Surface Step Induced Gap Heating in the Shuttle Thermal Protection System

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An analytical study has been performed to investigate the excessive heating in the tile-to-tile gaps of the Shuttle Orbiter Thermal Protection System due to stepped tiles. The excessive heating was evidenced by visible discoloration and charring of the filler bar and strain isolation pad that is used in the attachment of tiles to the aluminum substrate. Two tile locations on the Shuttle Orbiter were considered: one on the lower surface of the fuselage and one on the lower surface of the wing. The gap heating analysis involved the calculation of external and internal gas pressures and temperatures, internal mass flow rates, and the transient thermal response of the Thermal Protection System. The results of the analysis are presented for the fuselage and wing location for several step heights.

Nomenclature

A_c = cross-sectional area for flow
B = width of flow path
h = tile step height
k = thermal conductivity
K_p = permeability constant
$\dot{m}$ = mass flow rate
M = Mach number
P = pressure
$\dot{q}$ = conduction heat flux
Re_c = Reynolds number for base pressure correlation
s = straight line length between points
T = temperature
w = tile-to-tile gap width
X, Y = Shuttle Orbiter coordinates
ΔX = longitudinal coordinate measured in the downstream direction from the point of separation
ΔX_{ff} = longitudinal coordinate measured in the upstream direction from a forward-facing step
δ = velocity boundary-layer thickness
δ^* = boundary-layer displacement thickness
δ_{eff} = δ for laminar flow, 1.5 δ^* for turbulent flow
Λ = sweep angle of a tile with respect to the local flow
μ = viscosity coefficient
ρ = density

Introduction

THE Shuttle Orbiter Vehicle 102 (Columbia) has flown five orbital missions successfully. The Thermal Protection System (TPS) on the Orbiter exterior[1] performed satisfactorily although damage was observed on random individual tiles on the lower fuselage and lower surfaces of the wings after each flight. The TPS at these locations (Fig. 1) consists of silica tiles typically 6 × 6 in.^{2} and of variable thickness depending on their location on the Orbiter. The tiles are bonded to the aluminum skin of the Orbiter through a strain isolation pad (SIP). The tiles have gaps between them to allow for differential thermal expansion between the tiles and substrate. A nylon fiber filler bar, that has a silicone rubber membrane on its top surface, is directly beneath the tile-to-tile gaps. The filler bar is bonded to the aluminum skin but not to the bottom of the tiles. This filler bar material sustained damage at random locations on all flights of the Columbia.

One of the causes of damage to the TPS has been vertical and lateral relative movement between adjacent tiles. This relative movement can cause forward-facing steps on the TPS aerodynamic surface and large gaps between the tiles. The combination of forward-facing steps and large tile-to-tile gaps has caused higher than expected heating within the gaps during atmospheric entry at random locations on the lower surface of the Orbiter resulting in damage to the filler material and the SIP. The heat damage has been severe enough in some instances to require tile removal in order to replace the filler material and SIP. The lower fuselage and lower surfaces of the wings are geometrically flat regions so that aerodynamic pressure gradients on the TPS are essentially zero. Tile-to-tile gap fillers were not used in these regions for this reason.

Post-flight measurements, taken after the first flight around the tiles with damaged filler bar, are shown in Table 1. Tile-to-tile steps varied from −0.1 to +0.12 in. and tile gaps varied from almost complete closure (0.01 in.) to an opening of 0.13 in. The degree of damage to the filler bar was categorized by performing arc jet tests on a TPS panel and duplicating the varying degrees of observed damage.[2] Thermocouples were embedded in the filler bar to record temperatures for each category of damage. The threshold temperature to cause filler bar damage was 970°F causing the room temperature vulcanizing rubber (RTV) membrane to discolor. Temperature exposures above 1375°F caused both the RTV and nylon fiber material to char.

