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Simulation of Thin Film Thermocouple for High Temperature Measurement Applicable to Missiles

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ABSTRACT

Thermocouples have been extensively used for the measurement of temperature since the advent of seebeck effect. Numerous sensors have been developed for temperature measurement, yet measurement of high temperature flowing fluid has been a challenging task. For the measurement of static temperature the measuring device should travel with the fluid at the same speed without disturbing the flow, which is quite unrealistic. So indirect determination of static temperature of flowing fluid is done by using thermocouple exposed into the flowing fluid. Other sensors available for high temperature measurement may lead to problems like resistance in the flow path of fluid which changes the structural dynamics. Thin film thermocouple (TFTC) based on W-W26Re for super high temperature measurement has been investigated which can be used in missiles for surface temperature measurement of nozzle and rocket interior surface. TFTC does not cause disruption in the flow path with maintaining structural integrity. The W-W26Re thermocouple offers advantage of higher seebeck coefficient at high temperature i.e. above 750 K, and usability in vacuum, inert and hydrogen atmosphere. Zirconia Fiber has been proposed as insulation protection material over thermocouple. Modelling and simulation of the TFTC for the temperature range 300 K - 2900 K has been presented. FEA model using PDE has been presented to implement heat equation, current balance equation, Gauss theorem and Neumann boundary condition. The expected voltage production on exposed temperature gradient has been studied.

Keywords: Thermoelectric, seebeck effect, super high temperature, junction, emf, insulation, composite, thermal expansion coefficient, nozzle, missiles

1. INTRODUCTION

Temperature measurement has been prime importance in most of the industries, defense application, nuclear plants, and aeronautics. Various methods have been adopted for measurement of temperature like variation in resistance, radiation based measurements, and seebeck effect sensors, etc. The sensor based on resistance and radiation measurement has its own constraint of temperature range. The bulky and traditional sensors cause disruption to true environment and compromise the structural integrity. The thin film sensor provides a minimal intrusive means of measuring surface parameters such as temperature and strain in hostile environment. They are directly sputtered deposited onto the surface and have thickness of the orders of few micrometers[1]. Mutyala[2], *et al.* have reported an innovative approach of fabrication of thin film thermocouples (TFTCs) on a thin polyimide film, which was spin coated and cured on a glass substrate. Chen[3], *et al.* have prepared Indium Tin Oxide/Pt thin film thermocouples with multi-layer structure on the nickel based super-alloy substrates. The TFTC has negligible mass to the surface and create minimal disturbance of the gas flow over the surface[4]. The thin film thermocouple was originally developed for process application to super alloys and used in jet aircraft engine for temperature measurement up to 1270 K. TFTCs have been furnace tested in harsh environment[5] and in hydrogen-oxygen atmosphere[6]. Under influence of high temperature due to huge difference in thermal expansion coefficient, de-bonding of metal thermocouple on composite base is common problem. Thus TFTC material is intended to have almost similar thermal expansion coefficient as the base material. Also attachment of wire thermocouple with commercially available ceramic cements fails to provide sufficient adhesion at high temperatures. While advanced thin film TC technology provides minimally intrusive surface temperature measurement and has good adhesion on composites. TFTCs can be tailored to have very good adhesion to composites. Parvis and Barresi[7] have developed sub-micrometric thickness thin film thermocouple to follow the freeze-drying process of pharmaceutical chemical, without altering the wall thickness and properties[7]. Matsuki[8], *et al.* used thin film thermocouple array to measure the thermal distribution in focus switching method to improve the throughput of high intensity focused ultrasound treatment. Varrenti[9], *et al.* have demonstrated chromium- nickel thin film thermocouple over semiconductor substrate to proof concept of lithographically processed bimetallic on chip temperature sensor. Smart industrial thermometer with online data logging and linearisation features can be developed using thin film thermocouples as demonstrated by Sarma and Boruah[10].

Thermocouples work on the principle called seebeck effect. When two dissimilar metals or metallic wires are kept

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in contact with a temperature difference between the two junctions, an electromotive force (EMF) proportional to the temperature difference is produced. Tungsten can bear very high temperature having melting temperature 3695 K. For measurement of high temperature tungsten and its alloys are often employed as sensing element. The presented TFTC is based on the refractory materials alloy for metal base and composite base materials. These materials are chosen based on their working temperature range, thermal expansion coefficient and expected electrical output[11].

