Conclusions

The thermal matrix, input data, and procedure developed provide an excellent means for a preliminary thermal analysis of a module constructed with the die-cast aluminum frame and the standard 0.029-in.-thick, 2-oz-copper-clad PCB conformally coated. The input data is limited to application on the above type construction. Multilayer boards, sheet-metal frames, and potted modules cannot be analyzed, but the procedure can be used if input data is changed.

References

[1] "1620 Electronic Circuit Analysis Program (ECAP)," Rept. H20-0170-1, 1965, *Users Manual*, IBM Corp., White Plains, N. Y.

[2] Blanchard, J., "Modifications to ECAP," 1967, General Electric Ordnance Systems, Pittsfield, Mass.

[3] Wall, H. and Falk, H., "Circuit Analysis by Computer," 1966, IBM Corp., White Plains, N. Y.

[4] Dickerson, P., "Convenient PC Thermal Analysis Techniques," *Electronic Packaging and Production*, Vol. 1, No. 1, July 1967, pp. 108–118.

[5] "Heat Transfer Design Data Book," 1968, Advance Technology Labs., General Electric Co., Schenectady, N. Y.

A Channel Test Device for Arc Jet Material Ablation Studies

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Introduction

THE Sandia Channel Test Device (SCTD)[1] was designed and constructed for Sandia Laboratories by Plasmadyne Division of Geotel Inc. for material ablation testing in a turbulent boundary-layer flow environment such as that encountered during re-entry. To simulate these conditions, the design had to permit the flow in the channel to be arc heated, high-energy test gas, turbulent, subsonic, and flowing parallel to the test model. The device had to withstand an internal pressure of 10 atm at an enthalpy level to provide a cold-wall heat-transfer rate of 1000 Btu/ft^2-sec. The design also provided for measurement of the channel static pressure, optical measurement of the model surface temperature, steady-state calorimetry, and thermocouple measurement of test model in-depth temperature. The test model had to be protected from the plasma stream during the facility startup transients. This note presents information on the SCTD design, calibration, and utilization for ablation and heat-transfer studies.

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Index categories: Material Ablation; Thermal Modeling and Experimental Thermal Simulation; Nozzle and Channel Flow.

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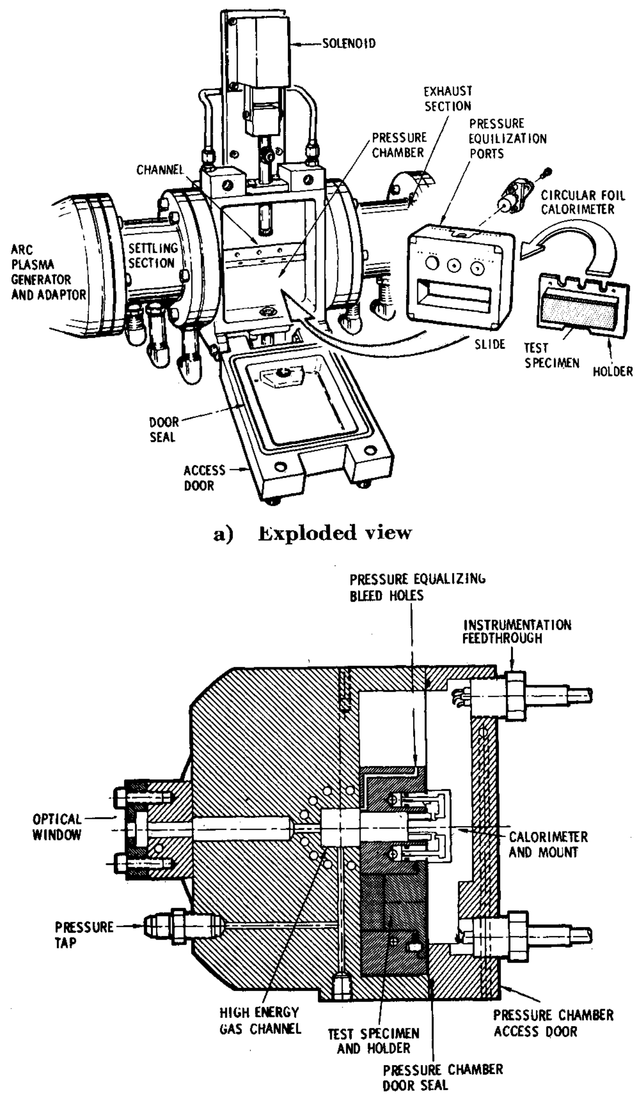

a) Exploded view

b) Cross section at Station 1

Fig. 1 Sandia Channel Test Device.