The probable cause of damage to the filler bar is shown in Fig. 2. A tile with a forward-facing step causes a local pressure disturbance in the external boundary layer. The flow tends to stagnate on the forward face directly over the tile-to-tile gap. Similarly, the aft-facing step creates a low-pressure region as the flow leaves the surface of the stepped tile and reattaches downstream. This combination of pressures around a stepped tile causes flow in the tile gaps that would not exist if all tiles were at the same height. The objective of the analytical study was to define the conditions under which a stepped tile could result in damage to the filler bar. To define these conditions, an analysis involving five phases of study was completed. The phases of study were: 1) definition of the local freestream conditions on the lower surface of the wing and fuselage; 2) development of a technique for predicting the distribution and magnitude of the pressure disturbance caused by a stepped tile; 3) predicting the temperature of the gases which enter the tile-to-tile gap from the external boundary layer as a result of the stepped tile;

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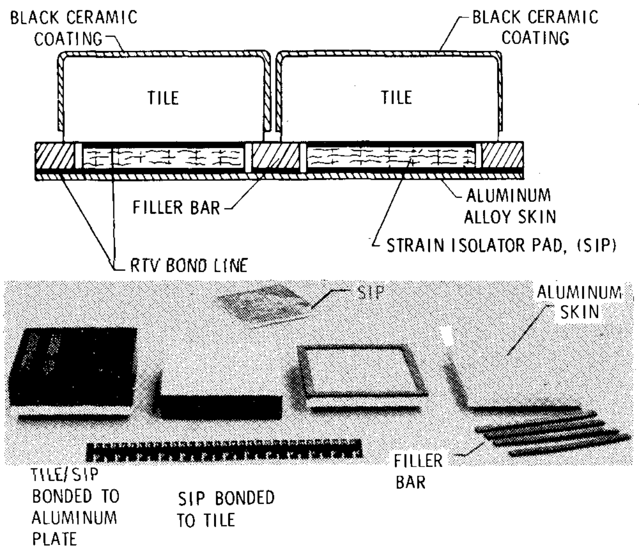

Fig. 1 Tile configuration on lower surface of Orbiter.

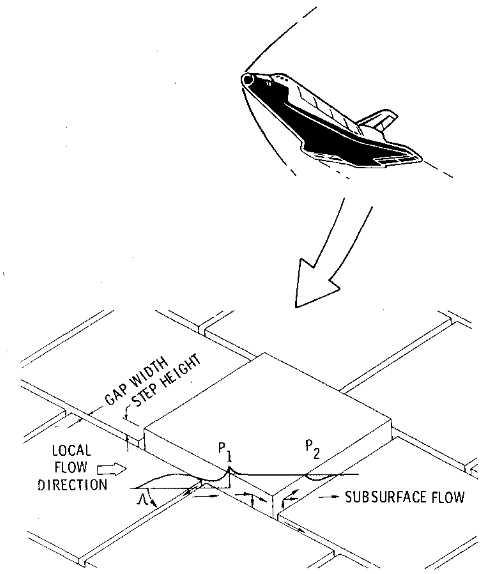

Fig. 2 Local pressure disturbances caused by a stepped tile.

Table 1 STS-1 Post-flight measurement extremes in damaged filler bar areas and categorization of damage based on arc jet tests[2]

Tile/tile steps		−0.099-+0.12 in.
Tile/tile gaps		0.010-0.13 in.
	Categorization of damaged filler bar	
Category	Temperature, °F	Damage
1	970	RTV discolored
2	1100	RTV charred
3	1375	RTV and filler bar charred

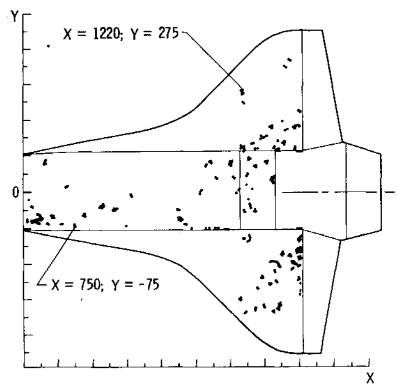

Fig. 3 STS-1 Orbiter lower surface, charred filler bar locations for analysis.

