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THE DEVELOPMENT OF CERAMIC-BASED THERMOCOUPLES FOR APPLICATION IN GAS TURBINES

D.M.Farrell
Rowan Technologies Ltd.
Carrington Business Park, Carrington
Manchester M31 4ZU, UK
Tel: (44) 161 775 4648
Fax: (44)161 776 4518
e-mail: rowantech@dial.pipex.com

J.Parmar
TUV Energy Services
12 Marshall Road, Swindon
Wiltshire SN5 9FZ, UK
Tel: (44)1793 882 422
Fax: (44) 1793 882 433
e-mail: jparmar@sw.tuv.co.uk

B.J.Robbins
Rowan Technologies Ltd.
Carrington Business Park, Carrington
Manchester M31 4ZU, UK
Tel: (44) 161 775 4648
Fax: (44)161 776 4518
e-mail: rowantech@dial.pipex.com

ABSTRACT

A research and development project has recently been carried out to develop ceramic thermocouple probes (CTPs) capable of measuring temperatures up to 2000°C and rugged enough to withstand extended service in high-temperature gas turbine environments. Existing metallic thermocouple technology cannot withstand such conditions for sustainable periods of time. Following initial laboratory studies, CTP trials were carried out in power generation boilers (Farrell and Higginbottom, 1995). Prototype CTPs were subsequently developed for evaluation in gas turbine (GT) combustors (at atmospheric and elevated pressures) and in a Spey engine (Patent,1996). The CTPs performed well under the harsh conditions imposed, demonstrating their mechanical integrity and consistency/sustainability of signal output. Initial studies have also been carried out with a view to applying ‘thin-layer’ ceramic thermocouples directly onto thermal barrier coatings to give surface temperatures on stator or other hot gas surfaces, and are briefly mentioned. Rowan Technologies and TÜV Energy Services are currently looking for companies interested in exploiting this new ceramic thermocouple technology.

INTRODUCTION

Evolution of Gas Turbine Technology

One of the first breeds of gas turbines for industrial usage came into operation in the early 1930s. These were born from the aero-thermodynamic evolution from the military gas turbines utilised during World War I and modified during World War II. Later in the early 1960s, lightweight small gas turbines were introduced in the power industry, marine propulsion, and pipeline compression applications. These gas turbines were fired between 600° and 800°C with compression pressure ratios approaching 12:1. The corresponding thermal efficiencies ranged from about 23% to 28%. In the mid 1970s, a second generation of gas turbines came into operation, most of them in open cycles based on aero designs. These gas turbines had open cycle thermal efficiencies of 31 to 37%. In the last ten years the gas turbine market has boomed and seen the industrial gas turbines in open cycle approaching thermal efficiencies of about 39 to 40%. By the same measure, the aero-derivative engines are now attaining simple cycle thermal efficiencies of 43 to 44%.

Performance and Financial Considerations

The efficiencies now attainable on aero-derivative and industrial gas turbines are mainly attributed to an increase in firing temperatures and the introduction of novel materials to sustain such high temperatures. These efficiency figures in many instances are customer driven in the competitive global market. Traditionally, the major cost focus of a power plant is on the acquisition phase of gas turbines with very little emphasis placed on the operational cost factors. Experiences within power utilities has shown that acquisition of higher technology gas turbines with higher efficiencies with low initial investment cost does not imply a lower total cost during the life expectancy of the purchased plant. Today, there is a need for all power utilities to assess and consider parameters that recognise the advancements in materials and life impact of such gas turbines. The assessment parameters must consider all of the cost elements in the operating life of the power plant.

During acquisition and subsequent operation of the power plants, the major factors that are taken into consideration are: initial investment cost, cost of financing, thermal performance, cost of fuel, direct operating costs, spare parts for preventive and corrective actions and availability issues. Many variables, such as application (simple or combined cycle) or duty cycle (peaking, cycling or base load) influence the expected reliability of the power plant. Hot section inspection and maintenance represents the greatest source of unavailability for any utility running state-of-the-art gas turbines. It is now recognised within many power utilities that efforts to improve availability can benefit from diagnostic instruments capable of measuring the interrelationships between hot gas components and detecting their degradation and obviously preventing any catastrophic failures.

