Engineering Notes

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Spacecraft Applications of High-Temperature Electrically Conducting Ceramics

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Introduction

THIS note describes the application of an old art—the Nernst glower—to some of today's spacecraft requirements. During the last 15–20 years there has been a renewed and growing interest in the properties, characteristics and applications of certain metal oxide ceramics which are classified as electrical insulators at normal temperatures but which exhibit significant and useful electrical conductivity at elevated temperatures. For high-temperature applications, the most interesting and potentially useful of these materials are the solid electrolytes based on certain oxides of the group IV-B metallic elements, notably doped thoria (ThO_2) and stabilized zirconia (ZrO_2), both of which exhibit predominantly anionic (oxide ion) conductivity at high temperatures. Zirconia is normally stabilized in its cubic form by the addition of controlled amounts of CaO, Y_2O_3, MgO, and/or rare earth oxides; thoria is normally doped, with Y_2O_3 for example, to enhance conductivity. The elevated temperature conduction characteristics of zirconia were first investigated by Nernst in the 1890's, leading to the development of the still very useful Nernst glowers.

The most significant use of the Nernst glower has been for infrared sources as, for example, in IR spectrophotometers. The device has not enjoyed wide acceptance because of poor cyclic life and the requirement to be "turned on" by an external heat source. Recent advances here now demonstrate excellent results in those areas. New materials and fabrication techniques have improved cyclic lifetimes of Nernst glowers by an order of magnitude, have resulted in lower "ignition" temperatures, and have resulted in higher operation temperature capability.

Applications

A recent and unique application of electrically conducting ceramics involves the biowaste resistojet being developed§ for stationkeeping and CMG desaturation of space stations. Biowaste resistojets using noble metal heater elements offer a chamber temperature capability of 1560°K, corresponding to 170 and 240 sec specific impulse, respectively, with the typical biowaste propellants CO_2 and H_2O.[1] This performance is increased significantly to 200 and 275 sec, respectively, using electrically conducting ceramics with a chamber temperature of 2000°K.[1,2] The ceramics are conservatively rated for a maximum structural temperature of 2100°K for lifetimes measured in thousands of hours and thousands of operating cycles.

Details of the 2000°K biowaste resistojet concept are presented in Ref. 2. Briefly, the final (and principal) stage of heating, from about 800 to 2000°K, occurs in axial flow through a multipassage electrically conducting ceramic cylinder. A regenerative heat exchanger provides preheating to 800°K to maintain a high thermal efficiency. The ceramic heater does not require the preheater for its operation once it is ignited. Interestingly, it will very effectively heat a cold gas by virtue of its having an electrical resistance with a negative temperature coefficient characteristic (resistance decreases with increasing temperature). Consider a cold gas flowing axially through a ceramic heater tube. In the inlet region, the temperature of the tube is reduced slightly resulting in a significant increase in resistance and, hence, in the ohmic heating (I^2R) where current is the same everywhere along the tube. The result is that heater tube wall temperature typically varies less than 100°K for a 2000°K maximum temperature condition. In contrast, a wall temperature variation of more than 1000°K would be expected for a metal tube.

An additional and favorable consideration with regard to the mechanical design of an electrically conducting ceramic heater element is that it has a relatively high resistivity (10^{-2} ohm-m at 2000°K, for example) as compared to metal. The consequence of these considerations is that a ceramic heater element for a biowaste resistojet can be relatively short and thick, a shape one would normally want to employ for ceramic materials when guided by structural considerations. As an example, the primary heater element in a 10-mlb noble metal biowaste resistojet[3] has dimensions of the order of 1.3-mm o.d., 0.15-mm wall thickness, and 50-mm length. Such a thrustor operates at low voltage-high current (3 v and 50 amp for 150 w, for example). The dimensions of a typical ceramic heater element, on the other hand, are 4.1-mm o.d., 1.2-mm wall thickness, and 50-mm long; it would operate at 120 v and 1.25 amp for 150 w of power. The ceramic heater, therefore, adapts well to the spacecraft electrical systems.