The motivation towards this work is to design and simulate thin film thermocouple for high temperature measurement applicable to missile nozzles and interior surface of rocket motors. The sensor should be easy attachable to the super alloy and composite substrate for which different thermocouples fabrication techniques are available. Wrbanek[11], *et al.* have investigated the thin film thermocouple based on Sample films of In_2O_3, ZnO, and AlZnO fabricated and tested for thermoelectric performance for SiC/SiC CMC sample disks.

An implementation of seebeck effect is described using the PDE FEA models. The coupled heat equation and Poissons equation are extended by the thermoelectric effects for the field variables temperature and voltage. Electro-thermal model, in which thermal domain and the electrical domain are coupled, represent the behaviour that heat generation converts heat input to electronic output through the model.

2. SENSOR DESIGN AND DESCRIPTION

In view of the requirement of rocket motor and nozzles, the TFTC shape and size should be small enough not to cause any disruption to the gas flow and disturb the structural integrity. For high temperature application Tungsten (W) and Rhenium (Re) alloys are extensively utilised. Common combinations of pure W, W26Re W3Re, W25Re and W5Re have been widely in acceptance by industries. These thermocouples can be used in the range of 3033 K but can be used up to 3300 K for short interval measurements[12]. These TFTCs can be used for metal surfaces effectively but use on composite surface results in de-bonding caused by difference in thermal expansion coefficients. Combination of Pure W and W26Re alloy as thermocouple is presented. The overview of the sensor in shown in Fig. 1.

The rectangular strips of W and W26Re having length 650 µm and width 350 µm makes a junction exposed to the hot environment. The substrate metal surface is electrically conductive layer thus thin film of MCrAlY is deposited over metal surface by electron beam deposition. M is alloy of base metal mainly contains *Mn*, *Si*, *Co*, *Ni*, *V* (substrate metal of roket motor). Al_2O_3 is sputtered to make the surface electrically isolated to thermocouple. Thermocouple materials are metal mainly contains Fe, Co, Ni or substrate metal. Al_2O_3 is sputtered which makes the substrate surface electrically isolating to thermocouple. Thermocouple materials are patterned with shadow masks during deposition of W and W26Re by sputtered over alumina. For conducting composite substrate surfaces SiO_2 is sputtered instead of MCrAlY whereas insulating composite substrate surfaces do not require insulating layer and thermocouple is directly sputtered over base substrate. Finally protective overcoat thin layers are sputtered over

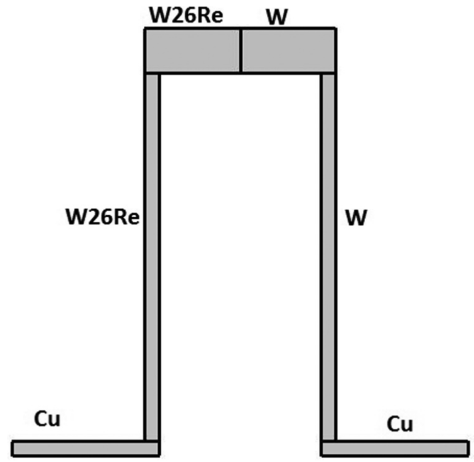

Figure 1. Sensor Overview: Thermoelectric junction of pure W and W26Re alloy. Ends is terminated with Copper which is isothermal.

TFTC. Zirconia fiber ZYBR-2 is proposed as the protective overcoat having melting temperature approximately 2900 K. For lower measurement range ceramic cements (SC and WC16) and flame-spray rokide coating have been used for TFTCs for composites[13]. SC is SiC based cement, WC16 is alumina based cement, and rokide is an alumina based flame retardant spray. For short interval measurements bare Tungsten or alloy can be exposed directly to hot environment without need of protective overcoat. The proposed fabrication process over substrate of rocket motor is shown in Table 1.

Average seebeck coefficients of Tungsten and W26Re are 7.5µV/K and 19.5µV/K, respectively. Thus the electrical output from the combination shall be higher that other combinations of thermocouple in this temperature range.

Details of the thermocouple and insulation material and properties are as shown in Table 2.

