**A new method for prescribing non-uniform wall temperatures on wind tunnel models**

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**Abstract**

This paper reports an initial study to test a new method for prescribing non-uniform wall temperatures on wind tunnel models. The ability of compact conformal resistive heater inserts to provide high, non-uniform wall temperature distributions was quantified, with potential application to wind tunnel models. This technique uses specially designed interchangeable reinforced-carbon-carbon resistance elements powered by a computer controlled power supply. Numerical simulations of the transient electrical heating of a range of candidate geometries have been performed using finite element methods. These simulations have demonstrated the efficacy of the heater design approach.

**Introduction**

Impulse facilities such as shock tunnels, gun tunnels and Ludwieg tubes have become widely used for making aerothermodynamic measurements on hypersonic configurations. One drawback of these facilities is their inability to reproduce the flow duration (of the order of 1ms in shock tunnels) is too short to heat the model significantly.

**The Importance of Wall thermal Condition**

There are nominally two types of thermal behaviour associated with high-speed flight. Short duration flights, such as those commonly used to-date for ballistic flight-testing, will induce highly transient thermal behaviour of the vehicle structure as the heat convectively transferred to the outer surface conductively soaks through the structure. If the vehicle continues to fly at a high-speed cruise condition it will eventually approach thermal equilibrium with the wall reaching its local radiation adiabatic wall temperature. Here the convective heat flux is balanced by the radiative heat loss [5].

Hirschel [6] noted this discrepancy in high-speed wind tunnels and proposed the so-called hot experimental technique (HET) in which models would be actively brought to the appropriate wall temperature ratio for simulating the flight conditions of interest. Table 1 sets out the issue in a range of high speed wind tunnels. While a number of options are available to induce the appropriate temperature ratio, including cooling the flow, the favoured option for the high-speed conditions of interest is to actively heat the model. This can be achieved by convective, radiative or internal (resistive or inductive) heating of the model, either during the test or immediately preceding it.

![Figure 1. Thermal state of the wall as a function of heat input and loss.](image)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Flow duration</th>
<th>M</th>
<th>flow model</th>
<th>chemistry</th>
<th>T0/Tw</th>
<th>HET candidate</th>
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<tr>
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<td></td>
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<td></td>
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<tr>
<td>Unheated Blowdown</td>
<td>&gt;5 mins</td>
<td>3</td>
<td>Cold</td>
<td>Cold</td>
<td>No</td>
<td>~1</td>
</tr>
<tr>
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<td>3</td>
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<td>Hot</td>
<td>Usually Wrong</td>
<td>~1</td>
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<tr>
<td>Short Duration</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Unheated Blowdown</td>
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<td>3</td>
<td>Cold</td>
<td>Cold</td>
<td>No</td>
<td>~1</td>
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<tr>
<td>Heated Blowdown</td>
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<td>Hot</td>
<td>Warm</td>
<td>Maybe</td>
<td>&gt;1</td>
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<tr>
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<td>Cold</td>
<td>No</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Heated Ludwieg Tube</td>
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<td>3</td>
<td>Warm</td>
<td>Warm</td>
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<tr>
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<td>Hot</td>
<td>Cold</td>
<td>Yes</td>
<td>&gt;&gt;1</td>
</tr>
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</table>

Table 1. Heating strategies for a range of facilities where HET indicates suitable candidate for the hot experimental technique and (HE) signifies high enthalpy flow conditions with the additional considerations of flow chemistry.
Resistive heaters

Resistive heaters employ Joule heating to dissipate electrical power within a resistive material. The amount of heat released is shown by Ohm’s law to be equal to the product of the square of the current and the resistance of the heater element. This resistance is a function of both the material resistivity and the geometric cross section used. Resistive heaters have been developed for a host of applications ranging from the commonly found including, incandescent light bulbs, electric ovens and stoves, radiative heaters to more specialized applications including polymer and composite curing, medical heating and food and chemical processing and now even electronic cigarettes.

Many of these applications rely on metallic resistance elements employing alloys such as nichrome or Kanthal. While these materials have been successfully used in a range of applications their relatively high electrical conductivity means that they are usually employed in the form of small cross-section wires that then radiatively or conductively heat the object of interest. Thin film heaters of platinum are also a possibility but must be very precisely deposited and can be fragile.

A number of hot wall studies in hypersonic impulse facilities have been reported [1,7] which have employed embedded resistive heater wire circuits in metal models. This heating approach, while sufficient to approximate the desired temperature ratios, was found to be somewhat cumbersome, requiring long heat up times, inducing thermal distortion and resulting in non-prescribed thermal non-uniformities.

A practical resistive heater material requires high electrical resistance but still with the ability to conduct electricity. Other desired attributes include low thermal inertia, fast response, thermal-structural stability, and machinability.