4) predicting the pressure distruibution around and under the tile and the mass flow rates in the tile gap as a result of the pressure disturbance; and 5) determining the temperature response in the tile gap and in particular the temperature on the filler bar caused by flow in the gaps.

Analysis

Two locations, one on the lower surface of the fuselage and one on the lower surface of the left wing, were selected for analysis from the regions where damaged filler bar was observed (Fig. 3). The location on the fuselage was selected because local flow conditions during entry can be predicted accurately for this position, flight measurements of pressure and temperature are available, and the boundary-layer thickness will be large since the point is about 40 ft from the nose of the Orbiter. The wing location was selected for the same reasons, except in this case the boundary layer will be relatively thin since the point is about 8 ft aft of the local leading edge. These are 6 × 6 in. tiles with thicknesses of 1.41 in. at the fuselage location and 2.25 in. at the wing location.

The pressure and other thermodynamic properties at the edge of the boundary layer at the fuselage location were calculated using a tangent-cone approximation where the half-angle of the cone is equal to the local flow deflection angle (i.e., the local body deflection angle plus the angle of attack). The real gas, axisymmetric flowfield solution over a cone was obtained using a time-asymptotic numerical procedure with equilibrium thermodynamic properties obtained from Ref. 3. The tangent-cone approximation has been shown to yield accurate predictions of the local flow on the windward surface of Shuttle-like configurations.[4] Local flow conditions on the wing lower surface were calculated assuming two-dimensional inviscid flow. The boundary-layer calculations on the fuselage were made using a "local infinite swept cylinder" analysis[5] and on the wing using two-dimensional "strip theory."

Pressure Disturbances

The characteristic shape of the pressure disturbance caused by a forward-facing step in supersonic flow is shown in Fig. 4. The step height needed to cause this disturbance is equal to or greater than the boundary-layer thickness for laminar flow and equal to or greater than 1.5 times the displacement thickness for turbulent flow. The step causes the boundary layer to separate locally from the body forward of the step. In addition, an oblique shock is formed at the point of separation. The pressure behind the shock is called the plateau pressure, P_{plateau}, in Fig. 4. There is a final peak pressure at the face of the step as the flow stagnates. The figure is a plot of $P_{\mathrm{plateau}}/P_{\mathrm{local}}$ vs Mach number from test data reported in Ref. 6 and experimental results reported in the literature.[7-9] The data are directly applicable to the lower surface of the Orbiter since the local Mach number behind the bow shock ranges from 2.5 to 3.75 during the high aerodynamic heating period of entry. The equation for a straight line correlates the data very well, as shown in the figure.

Boundary-layer thicknesses varied from 0.87 to 4.0 in. at the fuselage location and 0.54-1.54 in. at the wing location.