Table 1. Fabrication of TFTC over surface of Rocket Motor Substrate

Over super alloy base	Over composite base
Protective overcoat (ZYBR-2)	Protective overcoat (ZYBR-2)
W-W26Re thermocouple	W-W26Re thermocouple
Thermally grown Al_2O_3	Sputtered Al_2O_3
MCrAlY coating	Thermally grown SiO_2
Substrate (super alloy such as 16CDV-6)	Substrate(composite)

Table 2. Properties of Material of TFTC

Material	W	W26Re	ZYBF-2
Length (µm)	650	650	-
Width (µm)	350	350	-
Seebeck coefficient (µV/K)	7.5	19.5	-
Elect. conductivity (S/m)	60000	35336	-
Melting temperature (K)	3695	3033	~2900
Thermal conductivity (W/m.K)	95	69	-
Density (kg/m³)	19900	19700	5900
Heat capacity (J/Kg.K)	176	150	-

3. FEA MODEL OF THERMOCOUPLE

Heat conduction is a phenomenon described as the flow of heat energy. The energy flows from high temperature to lower temperature region when a temperature difference exists in a solid material. This is known as Fourier law as shown in Eqn (1).

$$q = -k\nabla T \quad (1)$$

This equation determines the amount of heat making transition through a unit of area per second W/m^2 for a given temperature T in Kelvin and thermal conductivity k in W/mK.

Electrical conduction expresses the current flow in the presence of electro-potential gradient[14].

$$J = -\sigma\nabla V \quad (2)$$

J is current density in A/m^2 and σ is electrical conductivity in S/m. Joule heating is the dominant for heat generation due to flow of electrical current. It is defined by Joules law

$$Q = J^2\rho \quad (3)$$

Q is produced heat per unit volume in unit W/m^3, ρ is the specific electrical resistivity in Ωm. Total electric field produced can be caused by various effects. S being seebeck coefficient

$$-\Delta V = \rho J + S\nabla T + rB \times J + NB \times \nabla T \quad (4)$$

Terms on right hand side of Eqn (4) is owing to Ohms law, Seebeck effect, Hall effect and Nernst phenomenon. Joule heating is irreversible whereas thermoelectric effect is reversible. Thermocouple is as thermoelectric device which produces emf owing to seebeck effect. The heat transfer equation signifies the complete spatial and time profile of a temperature distribution within a computational domain Ω and limited by the boundary $d\Omega$.

$$\nabla .q + mC_p \frac{dT}{dt} = Q \quad (5)$$

C_p is heat capacity of the materials in J/kg. K and m is mass density in kg/m^3. The coupling between thermal and electrical domain is required to be understood. Including thermoelectric effects. Equations (1) and (2) are modified as

$$q = -k\nabla T + PJ \quad (6)$$

$$J = -\sigma\nabla V - \sigma S\Delta T \quad (7)$$

where S is seebeck coefficient and P is Peltier coefficient. A weak solution, also called a generalised solution, to an ordinary or partial differential equation is a function for which the derivatives may not exist but is deemed to satisfy the equation in some precisely defined sense. For achieving weak contribution due to seebeck effect we use current balance continuity equation

$$\nabla .J = 0 \quad (8)$$

Multiplying with voltage test function V_{test} and integrating over computation domain Ω.

$$\int_{\Omega} (\Delta .J) V_{test} d\Omega = 0 \quad (9)$$

Applying vector identity theorem

$$\int_{\Omega} (J\Delta .V_{test} + V_{test}\Delta .J) d\Omega = 0 \quad (10)$$

Applying Gausss theorem in the closed boundary

$$\int_{\Omega} (J\Delta .V_{test}) d\Omega - \int_{d\Omega} (J.n) V_{test} d\Omega = 0 \quad (11)$$

Using current density as in Eqn (7)

$$\int_{\Omega} \left[(-\sigma\nabla V).\nabla V_{test} - (\sigma S\nabla T).\nabla V_{test} \right] d\Omega - \int_{d\Omega} (J.n) V_{test} d\Omega = 0 \quad (12)$$

First term is weak electric current due to ohms law and third term is the Neumanns boundary condition. Hence weak contribution due to seebeck effect is.

