Design of a resistor for an ohmic-heated hypersonic wind tunnel

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Abstract— **High-enthalpy wind tunnels are a fundamental tool for hypersonic aerodynamics research. Over the years, several different technologies have been proposed to provide high-quality hypersonic flow as close as possible to realistic in-flight conditions. Ohmic-heaters, using heated resistors to raise the temperature of an air flow, represent a good trade-off among flow quality, mass flow rate, temperature and test time, ideal to investigate the low Mach number supersonic regime.**

This paper presents the design and FEM verification of a high-performance resistor to be used as heating element in an ohmic-heated hypersonic wind tunnel. In the first part, the preliminary design methodology, based on semi-empirical analytical relations, is described in detail. The second part shows the verification and optimization of the preliminary design using the 3D electromagnetic FEM solver EMS by EMWorks®. The use of the software allowed to significantly improve the performance of the resistor in terms of temperature uniformity and heating time.

I. Introduction

EXPERIMENTAL research on hypersonic aerodynamics and high speed combustion strongly relies on the ability of producing flow conditions as close as possible to those encountered in real applications [1]. Nevertheless, the design of a wind tunnel with these characteristics is not trivial and, especially at very high speeds (above Mach 10), can be even unfeasible. When the flow is accelerated to supersonic speed through a converging/diverging nozzle, both pressure and pressure drop significantly. This requires that, in order to reach actual atmospheric values, it is necessary to start from larger pressure and temperature upstream of the expansion (stagnation conditions) [2].

Several pre-heating technologies have been developed during the past 60 years in order to match the required flow conditions [3]. The most widely used are briefly described below. Combustion heaters raise the flow temperature by burning a certain amount of fuel, usually hydrogen, in the test air. In this way stagnation temperatures up to 2,000 K can be achieved, but with the disadvantage of having the flow contaminated by the combustion products or possible unburned fuel. Impulse facilities like shock tunnels or expansion tubes can provide clean flow at realistic pressure and temperature, but their typical test time is limited to a few milliseconds at most [4].

Electric power can be used as source of heating in multiple ways. Ohmic-heaters use electric power to heat a bank of resistors by Joule effect. The air, flowing through the resistors, is heated up and, at the same time, provides cooling for the resistor material (see Fig.1). These devices are able to produce clean continuous flows at realistic flight pressures, but usually the temperature is limited to about 1,000 K, corresponding to a flight speed of 3.4. On the other hand, arc-heaters [5] heat the flow by means of an electric discharge through the gas. These devices can reach extremely high temperatures (above 7,000 K) and operate continuously, but they are affected by flow contamination from electrodes erosion. Also, the pressure and mass flow rates are often limited by the amount of power available.

The present work discusses the design and optimization of a new ohmic-heater for the ACT-II hypersonic facility at the University of Illinois at Urbana-Champaign [6]. The preliminary geometry of the heating elements was verified and optimized, by a trial-and-error approach, in SolidWorks® environment using the finite elements software EMS by EMWorks® [8]. The goal of the project is to expand the current capabilities of the ACT-II wind tunnel to higher pressure, lower temperature conditions. The use of the new ohmic-heater will be complementary to the currently available arc-heater and will allow to cover a wider range of the flight envelop (speed and altitude) of high-speed aircrafts.

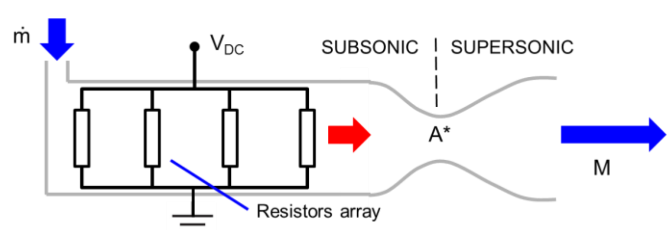

Figure 1. Schematic of an ohmic-heater for a high-enthalpy hypersonic wind tunnel.

The new heater is required to provide an air mass flow up to 233 g/s at a temperature and pressure of 800 K and 3.9 bars respectively. The maximum electric power available to the heater is set, by the ACT-II DC power supply, to 250 kW (600 VDC and 400 A). Since the heater will be operated in pulsed mode, with pulses in the order of 500 ms, the minimization of the settling time will be of fundamental importance. The heater will be initially powered in a vacuum until the resistors reach the required temperature. Then, air will be injected into the heating chamber by fast-opening solenoid valves. The high temperature, low speed air flow will be accelerated to by a contoured converging/diverging nozzle to produce a uniform supersonic stream at Mach 2.