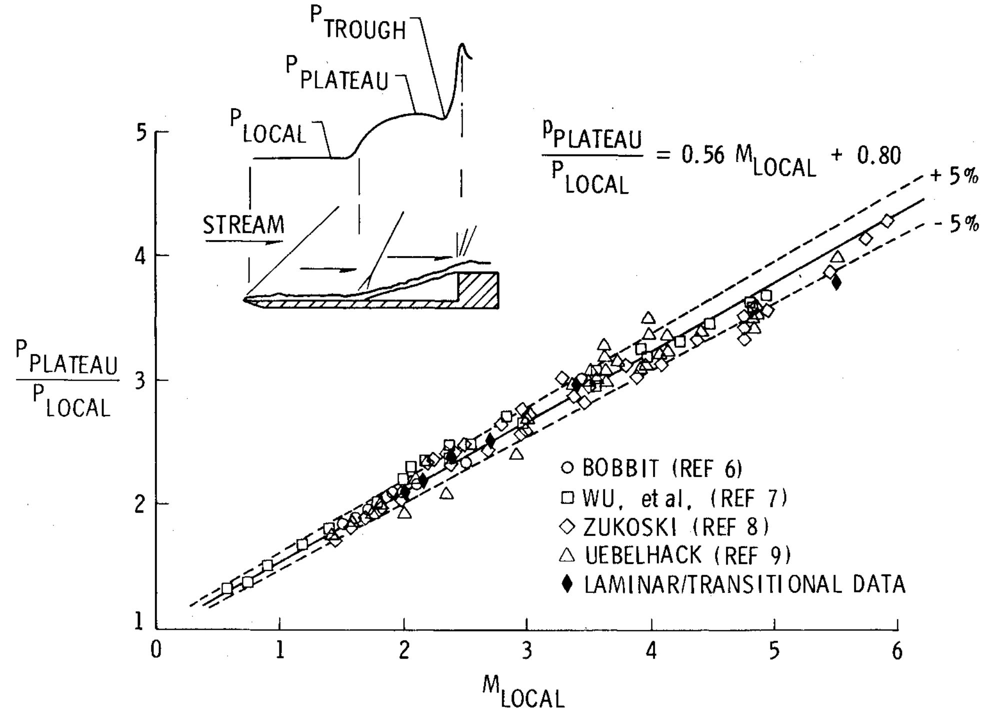

Fig. 4 Plateau pressure correlation.

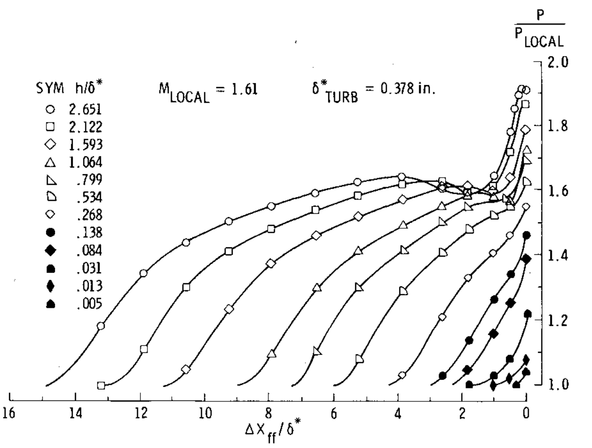

Fig. 5 Experimental pressure data for forward-facing steps.

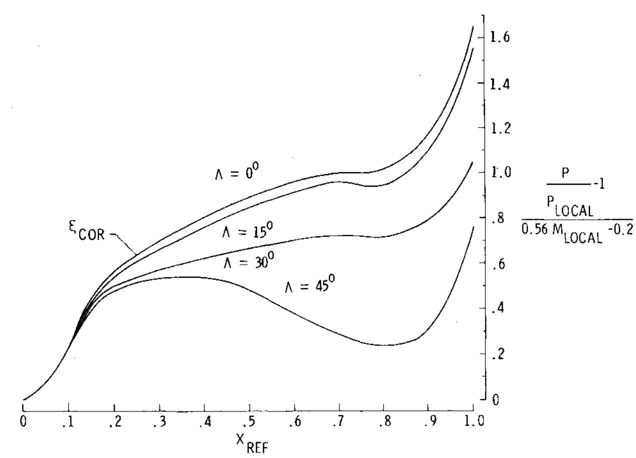

Fig. 7 Pressure distributions ahead of unswept and swept forward-facing steps.

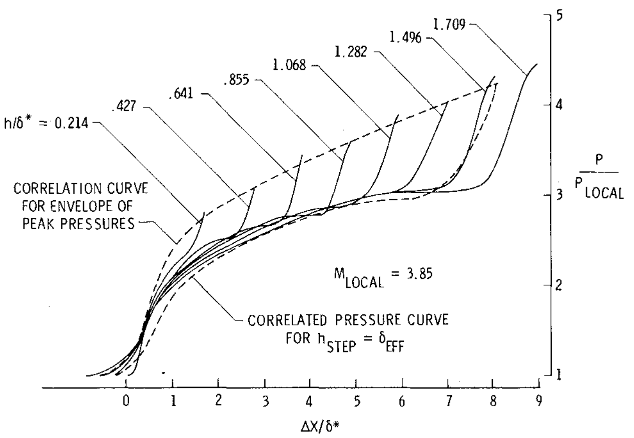

Fig. 6 Comparison of correlation and experimental pressure profile data.