Discussion

Tube flow analysis, which determines the main parameters which affect the local heat-transfer rates within a tube, is used to establish several of the design dimensions and operating conditions.

The heat-transfer rate is

$$\dot{q}_w = \frac{0.0395\mu^{1/4}\dot{m}^{3/4}(h_e - h_w)}{Pr^{2/3}A^{3/4}d^{1/4}} \tag{1}$$

The variations of Prandtl no. (Pr) and viscosity (μ) are small over the range of test conditions to be encountered; therefore, Eq. (1) results in

$$\dot{q}_w \propto [\dot{m}^{3/4}(h_e - h_w)/A^{3/4}d^{1/4}] \tag{2}$$

The right-hand side of Eq. (2) is defined as a channel parameter. The proportional relationship of expression (2) dictates that the mass flow rate ($\dot{m}$) and enthalpy potential ($h_e - h_w$) must be large and the cross-sectional area A and hydraulic diameter d be small for maximum heat-transfer rate to the walls of the channel. The capability of Sandia's arc plasma generator (a 1.5 *MW* Linde N-1000) set the channel dimension at 0.84 in. on a side for the square "full-channel" test section. By reducing the cross-sectional area, an increase in heat-transfer rate can be realized without increasing the arc plasma generator operating conditions. As a result, a rectangular "half-channel" test section 0.84 × 0.42 in. with the short dimension normal to the test specimen was constructed to reach the high wall heat-transfer rate requirement of 1000 Btu/ft²-sec.

The fully water-cooled channel test device was designed in four sections (Fig. 1). The first is an adaptor section, replacing the sonic throat and nozzle of the arc plasma generator with a conversion section which makes the transition from the circular cross section of the generator to the square cross section of the channel. Following are the settling section, test section, and exhaust section.

The 3.5-in. long settling section was designed to add sufficient length to the channel so that the gas flow over the test specimen would be fully developed turbulent flow. Deissler[2] shows that entrance effects in turbulent flow become small beyond a length-to-diameter ratio of six. The settling section also damps out the vorticity of the gas entering the channel from the vortex-stabilized arc plasma generator.

The settling section consists of a stainless steel housing, cooling water flow divider, and a copper insert which forms the channel. Two inserts were constructed: a "full-channel" with a constant cross section of 0.84 × 0.84 in. and a "half-channel" with a square cross section at the entrance to connect with the adaptor from the generator. With the latter, gas entering is immediately forced, by a 30° ramp, to the half-channel cross section of 0.84 × 0.42 in. The flow rate and temperature of the cooling water to the settling section is monitored to determine energy loss to the walls of the section.

The exhaust section also has both full- and half-channel copper inserts and is equipped with an interchangeable sonic orifice to provide a greater range in operating and flow conditions.

Both full- and half-channel test sections were constructed. Except for the door, flange plates and external hardware, the test sections are of copper and are fully water-cooled. A water-cooled movable slide forms a section of one wall of the channel test section and exposes a 4-in.-long test specimen to the test gas. The shortened dimension in the half channel configuration is perpendicular to the movable slide. Thus, in either test section the specimens are exposed to the same channel width.

Each of the three data acquisition stations within the channel test section has a quartz optical window and a pressure orifice for measurement of the wall pressure (Fig. 1). The windows are opposite the movable slide and allow a view of the exposed surface of the test specimen. Radiometer surface temperature measurements can be made during the tests. Small quantities of nitrogen are bled into each window cavity to keep the surface clear.

The movable slide is a two-position device. In the lower position (Fig. 1), three circular foil calorimeters are exposed to the flow in the channel and the test specimen is shielded.

After the arc plasma generator is started and pressure builds up within the channel, gas is bled from the channel through ten holes in the cooled slide, and the chamber and channel pressures are equalized. This feature eliminates the need for gas seals. All instrumentation is brought out through the feed-throughs in the access door.

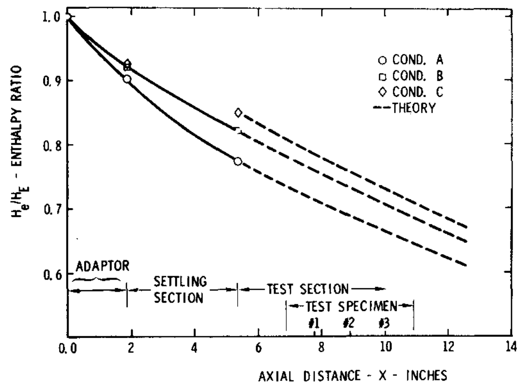

Fig. 2 Axial enthalpy (bulk) distribution within the SCTD.