Regarding the requirement of ignition of the ceramic heater element, this is the consequence of the ceramic behaving as a good electrical insulator when cold. An auxiliary heater is used to preheat the ceramic to its ignition point, typically 1000 to 1200°K, after which the ceramic heater is self-sustaining. Another factor to be considered in using electrically conducting ceramics is the "negative resistance" characteristic. With a constant voltage supply, the ceramic element would increase in temperature to destruction. A stabilizing ballast resistor, or better, an inductive impedance in the case of alternating current, is included in series with the ceramic element. This is a normal requirement for devices such as electric arcs and fluorescent lamps.

In the biowaste resistojet design of Ref. 2, part of the stertar heater winding (a Pt-Rh alloy wire coil) also serves as the ballasting resistor. In that design the ballast resistor and ceramic heater element resistances are selected, from stability considerations, such that about 20% of the total power is dissipated in the ballast resistor and about 80% is dissipated in the ceramic element. Since the same current flows through both elements, the input voltage—120 v a.c.—also divides in the same proportion. A high percentage of the ballast

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resistor power dissipation and the thermal losses from the ceramic heater element are recovered by the regenerator mentioned earlier.

Another application of electrically conducting ceramics is for very high temperature-oxidizing environment furnaces. Temperatures of up to 2500°K are being considered for long lifetime. The conducting ceramic oxides are unique in that they are the only resistive heater materials capable of such high temperature while directly exposed to oxidizing atmospheres. Stabilized zirconia, which melts at about 3000°K, is such a material. Growth potential to 3000°K is offered by thoria, which has a melting point temperature of about 3500°K. Such furnaces have broad aerospace and industrial applications. One of the more exciting concepts is for high temperature crystal growing where the oxidizing environment is requisite to high quality crystals. Wuenscher[4] discusses unique space manufacturing possibilities which take advantage of the zero gravity field and high vacuum available in space.

A high-temperature furnace using the conducting ceramic heater elements has now been experimentally demonstrated by the authors. In the space environment this offers the potential for producing high quality gadolinium gallium garnet crystals for use in magnetic bubble domain memories, for example. With an oxidizing environment in the furnace cavity, contamination from the heater elements is negligible at temperatures up to 2500°K and, with the zero-g field, contamination by crucibles is eliminated.

As solid electrolytes, the electrically conducting ceramics have been used for fuel cells[5] and oxygen recovery systems.[6] The latter uses the ceramic in an electrolysis process, the opposite of the fuel cell. In these systems, the transfer of oxygen ions is required, hence, they are direct current devices. Since the negatively charged oxygen ions (anions) move from the cathode to the anode, these electrodes must be porous to permit the flow of molecular oxygen from the anode and to permit the products to reach the cathode reaction region. Electrical conductivity requires elevated temperatures (above the ignition temperature) and such temperatures are limited by the electrode metals used rather than the capability of the oxide-electrolytes. Typically, platinum metal is used for the electrodes and metal evaporation data suggest a 1600°K temperature limit on the oxide-electrolyte fuel cells and electrolysis units.

Other applications for electrically conducting ceramics which could evolve from the biowaste resistojet development but are not themselves space oriented are:

1) High-temperature oxidizing gas heaters for wind tunnels and kinetic reactors. Particulate-free and chemically clean high temperature gas is possible in contrast to blow-down type heaters. The conducting ceramic heater concept offers the potential for prolonged operation and relatively rapid response.

2) A hot gas surgical scalpel which uses human body compatible gases CO_2 and H_2O is being studied by the authors as a new medical tool. Here, a small diameter (order of 1/4 mm) jet of 2000°K gas is used to provide simultaneous cutting and hemostasis of tissue.

3) Since they have oxidation resistance at very high temperatures, zirconia and thoria can be used effectively to decompose water vapor, carbon dioxide, etc. thermally. This process is being studied for solar power conversion systems.