Background to Ceramic Thermocouple Development

During research carried out by RTL in the early 1990s it was discovered that ceramics could give thermal voltages in a similar manner to bi-metallic thermocouples (background theory of the thermoelectric effect is given in Annex A). It soon became apparent that ceramic-based thermocouples could find application in high temperature and highly corrosive environments where other temperature measurement devices are either inappropriate or have a short working life, for example in high temperature power generation plant. The government-sponsored research programme was initiated in 1994 to develop ceramic thermocouple probes (CTPs) that could be reliably used in combustion systems. This programme included the development and evaluation of CTPs for use within gas turbine power plant, which would help optimise performance and reliability.

Primary issues to be addressed included:

- The identification of a combination of two commercially available ceramics that would give reliable and consistent emfs with temperature, with the ability to withstand high thermal shock.

- Achieving and maintaining good electrical contact between the two ceramics at both ‘hot’ and ‘cold’ ends of the CTP.

- The interfacing of suitable electronics for signal calibration and output.

Later stages of the development project were concerned with developing temperature sensors, which would ultimately be employed in the combustion zone of gas turbines.

INITIAL MATERIALS EVALUATION

A series of commercially available, electrically conductive engineering ceramics were evaluated in the laboratory to assess their electrical performance and reproducibility. Ceramics included silicon carbides and nitrides, lanthanum chromite, zirconium oxides, titanium oxides, molybdenum disilicide and others. A high temperature version of a commercially available silicon carbide, in combination with molybdenum disilicide, gave a reliable and reproducible CTP that could be used between the temperature range 150^{o} to 1850^{o}C. However, other ceramics were found to have specific characteristics which could prove useful under certain environmental conditions, e.g. zirconium oxide may be used at temperatures of up to 2100^{o}C but is not particularly resistant to thermal shock. Also, carbon may be used at temperatures in excess of 3000^{o}C but only in non-oxidising environments. The CTPs typically yielded emfs of between 15mV and 150mV at 1000^{o}C.

CTP DESIGN AND INSTRUMENTATION

Following the initial trials, work began on the design of suitable probe assemblies consisting of a ceramic tube, closed at one end, and a concentric rod. A schematic of a typical CTP is shown in Fig. 1.

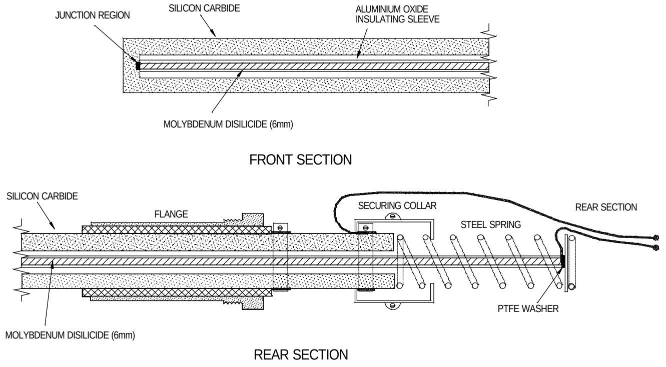

Figure 1: Schematic of a Typical CTP

The surfaces of the ‘hot’ end of the ceramics were diamond ground and the surfaces were forced together using a stainless steel spring located at the ‘cold’ end. The two ceramics were electrically isolated at their ‘cold’ end using insulating ‘washers’.

Prototype CTPs were tailor-made to suit particular applications. Large diameter (up to 44mm) silicon carbide sealed tubes were used for in-plant trials in boiler plant and smaller diameter (10mm) tubes were used for gas turbine tests. The diameter of the internal molybdenum disilicide rods varied between 2 to 6mm. The CTPs designed for higher temperature tests used stainless steel or nickel-based alloys for the ‘cold’ end springs, compared with hardened steel springs for lower temperatures.

Because of the rather weak and non-linear nature of the output signals from the CTPs, signal conditioning was employed to produce stronger signals that were linear with temperature. Signal conditioning was performed in three stages: using a 16 bit A/D converter, two 32Kbyte EPROMS (memory chips) loaded with a look-up calibration table and finally a 16 bit D/A converter. Buffered amplifiers were used to boost the signal and provide 0-10V and/or 4-20mA signals for on-line monitoring. Look-up calibration tables were produced from the CTP thermal emf/temperature profiles derived from laboratory tests.