The circular foil calorimeters continuously record the wall heat-transfer rate, and when the required steady-state operation is achieved, the upper solenoid is activated and a driving rod moves the slide to its second position where the test specimen is exposed to the channel.

The model holder may be made of a high-temperature insulation material to minimize heat conduction, or the sides may be extended around a narrow test specimen to insulate the sides and base of the specimen. Maximum specimen thickness is 1 in.

During a test, ablation causes a change in the channel cross-sectional area of a test specimen. For accuracy, the specimen should undergo testing for only a brief period so that the change is negligible, or reduction in the wall heat-transfer rate should be considered.

The SCTD has been used for three ablation studies where surface and in-depth temperatures and mass-transfer rates were obtained as a function of cold-wall heat-transfer rates. These tests were conducted at the Hyperthermal Test Facility of Plasmadyne Division of Geotel, Inc. The data presented here pertain to the smooth wall heat-transfer rates and bulk enthalpy distribution along the channel.

Three basic test conditions were established as shown in Table 1. The full channel configuration was utilized in the first two test conditions (*A* and *B*), while the half channel configuration was used in test condition *C*. The maximum Mach number in the test section was less than 0.4.

The data points in Fig. 2 are the average of each test condition for all the test performed. The solid lines are curve fits and the dashed lines result from the theory of Ref. 1. No curve fit for condition *C* was attempted between the exit of the generator and entrance of the test section because the transition from full to half channel is made within the settling section.

The movable slide lends itself to use of thermal capacitance (slug) calorimeters. A model holder was constructed to hold three isolated OFHC copper calorimeters at the three test stations. Rapid movement of the slide allowed nearly instantaneous exposure of the calorimeters to the high-energy plasma.

Table 1 Environmental conditions of three typical tests

Test condition[a]	Plasma generator gas enthalpy, h_E(Btu/lb$_m$)	Test Sec. gas enthalpy, h_e(Btu/lb$_m$)	Gas flow rate,[b] $\dot{m}$ (lb$_m$/sec)	Test Sec. static pressure, P_w(atm)	Heat-transfer rates,[c] $\dot{q}_{cw}$(Btu/ft²-sec) Sta. no. 1	Sta. no. 2	Sta. no. 3	Calcd. shear stress, τ_w (lb$_f$/ft²)	Tube Reynolds no.
A (F)	8000	6060	0.03	1.4	375	332	320	2.5	5230
B (F)	8300	6750	0.06	4.7	573	522	486	2.2	9750
C (H)	8900	7100	0.06	4.6	895	784	712	6.8	12770

[a] (F) Full channel, (H) half channel.
[b] Simulated air (79% N_2; 21% O_2).
[c] Thermal capacitance (slug) calorimeter data.

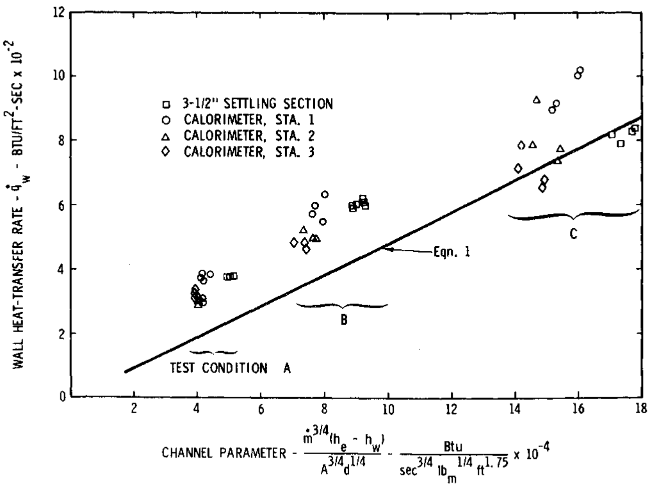

Fig. 3 Heat-transfer rates to the channel walls.

Data for the settling section are presented in Fig. 3 along with data from the thermal capacitance calorimeters as a function of the channel parameter shown earlier in expression (2). Equation (1) is plotted on the figure to compare the theoretical wall heat-transfer rates to the data. In all cases, the data are considerably higher than theory predicts for the full channel at operating conditions (*A* and *B*). There is considerable scatter in the data for condition *C* operating with the half channel. For the full-channel condition, the average heat-transfer rates to the settling section are in very good agreement with the calorimeter data. For condition *C*, the settling section heat-transfer rates are lower than the data from the calorimeter at station No. 1 and are unlike conditions *A* and *B*. This may be because the transformation from full to half channel is made in that section.