Tile step heights considered in the analyses were 0.12 in. maximum in accordance with measured tile steps after the first flight. Therefore, forward-facing steps in the tiles were submerged deeply in the boundary layer and do not cause the severe pressure disturbances shown in Fig. 4. Figure 5 shows experimental data pressure distribution vs separation distance for various step heights. The face of the step is at $\Delta X_{ff}/\delta^* = 0$ in the figure. The shaded symbols indicate data that is in the range of step height-to-displacement thickness ratios that apply for the filler bar analysis. A significant feature of the plots in Fig. 5 is the similarity of the curves as step height is decreased. The characteristic shape of the pressure distribution for a large forward-facing step ($h/\delta^* = 1.5$) can be used to obtain the pressure distribution for a smaller step height by using the lower portion of the curve starting at the point of separation and scaling the peak pressures as a function of h/δ^*. A correlation technique was developed to obtain pressure disturbance distributions for small step heights at various Mach numbers between 2.35 and 3.85 based on the

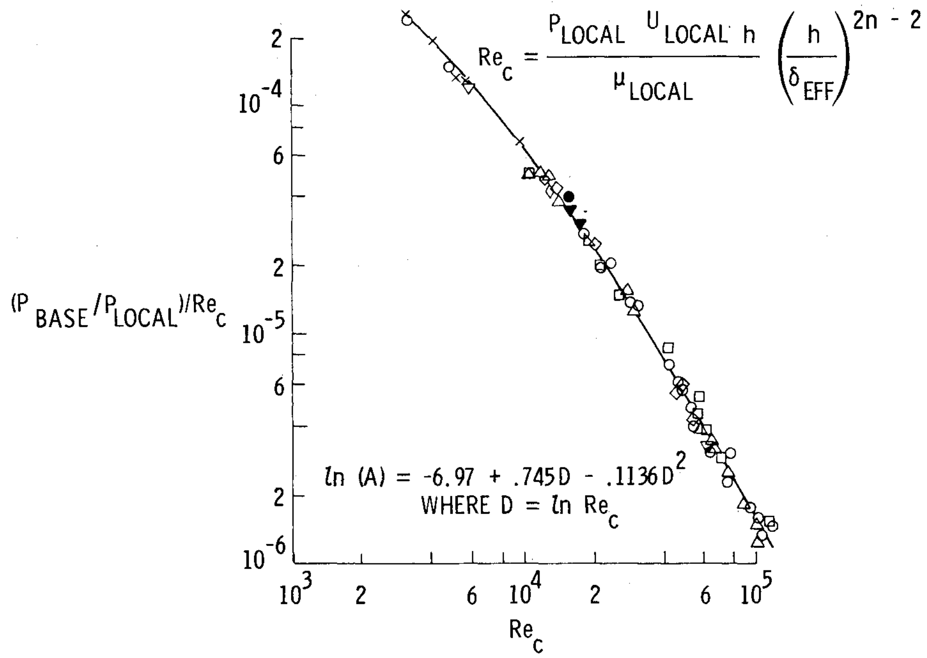

Fig. 8 Base pressure correlation.[12]