Experience

In order to conduct electricity through the ceramic oxide heater elements, metallic electrodes must be interfaced with the hot ceramic. It is not necessary, however, that the interface temperature be equal to the maximum operating temperature of the ceramic heater. With a flowing gas type of heater, the cooler incoming gas can be used to cool and control electrode temperatures. In a furnace, where the environment tends toward an isothermal one, electrode temperature control is handled by contouring and/or staging the metal-to-ceramic interface and locating the interface region in a lower temperature zone. The National Bureau of Standards furnace described in Ref. 7 is an example of this technique. One-cm-diam heater element rods of thoria are interfaced with 1.3-cm-diam by 2.5-cm long cylinders of stabilized zirconia which in turn contain platinum-rhodium alloy lead wires. The NBS thoria element furnaces are used to temperatures of 2300°K. Typical specimen size for these furnaces is up to 4 cm diam by 5 cm long.

Rothwell[8] describes a thoria-base heater element consisting of a 1 cm o.d. thin tube interfaced with stabilized zirconia contact blocks and platinum-rhodium lead wires. The cavity for this furnace is small, consisting of the inside of the heater element tube and measuring about 0.8 cm diam by about 3 cm long. This furnace was operated to 2570°K, with lifetime at high temperature being a couple of days.

The authors' experience with electrically conducting ceramics has been in two areas, high-temperature furnaces and heaters for flowing gases (biowaste resistojets[2]). The largest furnace tested consisted of a cylindrical heater element with an internal cavity of 2.5 cm diam by 6 cm long. With regard to the biowaste resistojets, both cyclic tests and long duration tests with typical biowaste gases (air, CO_2, H_2O and N_2) have been conducted. Two thousand-hour cyclic tests, with 1 cycle/hr, have been run at 1920°K on stabilized zirconia. At 2200°K, stabilized zirconia has been operated for 1000 hr. Both endurance tests were without ceramic failure. Maximum temperature tests which have been conducted include 2550°K on stabilized zirconia and 2775°K on thoria, both in air. Heat flux rates for these conditions were 223 and 264 w/cm^2, respectively.

A more meaningful thermal flux limit is expressed in terms of the flux rate times the thickness of the ceramic through which the heat is transferred (QX/A). This represents the temperature difference which is proportional to thermal stress. This parameter is referred to as a thermal stress loading parameter. For the above cases, the QX/A was 11.5 and 12.2 w/cm, respectively. For the 1000 hr–2200°K test, QX/A was 7.1 w/cm, (93w/cm^2) without failure of the ceramic element. A conservative value recommended for ceramic heater elements is 4 w/cm.

Conclusions

Technological improvements have been made in an old art—the Nernst glower—that makes the use of electrically conducting ceramics for high temperature heating attractive for spacecraft applications. Temperatures of up to 2500°K for thousands of hours and thousands of cycles in oxidizing environments now appear possible.

References

[1] Halbach, C. R., Page R. J., and Short, R. A., "High Temperature Biowaste Resistojets Using Electrically Conducting Ceramic Heaters," AIAA Paper 72-454, Bethesda, Md., 1972.

[2] Halbach, C. R., Page, R. J., McCaughey, O. J., and Short, R. A., "Investigation of Biowaste Resistojets for Space Station Application," CR-112159, July 1972, NASA.

[3] Halbach, C. R. and Yoshida, R. V., "Development of a Biowaste Resistojet," *Journal of Spacecraft and Rockets*, Vol. 8, No. 3, March 1971, pp. 273–277.

[4] Wuenscher, H. F., "Manufacturing in Space," *Astronautics & Aeronautics*, Vol. 10, No. 9, Sept. 1972, pp. 42–54.

[5] Liebhafsky, H. A. and Cairns, E. J., *Fuel Cells and Fuel Batteries*, Wiley, New York, 1968, Chap. 13.

[6] Elikan, L., Morris, J. P., and Wu, C. K., "Development of a Solid Electrolyte Carbon Dioxide and Water Reduction System for Oxygen Recovery," CR-2014, May 1972, NASA.

[7] Lang, S. M. and Geller, R. F., "The Construction and Operation of Thoria Resistor-Type Furnaces," *Journal of the American Ceramic Society*, Vol. 34, No. 7, July 1, 1951, pp. 193–200.

[8] Rothwell, E., "Oxide Resistor Furnace for High Temperature Operations," *Journal of Scientific Instruments*, Vol. 38, May 1961, pp. 191–193.