhanced convective heat transfer with a jet impingement system has been demonstrated in a thermionic converter. The recently-developed cellular ceramic radiative heat transfer system has also been applied to a thermionic converter. By comparing the jet impingement and cellular ceramic radiative heat transfer systems, an appropriate system may be selected for utilization in advanced thermionic power modules.

1.0 JET IMPINGEMENT

In the jet impingement heat transfer system a high velocity jet impinges on the workpiece, thereby breaking up the boundary layer and enhancing the local heat transfer. There is a trade-off between the increase in heat transfer and the increase in pump work required to form the jets. However, in many cases the increase in pump work is small compared to the increase in heat transfer. Rasor Associates has applied jet impingement heat transfer to a thermionic power module and a Stirling engine.

Figure 1 illustrates jet impingement as recently applied to the GPU-3 Stirling engine to enhance the combustion gas heat transfer (1). Actual tests comparing Stirling engine operation both with and without jet impingement were performed at the NASA Lewis Research Center. The results of the engine test, presented in Figure 2, clearly show the increase in effective heat transfer coefficient due to the jet impingement system. In addition, both the variation in the circumferential temperature profiles around the heater head and the vertical tube temperature profiles were made more uniform as shown in Figures 3 and 4.

The local heat transfer coefficient varies widely under the jet. However, the local temperature is a function of the local heat transfer coefficient, the thermal conductivity of the material, and the local heat flux removed. For the Stirling engine, this temperature variation was computed to be less than 55°C (100°F) as shown in Figure 5.

The jet shell used in the tests of ZEPO (2), the worlds largest thermionic converter, is shown in Figure 6. Several silicon carbide panels with precisely located holes formed the heat transfer system. This system provided 61 w/cm^2 at 1175 K to the emitter of the thermionic converter. The arrays of jets provide a means for tailoring the heat flux to meet specific design objectives. As illustrated in Figure 7, the jet impingement system provided the required heat flux to maintain

Fig. 1 Schematic of jet impingement concept

Fig. 2 Heat transfer enhancement due to jet impingement in the GPU 3 Stirling engine

Fig. 3 Circumferential heater tube temperatures. Thermocouples are located around the heater head at 90° intervals.

Fig. 4 Vertical heater tube temperatures.

Local Temperatures and Convection Coefficients

h = 1192 T = 801	h = 1050 T = 791	h = 624 T = 776	h = 426 T = 767	h [W/ m ² °C] T [°C]
h = 1164 T = 798	h = 999 T = 788	h = 454 T = 772	h = 341 T = 761	
h = 1022 T = 793	h = 903 T = 783	h = 255 T = 766	h = 85 T = 757	
h = 681 T = 787	h = 545 T = 778	h = 170 T = 762	h = 57 T = 753	

Fig. 5 GPU-3 Stirling Engine heater tubes. Local temperature distribution with jet impingement.

Fig. 6 Combustion-heated SiC jet impingement shell used in thermionic converter testing. This shell delivered $193,370 \text{ Btu/hr-ft}^2$ (61 W/cm^2) at 1652°F (900°C)

Fig. 7 Effect of tailoring heat flux profile on temperature by using jet impingement.

uniform operating temperatures. For the range of heat transfer coefficients required for a thermionic converter, the interrelation of flow rates, pumping power, and hole geometry is presented in Figure 8.

Silicon Carbide was selected for the jet shell material in both applications due to its ability to sustain continued high operating temperatures and its excellent thermal shock resistance. The holes in the jet shell were drilled with a laser because silicon carbide is an extremely hard material and cannot be machined economically by conventional techniques. A photo taken during the laser drilling operation is shown in Figure 9.

Fig. 8 Jet impingement heat transfer system design chart

Fig. 9 Laser drilling holes in SiC jet shell

2.0 CELLULAR CERAMIC RADIANT HEAT TRANSFER

The cellular ceramic radiant heat transfer system was developed to provide high heat fluxes ($>20 \text{ w/cm}^2$) to high temperature surfaces ($>1500\text{K}$) without danger of ablating delicate coatings on refractory metals. An illustration of the radiant heat transfer concept is shown in Figure 10. Rather than directly heating the burner tile or furnace wall as in a conventional radiant furnace, an intermediate wall made of a cellular ceramic is placed between the furnace wall and the workpiece. The cellular wall then radiates to the workpiece as in a conventional furnace except with a higher radiant transfer efficiency. The increase in radiant transfer efficiency is accomplished as a result of two mechanisms. First, the large hole-depth/hole-diameter ratio of the cells result in the cellular ceramic approximating an array of black-body cavities, thereby resulting in higher emissivity than is available from a flat furnace wall. Figure 11 shows the effective heat transfer coefficient for a cellular ceramic system compared to combustion gas radiation for the same gas and receiver temperatures. Second, the large surface area of the cell walls gives a much larger area for heat transfer from the combustion gases to the radiating intermediate wall. The relatively high pressure drop associated with a jet impingement system is avoided in the cellular system due to its high open cell area.

Unique to the cellular ceramic radiant system is its directional radiating characteristics. As shown in Figure 12, there is a definite peak in the radiant flux. The minimum at normal incidence is due to viewing through the cells. However, when viewed slightly off normal ($\sim 3^\circ$) a deep, nearly-isothermal cavity is seen with an emissivity approaching unity.

Several materials were tested to find a suitable material for the cellular structure. Figure 13 shows some of the samples for testing supplied by the Corning Ceramic Products Division. Based on basic considerations and jet shell experience, silicon carbide is an ideal material: it has excellent thermal shock resistance, high temperature

Fig.10 CONCEPTUAL DRAWING OF RADIANT HEAT TRANSFER FURNACE

Fig. 11 Comparison of radiant heat transfer coefficients for natural gas/air combustion products and cellular ceramic. (3)

Fig. 12 Angular variation of heat flux from combustion-heated cellular SiC

strength, and long life at high operating temperatures. To provide material for these tests, Corning teamed up with Carborundum to use Carborundum's α silicon carbide in Corning's extrusion dies to produce the first extruded cellular silicon carbide. The cellular silicon carbide was then used in tests of the radiant heat transfer system.

Early tests of the cellular ceramic radiant heat transfer system were performed in the furnace shown in Figure 14. Based on these early tests, the cellular silicon carbide "castle" shown in Figure 15 was built for heating the thermionic converter HC-2. In tests of the heat transfer system, the design heat flux of 20 w/cm^2 to a 1500K surface was obtained.

Fig. 13 Cellular ceramic materials supplied by Corning Ceramic Products Division.

Fig. 14 Overall view of furnace with "castle" installed and furnace lid open.

Fig. 15

Cellular silicon carbide "castle" used in thermionic converter testing.

3.0 COMPARISON

Thermionic converters require heat fluxes typically in the range of 20-40 w/cm^2 to emitter surfaces at temperatures from 1500-1800K. Figure 16 shows a comparison of the heat flux versus receiver temperature for both the cellular ceramic and jet impingement heat transfer systems. As illustrated in the figure, jet impingement can be more effective at low receiver temperatures when very high heat fluxes are required into low emissivity receiver surfaces. However, the radiant system may be the only reasonable alternative when jet impingement would ablate or distort the surface, when local hot spots are undesirable, or when pumping power losses are critical.

Fig. 16 Comparison of jet impingement and cellular ceramic heat transfer

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