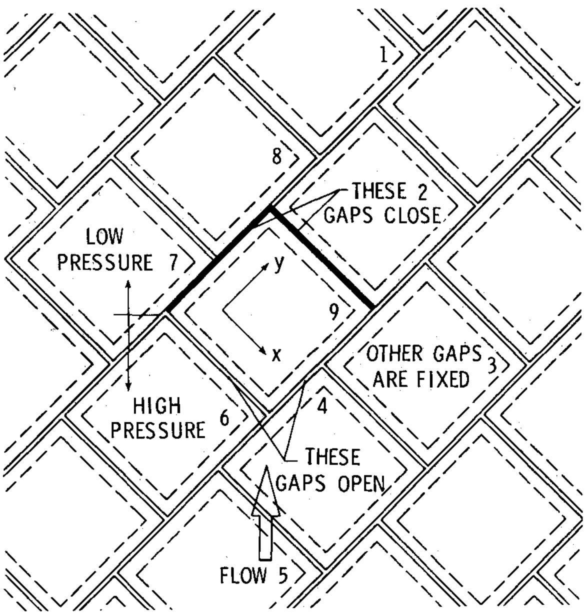

Fig. 9 Flow model tile array.

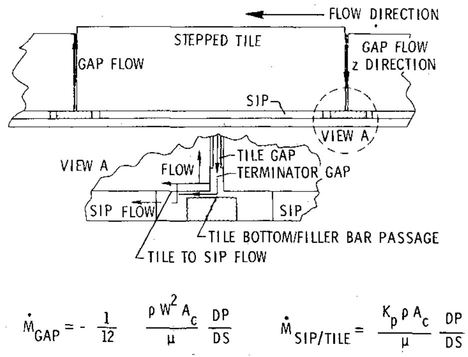

Fig. 10 Typical flow paths in Shuttle tile flow model.

experimental data previously referenced. Figure 6 shows the result of the correlation technique being applied at $M = 3.85$. The pressure distribution curves are plotted as a function of the nondimensionalized separation distance. The separation point is at $\Delta x/\delta^* = 0$. The lower dashed curve is the correlated pressure curve for the step height that is 1.5 times the displacement thickness of the turbulent boundary layer ($\delta_{eff} = 1.5\delta^*$). It has the characteristic shape of a pressure disturbance that has an oblique shock at the separation point shown previously in Fig. 4. The top dashed curve envelopes the peak pressures for various step heights. For the filler bar analyses, the pressure disturbances were obtained by using the lower dashed curve from the point of separation to an appropriate point and then fairing a distribution to the enveloping curve for the step height of interest. Details of the development of the correlation technique can be found in Ref. 10.

The effect of sweep angle on the pressure distribution in front of a forward-facing step was taken into account using data from Ref. 11 (Fig. 7). The forward face of a stepped tile was assumed to be swept 45 deg with respect to the local flow. Base pressure predictions on the aft-facing steps were based on data from Ref. 12 (Fig. 8). The exponent n in the definition of characteristic length for the Reynolds number was empirically determined to be 0.9 in the reference.

Flow Model

With the pressure disturbances around the top of a stepped tile defined, pressure distributions in the tile gaps, SIP, filler bar, and within the silica foam tile can be calculated along with the resulting mass flow rates. Figure 9 is a schematic diagram of a 9-tile array flow model that was developed to analyze the flow around a stepped tile (tile 9 in Fig. 9). The tile gaps were modeled as flow passages around the tiles. Boundary conditions at the top of tiles were the calculated pressure disturbances around the stepped tile and a constant pressure, P_{local}, around the other tiles in the array to simulate the zero aerodynamic pressure gradient assumption. Lateral movement of the stepped tile caused by the pressure differences around it were simulated in the flow model because the SIP material is flexible and allows tile movement. The position of the remainder of the tiles in the array was held constant. Figure 10 shows further details that were incorporated into the flow model. View A in the figure shows

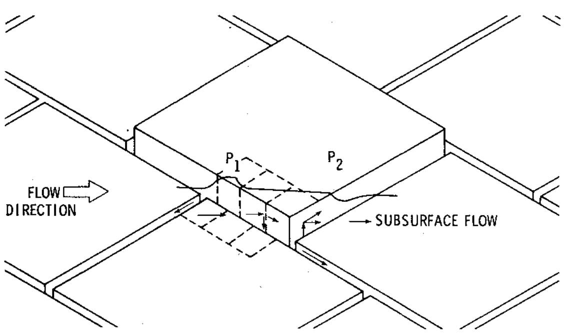

Fig. 11 Region modeled for thermal analysis.