$$weak_{seebeck} = -(\sigma S\nabla T).\nabla V_{test} \quad (13)$$

Considering heat equation and including thermal conductivity k the coupled equations for temperature and electric potential V on the steady state for the thermoelectric field is given in Eqns (14) and (15) as

$$-\nabla .\left((\sigma S^2 T + k)\nabla .T \right) - \nabla .(\sigma ST\nabla .V) = \sigma\left((\nabla .V)^2 + S\nabla .T\nabla .V \right) \quad (14)$$

And

$$\nabla .(\sigma S\nabla .T) + \nabla .(\sigma\nabla .V) = 0 \quad (15)$$

4. SIMULATION

The combinations of W/W-26Re material may be used as thermoelectric material for fabrication over rocket motor base or composite materials. The thermocouple is exposed to the flowing gas. The terminals are expanded using copper strip which are isothermal, hence the produces emf shall be zero. The thermocouple model has been presented in previous section. The simulation has been done using multiphysics method where interaction of heat transfer and current generation is presented. Heat transfer and electric circuit modules of COMSOL multiphysics software has been used for simulation. Two heat boundary conditions are defined, first the junction exposed to input temperature and second the far ends kept at ambient temperature. Other boundaries have thermal isolation hence heat transfer shall not occur through these boundaries. Electrical boundary conditions defined is the end terminal referred as ground or zero potential. Second terminal is the reference of measurement of produced emf on temperature gradient. PDE weak form has been used to dictate the weak contribution caused by seebeck effect in 2D simulation. The junction is exposed to conductive heat source from 300 K to 2900 K. It is assumed that the insulation material conducts the heat completely to the thermocouple without heat dissipation. The voltage distribution profile and maximum terminal voltage has been analysed.

5. RESULTS AND DISCUSSION

The TFTC designed above, has been simulated and the temperature distribution profile has been studied. The voltage gradient across the thin strip of thermocouple has been observed the finally voltage difference between two extreme terminals of TFTC has been recorded.

Temperature profile on heating of the thermocouple at 2900 K is as shown in Fig. 2.

Seebeck effect and generated emf can be observed in Fig. 3. Heating hot junction causes the thermoelectric voltage to be generated at far end. Maximum voltage generated at 2900 K is 31.041 mV.

TFTC was exposed to temperature ranging from 300 K to 2900 K. The produced thermoelectric potential increases almost linearly with increasing temperature which is shown in Table 3. Linear relationship between temperature and potential generated is shown in Fig. 4.

The objective of this work is to propose thin film thermocouple for temperature measurement of interior of motor chamber and nozzle. This can also be utilised in measurement of flow of gases and heat flux. The simulation has been performed considering seebeck coefficient constant throughout the presented temperature range. The seebeck coefficient varies with change in temperature: hence the actual voltage produced shall be different than presented.

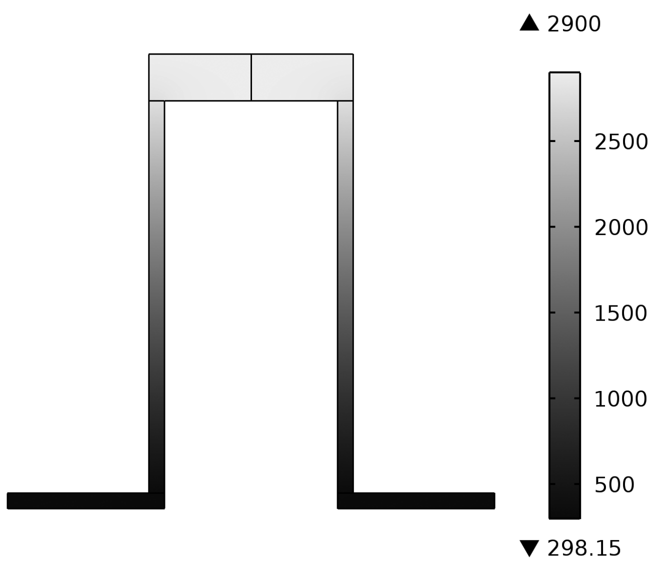

Figure 2. Temperature profile on heating of thermocouple. The exposed junction is heated uniformly and heat gradient exists across the length.