II. Preliminary design method

To determine the approximate dimensions of the resistors required to generate sufficient heat, Matlab simulations were conducted using a simplified model in which the resistors are modeled as flat plates with the airflow direction parallel to the plates. In reality, the resistors are formed from a sequence of parallel plates that snake back and forth, but since the thermal boundary layers will not interfere with one another on adjacent faces, the flat plate model is accurate.

The target air temperature is at least 800 K, so the surface temperature of the resistors needs to exceed 800 K but stay below the melting point of 1700 K for 310 stainless steel. The resistors near the inlet will transfer more heat to the air than the resistors near the outlet due to larger temperature difference between the air and resistor surface. This introduces the potential for overheating of some resistors, but since the test duration is on the order of milliseconds, the tests can be completed and the power supply turned off before the resistors overheat. Thus, in order to simplify the design, each resistor will be identical, measuring 6 cm × 6 cm × 4.5 cm in outer dimensions. Each resistor snakes back and forth to increase surface area and electrical resistance. The resistor assembly will be modular to make the heater versatile for different testing requirements. Fig. 2-5 show the resistor design and assembly. The resistors are held in place by electrodes that thread into the nuts on the resistor. The resistors are contained in a high-temperature ceramic duct, which is surrounded by a thick steel casing. Each module is bolted together with an O-ring seal to prevent air leaks.

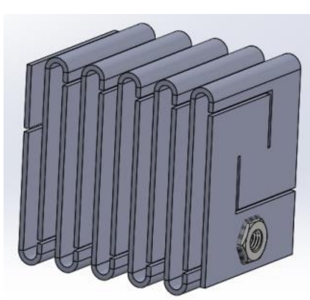

Figure 2. Individual resistor. The electrodes thread into the nuts, which are fastened onto the resistor

Figure 3. Flat pattern of the resistor

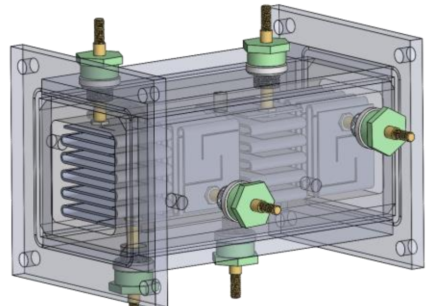

Figure 4. Resistor array module

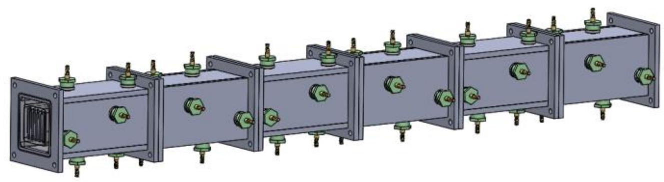

Figure 5. Ohmic-heater assembly

Equations

The determination of the convective heat transfer coefficient is done using the following relation for turbulent flow over a flat plate [7].

$$h = \frac{0.037k}{w}\, Re^{\frac{4}{5}}\, Pr^{\frac{1}{3}}$$

where w is the width of the resistor in the direction of flow, k is the conduction coefficient of air, Re is the Reynold's number, and Pr is the Prandtl number.

The thermal energy q_{indiv} generated within each resistor is also calculated using the following equation:

$$q_{indiv} = \frac{L}{A_c}\rho I^2$$

where L is the length the electricity travels within the resistor, A_c is the cross sectional area of the resistor, ρ is the stainless steel resistivity, and I is the current passing through the resistor. With an available power supply of V = 600 V, the current passing through each resistor is determined to be 258 A by the following equation.

$$I = \frac{q_{total}}{V}$$

where q_{total} is the sum of q_{indiv} from each resistor.

III. Simulation results

EMS by EMWorks® software package is used to simulate the electrical heating in the resistor. This allows for optimization of the resistor geometry to obtain a uniform surface temperature, proper electrical resistance, and adequate power generation in each resistor.

The material used is 310 stainless steel, with the material property inputs described in Table 1. Electrical conduction studies are performed with transient conditions for a 30 s duration at 1 s time steps. The current is 258 A, the voltage of the exit port is set to 0 V, and the mesh size is approximately 1 mm with finer mesh in high current density regions. Multiple geometries have been simulated, with the primary iterations shown in Fig. 6 – 9.