COMBUSTION RIG AND SPEY ENGINE TESTS

Tests were carried out in the combustor sections of an atmospheric combustion rig, an 8 bar combustion rig and in the jet-pipe of a Phantom Spey aero-engine at the UK Defence Research Establishment Agency (DERA), Farnborough, UK.

Combustion Rig Tests

A 10mm silicon carbide/molybdenum disilicide CTP was mounted in front of the exhaust port of the atmospheric gas turbine combustor. A type B (platinum/platinum 30% rhodium) thermocouple was located adjacent to the CTP in order to check the laboratory-based calibration, Fig. 2. The combustor was fired on kerosene and was initially pre-heated before the main jets were ignited. On combustor ignition, the logged temperatures increased rapidly (within 0.5sec) from 200 to 1200^{o}C. Pilot and main fuel flow rates (of up to 10gs^{-1}) were varied and multiple ignition tests performed to assess the CTP's ability to withstand thermal shock; the CTP withstood the severe conditions and yielded good results over the tests.

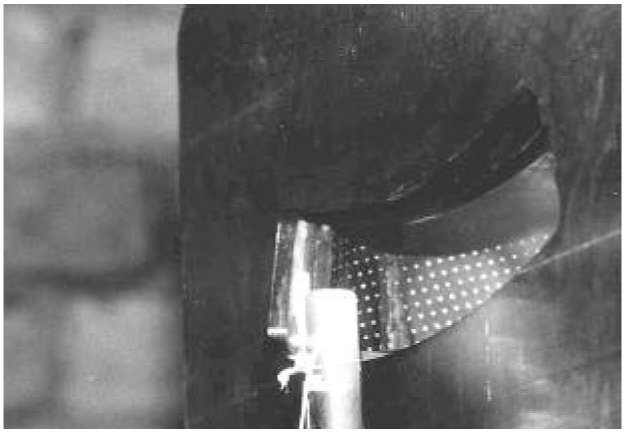

Figure 2: CTP Combustor Tests

The potentials logged from the CTP reached a maximum at 125mV (around 1800^{o}C). The type B thermocouple (maximum operating temperature 1750^{o}C) degraded rapidly during the tests and failed after a total exposure of around 5 minutes. During the tests, the CTP was used to assess temperature profile across the smile (exit aperture) of the combustor. Following these atmospheric tests, a second CTP design was evaluated in a pressurised combustor at around 8 bar. Performance was satisfactory at this pressure although mechanical movement of the combustor casing resulted in fracture of two CTPs.

Phantom Spey Engine Tests

A CTP was installed into the forced mixer position of a phantom Spey engine at DERA, Fig. 3. The CTP (and adjacent industrial type K thermocouple) measured the engine core flow stream temperature of the low pressure turbine just before mixing with the bypass air. The temperature in this region can exceed 900^{o}C.

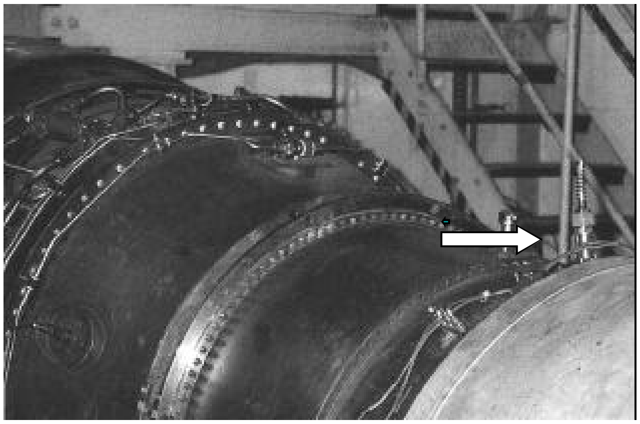

Figure 3: CTP Spey Engine Tests
(CTP is located at top of engine, far right)

CTP data for a typical test run is given in Fig. 4. The CTP was subjected to more than 15 hours of engine running in which the GT engine reached full power (93% shaft speed) many times and the engine was surged repeatedly.