One reason for use of the settling section was to damp out vorticity in the flow from the vortex-stabilized arc plasma generator. But during tests, there was still considerable vorticity left in the flow in spite of the square cross section. Equations for the Reynolds number and wall heat-transfer rates assume that the only component of velocity is in the axial direction. Bergles et al.[3] have shown that flow with a vortex can give considerably higher wall heat-transfer rates than flow without swirl. Their data show Nusselt numbers for smooth tube flow with swirl that are 50% greater than Nusselt numbers for smooth wall without swirl. The data for conditions *A* and *B* are approximately 50% greater than the smooth wall theory. For condition *C*, the channel geometry is more adverse to gas swirl and the swirl may be damping out quicker, giving rise to a steeper gradient in the heat-transfer rate distribution along the test section length.

Conclusions

The SCTD is a valuable and versatile tool for examining the ablation characteristics of materials in a turbulent flow reentry environment. The channel parameter predicts the trends in wall heat-transfer rates for the various test conditions. The persistance of flow vorticity from the arc plasma generator through the test section of the device may be the reason the heat-transfer rate data are higher than predicted by theory. Operational requirements were met. The movable slide with its pressure equalization principle shields test models until conditions in the channel are stable as determined from the continuous-reading circular foil calorimeters.

References

[1] Sheldahl, R. E., Wright, G. F., Jr., and Muehlberger, E., "A Channel Test Device for Arc Jet Material Ablation Studies," AIAA Paper 71-260, Albuquerque, N. Mex., 1971.

[2] Deissler, R. G., "Turbulent Heat Transfer and Friction in the Entrance Regions of Smooth Tubes," *Transaction of the ASME*, Vol. 77, Nov. 1955, pp. 1221–1223.

[3] Bergles, A. E., Lee, R. A., and Mikic, B. B., "Heat Transfer in Rough Tubes with Tape-Generated Swirl Flow," *Transactions of the ASME, Journal of Heat Transfer*, Vol. 91, Ser. C, No: 3, Aug. 1969, pp. 443–445.

FEP Encapsulated N/P Silicon Solar Cells after Simulated Micrometeoroid Exposure

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THE effect of simulated micrometeoroid exposure on the performance of quartz covered N/P silicon solar cells and Mylar or Kapton encapsulated CdS solar cells was reported in Ref. 1. Since the results of Ref. 1 were published another type of plastic material, fluorinated ethylene propylene, FEP, is being considered as a protective cover for silicon solar cells. At Lewis, FEP covered N/P silicon solar cells are being evaluated (Ref. 2) and one aspect of this evaluation is the possible reduction in performance of these cells due to the micrometeoroid environment. Therefore, N/P silicon solar cells encapsulated in FEP were exposed in a shock tube to simulated micrometeoroid impaction using 6μ silicon carbide (SiC) particles at a velocity of 2.65 km/sec (Ref. 3). The apparatus described in Ref. 4 using filtered 600 w tungsten iodine lamps was used to obtain the current-voltage (I–V) characteristic curves of the cells for a light intensity corresponding to zero air mass (Ref. 5).

The characteristic curves of one of the FEP-covered solar cells before exposure and after two levels of exposure are

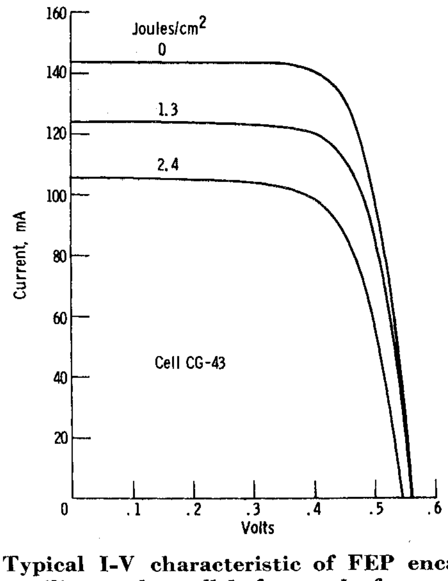

Fig. 1 Typical I-V characteristic of FEP encapsulated 2 × 2 cm silicon solar cell before and after exposure to simulated micrometeoroids.

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