Reinforced carbon-carbon (RCC) has the specific attributes required for this application. That is, exceptional high temperature mechanical properties, high specific strength and stiffness, high fracture toughness, dimensional stability due to low thermal expansion, high thermal shock resistance, graceful failure modes, tailorable properties and machinability [11]. RCC has low electrical conductivity/high electrical resistivity, which makes it a very efficient resistive heater. RCC does have poor oxidation resistance though this drawback can be overcome by the use of C/SiC or SiC/SiC.

As a resistive heater it also has the advantage of having an order of magnitude higher resistance than traditional heater element materials such as Kanthal AF and Nichrome. This allows the manufacture of thicker and hence more robust heater elements more suited for accurate contouring.

Zander et al. [13] developed the use of RCC resistive heaters for hot wall experiments in short duration hypersonic wind tunnels. They demonstrated the use of a curved heater element, resistively heated to 2000K to simulate a re-entry body in the flow produced in the X-3 superorbital expansion tube facility.

We have already successfully adapted this method to reproduce uniform flight-representative wall temperatures to test component durability for the SCRAMSPACE flight experiment [2] (Fig 2) and we are adapting it to here to reproduce non-uniform temperature profiles by selective contouring of the resistive elements.

Realistic Wall Thermal Conditions on Flight Vehicles

Real airframe structures are non-uniform and often employ semi-monocoque designs. Here, thin, load-bearing shells are reinforced with a heavier substructure of frames and ribs, stringers or longerons. This results in a non-uniform distribution of thermal mass in direct thermal contact with the wetted surface. When convectively heated with a nominally uniform flow the resulting surface temperature distribution will be highly non-uniform as the regions of unsupported thin wall heat more quickly than those in direct thermal contact with the underlying substructure, which serves as an additional thermal heat sink. This non-uniformity will be exacerbated both by more realistic non-uniform heat flux distributions and by variations in thermal conductivity of the materials employed.

This resultant non-uniformity was clearly demonstrated by the design and analysis of NASA’s X-43 scramjet-powered hypersonic test-flight vehicle [8]. Coupled CFD and FEM simulations predicted highly non-uniform temperature distributions on the vehicle’s vertical tail fin resulting from the combined effect of non-uniform heat transfer superimposed onto the non-uniform structure (figure 3). These non-uniform temperature distributions were confirmed by inflight measurements from an array of thermocouples embedded in the fin structure.
Reproducing Non-uniform Wall Conditions

To reproduce this class of non-uniform wall condition the RCC heater approach is adapted via contouring of the heater element. Here the wetted surface geometry of the heater element is retained but the subsurface is contoured to deliberately vary the material cross section. This contouring prescribes the distribution of electrical resistance through the element and thus the distribution of Joule heating. This geometric contouring roughly mimics the structure of the airframe being modelled. The contouring is best achieved by milling the rear face of the RCC heater element. Buss bars are then attached at either end of the element to supply the electrical power to the heater via a computer controlled power supply.

Example Non-uniform Heater Simulations

A number of different geometric heater configurations were simulated for this initial proof-of-concept study using the commercial ANSYS FEM solver to firstly model the Joule heating and then the resultant transient thermal and transient structural behaviour. External radiation loss to the ambient surroundings was applied to the wetted surface.

Simple one- and two-dimensional non-uniform temperature distributions were achieved by contouring the rear of the heater element in one and two dimensions (figure 4). Both discontinuous and tapered geometric steps were simulated using rectangular and curved (cylindrical, spherical) cutouts respectively. This contouring serves to both decrease the local electrical resistance and increase the local thermal mass.

The 2D distribution produced by the heater element using rectangular cutouts required that the electrical conduction path of the axial rib running along the centre of the substructure was broken with an air gap at each cross rib.

In this case high thermal conductivity is no longer a desirable attribute, as it will tend to smear out the induced thermal non-uniformity. For the impulse facility application of primary interest this is not an issue due to the short flow times for these facilities ranging from the order of 1ms for a shock tunnel to 100ms for a Ludwieg tube.

The transient behaviour of the 2D contoured heater is shown in figure 5. Here it is seen that the thermal non-uniformity is strongly apparent at 2s after the beginning of heating but the distribution begins to smear out and by 25s as the bulk of the element is reaching thermal uniformity. This non-ideal effect can be delayed by further reducing the cross section of the thermal conduction path and thus increasing the thermal resistance. This will also tend to increase the local joule heating.

Application in geometrically accurate models requires that the heater must be able to be mounted conformally and that it must be geometrically stable even when energised. RCC maintains its strength and stiffness at elevated temperatures and has a low coefficient of thermal expansion. Figure 6 shows both the minimal degree of distortion and thus the low induced thermal-structural stresses, which are well below the failure stress of the material, even when the heater element is clamped at either end and heated to 1000°C.
Conclusions

A new method for reproducing prescribed non-uniform wall temperature distributions has been described for use in wind tunnel experiments and other ground tests. Multiphysics FEM simulations were used to model the simultaneous electrical, thermal and structural behaviour of the RCC heater elements. These demonstrated that prescribed non-uniform temperature distributions could be transiently induced on the surface of the heater element without significant distortion or stressing of the elements.

References