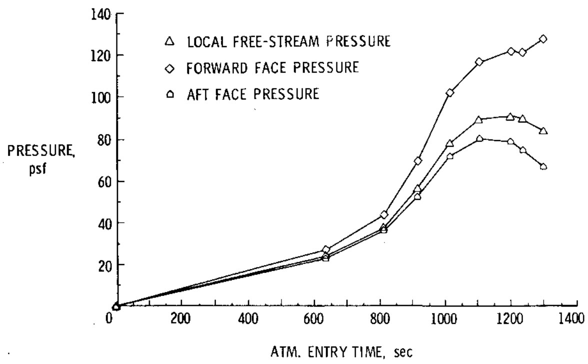

Fig. 12 Pressure at fuselage location, 0.1 in. step.

flow passages near the filler bar that were modeled. The flow passages include flow in and out of the bottom of the tile where it is not bonded to the SIP, flow between the tile and filler bar, and flow in and out of the SIP. Flow through the fibrous material of the filler bar was considered also.

The equation that describes flow through porous media,

$$\dot{m} = -\frac{K_p \rho A_c}{\mu} \frac{\mathrm{d}P}{\mathrm{d}s} \tag{1}$$

is analogous to the steady-state heat conduction equation

$$\dot{q} = -kA_c \frac{\mathrm{d}T}{\mathrm{d}s} \tag{2}$$

The flow in the tile gaps can be described as flow between parallel walls. Mass flow rates between parallel walls for laminar incompressible flow (calculated Reynolds numbers in the tile gaps indicate the flow is laminar to transitional) can be obtained from

$$\dot{m} = -\frac{1}{12} \frac{\rho w^2 A_c}{\mu} \frac{\mathrm{d}P}{\mathrm{d}s} \tag{3}$$

This equation is also analogous to the equation for steady-state heat transfer. Using these analogies the Martin Interactive Thermal Analyzer System (MITAS), a general-purpose, finite difference, heat-transfer computer program, was used to obtain the pressure and flow distribution around the stepped tile.[13] The flow model, originally developed for a tile loads analysis using ascent conditions, was modified during the study to account for compressibility effects in the tile gap flow. This modification was necessary because pressure differences calculated around the stepped tile were large enough to cause compressible flow. The compressible flow in the tile gaps was modeled assuming internal flow of an

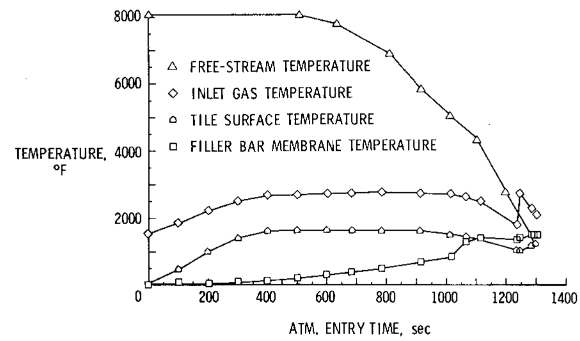

Fig. 13 Gap temperatures at fuselage location, 0.1 in. step.

ideal gas with constant cross-sectional area and frictional effects (Fanno line flow). Complete details of the modified flow model can be found in Ref. 10.