Property	Conductivity [Mho/m]
Thermal conductivity [a] (W/m/K)	0.06 – 33.21
Specific heat (J/kg/K)	490
Electrical conductivity [a] (Mho/m)	1.91e6 – 0.76e6
Density (kg/m^3)	7700

Table 1. 310 stainless steel material properties (a. Temperature dependent property. Range listed from 0 K to 1700 K)

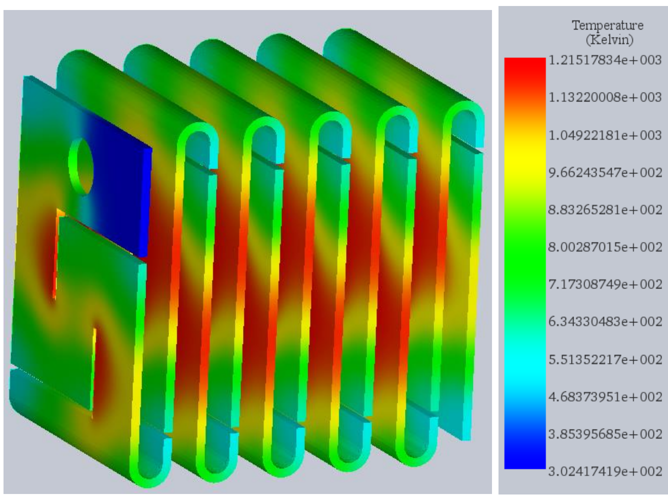

Figure 6. Design 1 temperature profile after 15 s.

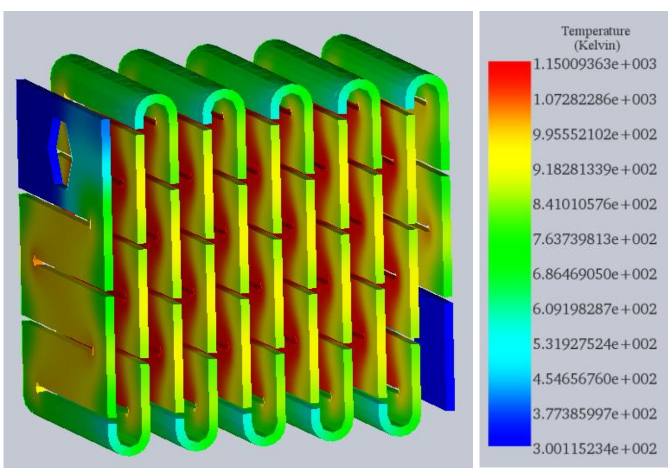

Figure 7. Design 2 temperature profile after 12 s.

Design 1 (Fig. 6) results predict uneven heating. The air would be insufficiently heated with such varied surface temperature. The first physical prototype made and tested was design 1. After applying a current of 258 A for 5 seconds, the temperature on the bends increased by 150 K, which exactly matched the simulation results at that time step. Additional tests will be run to compare the temperatures of the hot and cold zones in the physical prototype with those of the simulated model.

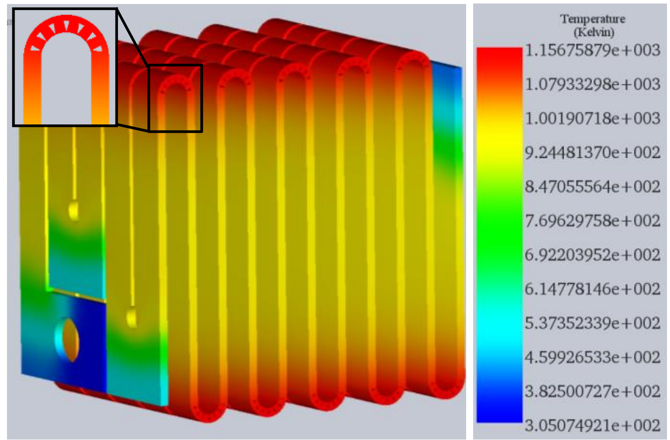

Figure 8. Design 3 temperature profile after 10 s.

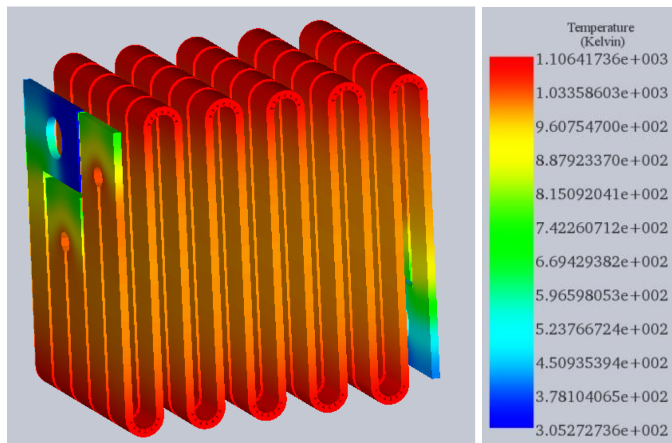

Figure 9. Design 4 temperature profile after 18 s.