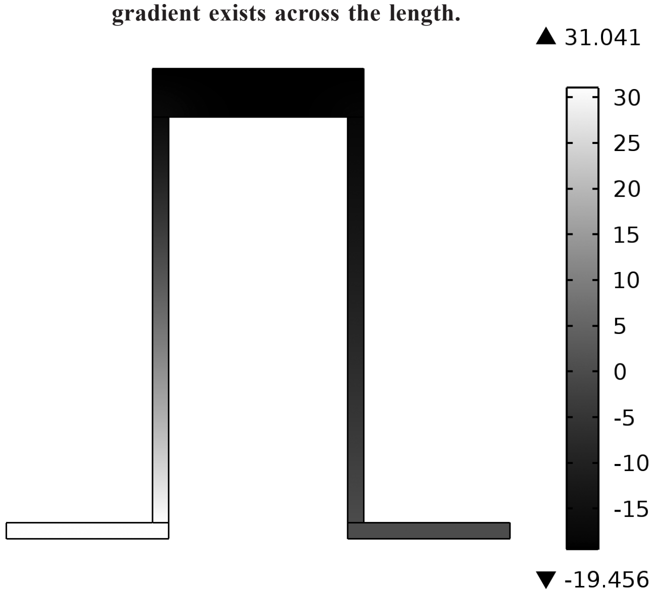

Figure 3. Thermoelectric voltage generated on temperature gradient of 2900 K is 31.041 mV.

Table 3. Simulated Thermoelectric emf output with increasing temperature

Temp. (K)	Potential (mV)	Temp. (K)	Potential (mV)
300	0.0221	1700	16.724
500	2.4081	1900	19.110
700	4.7941	2100	21.496
900	7.1802	2300	23.882
1100	9.5662	2500	26.268
1300	11.952	2700	28.654
1500	14.338	2900	31.041

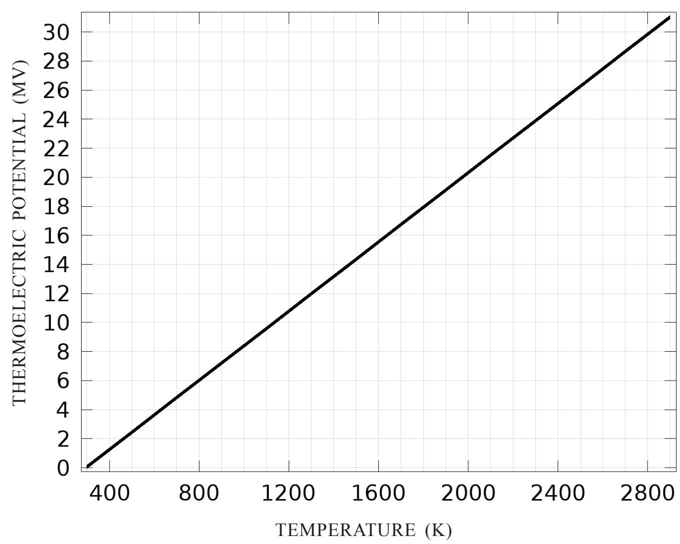

Figure 4. Generated potential increases linearly with increasing temperature.

6. CONCLUSION AND FUTURE SCOPE

We designed and simulated a thin film thermal sensor for the measurement of super-high temperature which can be used in maximum temperature range of 2900 K. The sensor is realised by making junction of W and W26Re. Heating the junction causes generation of thermoelectric potential. The output is linear with increasing temperature. We proposed a thermal insulator ZYBR-2 fiber material for this temperature range. The sensor can be used for measurement heat flux and flow of the gases through nozzle in missiles.

Simulation was done which suggests the TFTC shall perform well in measuring aforesaid temperature range. The self generating TFTC can be used in high temperature locations directly by fabricating thereon. MEMS fabrication techniques can be used for direct installation of TFTC over object considering as substrate.

The work is mainly aimed at proposal of a TFCT for missiles application and simulation shows the performance in high temperature. The simulation has been done with keeping seebeck coefficient constant but in actual the seebeck coefficient is temperature dependent thus including that fact the produced voltage will differ and relationship may not be linear these study can be done to get actual thermoelectric voltage.

Furthermore the TFTC in this work is expected to work in environment of high mach (velocity) flowing hot gases.

Modelling and simulation to study effectiveness of the sensor and its working range in presence of high velocity impinging fluids is the interest for analysis in future.

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