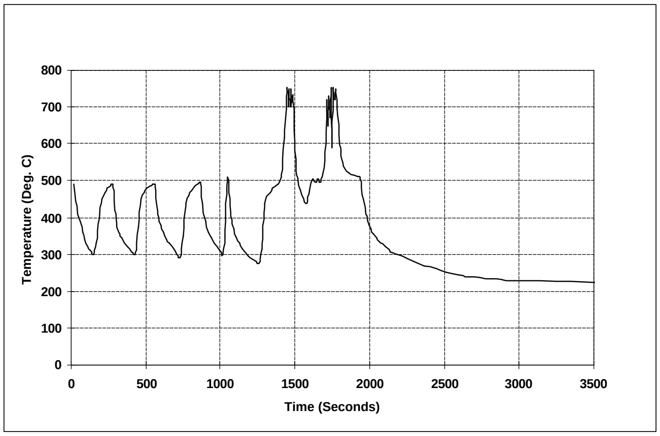

Figure 4: CTP Data from Typical Surging Tests

The main objective of these tests was to determine whether the CTP could withstand the conditions of vibration and thermal stress presented by the engine. Secondary objectives were to assess accuracy, repeatability and dynamic response in relation to other commercial metallic thermocouples installed within the same region of the engine. At the end of these tests the

CTP appeared to be structurally intact and demonstrated good mechanical strength in the severe conditions within the engine exhaust.

‘THIN LAYER’ CERAMIC THERMOCOUPLES

Preliminary studies suggest that it is feasible to create thermocouples within the ceramic thermal barrier coatings of gas turbine blades. This could be achieved using suitable combinations of ceramic layers coated onto the blade surface. Issues to address include:

- Choice of ceramics: suitable emf/temperature characteristics combined with the ability to withstand the harsh environment e.g. thermal cycling and excellent surface adhesion.
- Techniques for applying the coatings on the blade surface: to provide a suitable thermocouple circuit with appropriate electrical insulation.
- Ways of bringing the thermocouple signals from the blades to the outside world.

Although this technique has been found to work in the laboratory, a significant amount of R+D is required prior to its application in a gas turbines.

DISCUSSION

The silicon carbide based CTPs showed their ability to withstand the severe conditions encountered in the gas turbine combustor tests, both at atmospheric pressure and at 8 bar. Numerous attempts were made to fracture these CTPs through thermal stress but they coped well. However, a thin walled zirconia CTP was also evaluated in the atmospheric combustor and this failed due to thermal stress when the main fuel flow was ignited.

CTP output signals showed similar behaviour to the type B thermocouple during the combustor tests except that the life of the latter was short compared to the CTPs. With the help of the CTPs it was possible for DERA to carry out some high temperature tests and correlate this with rig operation and gas sampling results.

During the lower temperature tests carried out in the Spey engine, the CTPs were again installed alongside type K thermocouples. The dynamic response of the CTPs was slightly slower than the conventional thermocouples; this was associated with differences in thermal capacity and conductivity of the ceramics compared with metal-sheathed thermocouples. The main objective of the tests was achieved in that the mechanical integrity of the design was demonstrated.

A number of improvements have recently been made to the CTPs to simplify manufacture and improve their reliability and the first ‘industrial’ versions are currently being evaluated in the process industry.

The availability of ‘thin layer’ CTPs is still some way off but is considered to represent the way forward to help control future generations of gas turbines.

CONCLUSIONS

- Ceramic thermocouples have been designed and extensively tested in laboratory furnaces. The thermoelectric characteristics of bi-ceramic junctions using most commercially available ceramics have been evaluated.

- CTPs have been used to measure gas temperatures in gas turbine combustion rigs and the engine core flow stream, downstream of the low-pressure turbine, in a Phantom Spey engine. The sensor withstood the severe conditions of vibration and thermal stress presented by the engine during both full power tests and under repeated surging.

- Long term boiler and furnace tests have also shown that temperatures in excess of 1850°C can be monitored on a continuous basis. CTPs could be used to measure gas temperatures in corrosive environments such as gas turbines, coal and oil fired boilers, incineration plants and hydrogen sulphide conversion systems in high temperature refinery plant.

- Initial studies suggest that thin layer CTPs, applied directly to thermal barrier coated surfaces, may provide a reliable way of measuring blade temperatures in GT engines. This could help to predict blade life and be a useful indicator of turbine performance. Such a development project would be of interest to large power utilities and OEMs for monitoring the performance and life expectancy of gas turbine components in the hot gas path.