Design 2 (Fig. 7) seeks to produce more uniform surface temperature than design 1. While the internal faces have a uniform temperature, the outer edges and bends are up to 300 K cooler, which would also insufficiently heat the air.

Design 3 (Fig. 8) allows the current to flow along a straight path with minimal turns. This promotes uniform current density and thus uniform heating. In order to make the prototype easier to form, relief slits were cut into the bend to reduce the material thickness. The simulation shows a uniform surface temperature on the flat faces, but the bends are approximately 200 K hotter than the flat faces. In order to get the flat faces hot enough to heat the air adequately, the bends would potentially overheat and become damaged. The reduced material thickness caused by the bend slits increases local current density, so the surface temperature is also greater in those regions. To combat this issue, the bend slits in Design 4 (Fig. 9) were reduced from a depth of 1 mm to 0.75 mm, which is half of the material thickness. This small adjustment resulted in nearly uniform surface temperature across both the bends and flat faces. The maximum temperature difference is 50 K. Design 4 is the next prototype that will be fabricated and tested.

IV. Conclusion and Future Work

The desing of a heating element for an ohmic-heated hypersonic wind tunnel was performed in two steps. A preliminary thermal-electric design based on semi-empirical models and a FEM verification using EMS by EMWorks®.

The numerical simulations proved to be extremely helpful in guiding the optimization of the resistor geometry in many key aspects. The overall resistance was strongly overestimated by the preliminary calculations and it was therefore necessary to significantly increase the length of the electrical path. The simulations also revealed potentially dangerous hot spots localized at the turning points of the path, were the temperature was 30 to 40% above the average. An effective solution to this problem was the introduction of round cuts at these points to reduce the local current density. Another problem highlighted by the simulations was the high non-uniformity of the temperature in the initial design. Uniformity of heating is a critical factor for heat-transfer efficiency and for the quality of the wind tunnel free stream. The design of the electrical path was completely revised switching from L-shaped cuts to horizontal and ultimately to vertical cuts. The improvements is uniformity can be clearly seen from Fig.6 to Fig.9

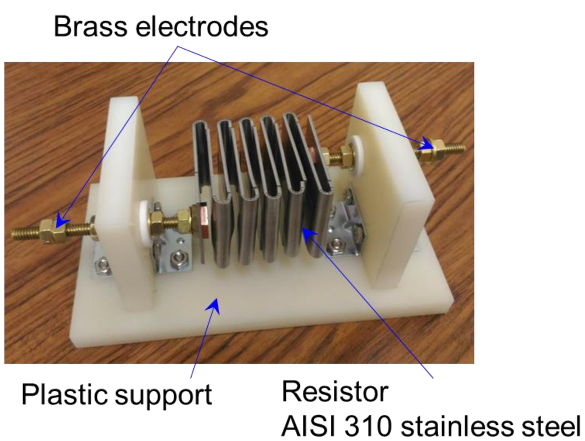

Figure 10. Prototype of the design 1 resistor for preliminary testing.

In the next steps of this activity, a few prototype of resistors will be built (Fig.10 shows the prototype of the design 1 resistor) and tested. The resistor will be mounted on an insulating support and powered at the design values of voltage and current. Temperature will be measured at selected locations on the surface, to evaluate heating dynamics and uniformity. The tests will be performed at atmospheric pressure and in a vacuum chamber. The results will be used to validate the design procedure and to investigate the behavior of the resistor in off-design conditions. Once the design of the single resistor is finalized, a heater module (Fig.4) will be built and tested with the air flow to evaluate the overall performance. The new ohmic heater is expected to be operating within the end of this year.

References

[1] Curran E. and Murthy S., "Scramjet propulsion." AIAA Progress in Astronautics and Aeronautics, vol. 189 (2001).
[2] Pope A. and Goin K. L., "High-speed wind tunnel testing." Krieger Pub Co (1978).
[3] Lu F. K. and Marren D. E., "Advanced hypersonic facilities." AIAA Progress in Astronautics and Aeronautics, vol. 198 (2002).
[4] Ben-Dor G., Igra D. and Elperin T., "Handbook of shock waves." Academic Press (2000).
[5] Pfender E., "Electric arcs and arc gas heaters," in Gaseous Electronics (Academic, New York, 1978), Vol. 1, Chap. 5.
[6] Baccarella D., Liu Q., Lee T., Hammach S. and Do H., "The supersonic combustion facility ACT-I," AIAA Paper 2017-0103 (2017).
[7] Bergman T. L., Lavine A. S., Incropera F. P. and Dewitt D. P., "Fundamentals of heat and mass transfer (7^{th} ed)," Wiley (2011).
[8] "EMS software," [Online]. Available: https://www.emworks.com/products/EMS.