Thermal Model

A thermal model representing the region around a stepped tile was developed to determine response to hot gas flow in the tile gaps. The region modeled is shown in Fig. 11. The model included portions of the two tiles on each side of the gap and the filler bar, SIP, and aluminum substrate at the base of the tiles. This region was chosen because the mass flow rates in the tile gap are highest at the corner of the tile where the pressure distribution goes from a high-pressure region on the forward face to the low-pressure region on the aft face of the stepped tile. The thermal model was limited in size to keep the model size within the capacity of MITAS. It was assumed that the temperature of the gas entering the modeled region in the horizontal direction was equal to the temperature of the gas in the gap in the center of the model at the same depth from the surface. This assumption was made because the flow down the gap is much larger than the flow entering the gap in the horizontal direction. The inlet temperature of the gas that entered the tile gap in the vertical direction was assumed to be the integrated average stagnation temperature of the boundary-layer air from the tile surface to a point in the boundary layer equal to the tile step height. Convection, conduction, and radiation on the tile sidewalls and top surface were accounted for in the analysis. An energy balance also was maintained on the gas as it flowed through the tile gap.

Analysis Results

Figure 12 is an example of the results from the pressure disturbance calculations. The zero point for atmospheric entry time is taken to be the time at which the Orbiter reaches 400,000 ft altitude during entry. Pressure and flow calculations were made at discrete time points with freestream conditions held constant. Flow data for the discrete time points were used in the transient temperature calculations over corresponding time intervals. The curves are terminated at the time when maximum filler bar temperature occurs. The maximum pressure difference across a 0.1 in. stepped tile at the fuselage location was approximately 0.33 psi. Figure 13 is an example of the results obtained from the transient thermal analysis. The result is for a 0.1-in. stepped tile at the fuselage location. The filler bar temperature peaks at 1470°F. It occurs after boundary-layer transition (transition is indicated by the rapid rise in inlet gas temperature at 1250 s) and after the tile surface temperature has begun to fall. Table 2 shows a summary of peak filler bar temperature results for the fuselage location. Tile step heights (0.04 and 0.1 in.) were held constant and the tile gap width was allowed to vary. The maximum step size (0.03 in.) and maximum gap width (0.065 in.) that are acceptable during tile installation are also indicated on the figure. Extrapolation of the calculated results to these maximum installation tolerances indicate damage to

Table 2 Predicted peak filler bar temperatures at fuselage location

Step in.	Initial gap, in.	Final gap, in.	Peak filler bar temperature, °F	Category
0.04	0.05	0.067	970	1
0.10	0.05	0.092	1500	3
Installation specifications:				
Tile step, −0.030 in. max				
Tile gap, −0.065 in. max				

Table 3 Predicted peak filler bar temperatures at wing location

Step in.	Initial gap, in.	Final gap, in.	Peak filler bar temperature, °F	Category
0.017 (Installation specification)	0.05	0.063	864	
0.03	0.05	0.080	1286	2
0.06	0.05	0.103	1747	3

the filler bar would not occur, or at least would be minimized, if the tile step height and gap width could be held within the tolerances. Table 3 is a summary of the peak filler bar temperature results at the wing location. Only one gap width (0.05 in.) was analyzed. These results also indicate filler bar damage can be minimized by maintaining tile steps and gaps within the specified installation tolerances.

Conclusion

An analysis of the heating that occurs during entry in the tile-to-tile gap due to uneven tile heights in the Shuttle Orbiter TPS has been performed. In order to conduct the analysis a technique was developed for predicting the local pressure disturbances caused by a stepped tile. In addition, a method was developed for calculating the airflow rates in the tile-to-tile gaps, and for predicting the temperature level of the gas ingested from the boundary layer. A thermal analysis was conducted on the stepped tile configuration to determine the extent of heating on the tile sidewalls, filler bar, and SIP due to the hot airflow in the gap. Combinations of tile step heights and tile-to-tile gaps that could cause varying degrees of damage to the filler bar on the lower fuselage and wing were determined. The magnitudes of the predicted step heights and gaps were comparable to those observed in damaged regions after each of the initial flights of the Shuttle. The results indicate that the steps and gaps must be controlled within tight tolerances during tile installation and the tolerances must be maintained in flight. If the tolerances cannot be maintained, tile-to-tile gap filler would be an alternative. At the present time, the TPS is inspected after each flight for damaged filler bar. If there is sufficient damage, the filler bar is replaced and a rigid temporary gap filler is added.

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