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ANNEX A

THERMOELECTRIC EFFECTS AND CERAMIC MATERIALS

When valence electrons, which are loosely bound to atoms, gain sufficient external energy they become free to move within an electrically conducting material. The energy and density of these electrons may differ between two different materials for a given temperature and, if the materials are brought into contact, there will be a net diffusion of electrons in one direction resulting in an electric field. Equilibrium is reached when the interface potential balances this diffusion force (Benedict). This is the thermoelectric effect. In the case of semiconductors, both electrons and holes (n and p type charge carriers) contribute to these thermoelectric processes.

The Effect of Phonons

In a standard thermocouple circuit, there are two junctions at different temperatures resulting in a net diffusion current. At low temperatures, phonons (quanta of lattice vibrational energy) scatter from electrons and impurities, rather from other phonons. As the temperature difference increases between the two junctions, more phonons become available and start to drag the electrons along. At still higher temperatures, phonons begin to scatter more frequently from each other; this scattering eventually becomes dominant and the electrons are no longer dragged along. Phonon interaction can have a big influence on a thermal emf/temperature profile and in the case of 'poor' ceramic combinations may cause the profile gradient to change sign at fixed temperatures (McGraw Hill), Fig. 5.

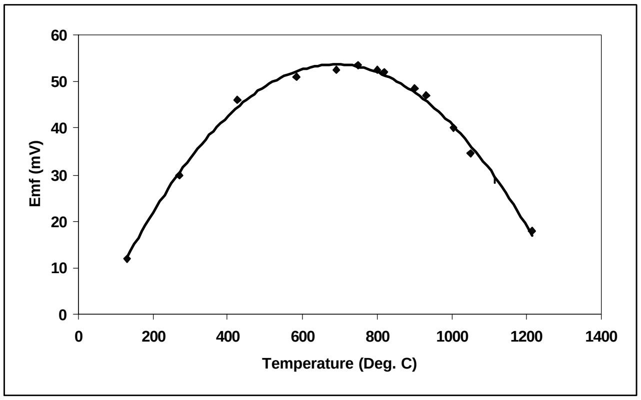

Figure 5: Thermal Emf/Temperature Profile for a 'Poor' Ceramic Combination

For bimetallic combinations, thermal emf vs temperature relationships are often approximated by Eq.(1):

$$\text{emf} = at + bt^2 \qquad (1)$$

Where (a) and (b) are constants and (t) is temperature. As an example, for type K thermocouples, $a = 41\ \mu V^{o}C^{-1}$ and b = approx. zero $\mu V^{o}C^{-2}$ in the range 0-900 ^{0}C. At temperatures above 900 ^{0}C, the constant (b) starts to become significant.

For 'good' ceramic combinations the situation is somewhat more complicated, the shape of the curve being more akin to a logistic function consisting of three distinct sections, Fig. 6:

1. A low thermoelectric power at low temperatures generates only a small emf. This corresponds to minimal phonon/electron scattering phenomena.
2. A rapid increase in thermoelectric power coefficient at around 100-200^{o}C results in a much greater emf/temperature profile gradient. This may increase to temperatures in the range 800 to 1400^{o}C. This is due to the increased incidence of phonons and phonon drag.
3. A reduction, at even higher temperatures, in thermoelectric power coefficient causing the emf/temperature profile to level out. This probably represents the gradual domination of phonon/phonon scattering events.

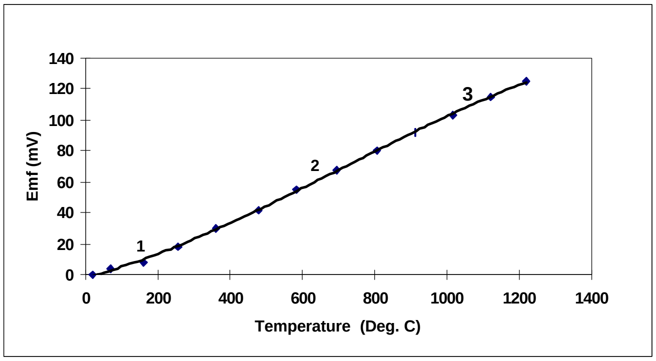

Figure 6: Thermal Emf/Temperature Profile for a 'Good' Ceramic Combination

The exact form of the curve varies greatly from one bi-ceramic combination to another and a polynomial expression is normally used to describe its performance.