Proceedings of the International Conference on Applied Mechanical Engineering Research (IC-AMER2019)
NIT Warangal, India- May 02-04, 2019
Paper No. XXX

Characterisation and Performance Measures Evaluation of Nanofluid based Temperature sensor

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Abstract

For the short duration facilities, surface temperature history and determination of convective heating rate are very important in their design. With this motivation, ‘Thin film gauges’ (TFGs) have been developed by depositing transition metals blended with CNT nanofluid on the surface of highly polished ceramic substrates. An experimental investigation is performed for finding the performance measures of the sensor, i.e. the Temperature coefficient of resistance (TCR). The experimental model is compared with the theoretical interpretation using XRD material characterisation method. An existing resistance-temperature relationship model was modified using the basics of solid-state physics and quantum mechanics. The temperature coefficient of resistance of nanofluid-based temperature sensor was increased with the concentration of CNT on the base metal and the static calibration of TFGs showed an adequate linear behaviour.

Keywords: ‘Thin film gauge’, ‘X-ray diffraction’, ‘TCR’, Characterisation’

1. Introduction

For facilities such as shock tubes, I.C engines, gas turbine engines and high-speed aerodynamics, the heat flux and temperature measurement must have a good response time. The most exciting and recent advancement in the field of temperature measurement has been produced by thin film technology. Since the 1970s, thin film technique had been developed on heat flux measurement and used in a variety of applications. Kinnear and Lu (1998) introduced a method for the design, construction, calibration and testing of thin film platinum resistance temperature detectors. Lei et al. (1998) introduced advanced thin film sensor techniques that can provide for temperature measurements, being developed at the NASA Lewis Research Center. Tsutsumi et al. (2002) presented fairly accurate results of the temperature coefficient of resistance (TCR) measurements on platinum (Pt) thin films as a detecting resistive material for thermal type sensors. Rakesh and Sahoo (2010) discussed the thin film gauge that can provide for transient surface temperature measurement. Platinum film is deposited on the insulating substrate for thin film heat transfer gauge. Keblinski et al. (2005) made an interesting review to discuss the properties of nanofluids and future challenges in the field. Xu et al. (1998) proposed the combination of Aluminium-carbon nanotube composites and investigated their microstructural characteristics and disturbances of CNTs in the Al matrix. Zhuang et al. (2008) discussed the interactions between 3d transition-metal atoms (Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn) and carbon nanotube (CNT) with a vacancy defect are quantitatively characterised using first-principles calculations. Lacy (2010) evaluated the resistivity– temperature relationship for the RTDs and other conductors like platinum and nickel. A physical model was incorporated using the microscopic parameters associated with FCC lattice structure. Thin film gauges (TFGs) were the most competent dynamic temperature measurement sensors because of their microseconds responsive time. Being the next-generation heat transfer fluids, the nanofluid’s reliability to the transient metal-based TFG’s on the performance measures is considered in this work.

2. Experimental performance measures evaluation

The standard preparation procedures were maintained for fabricating the thin film gauges. Assumptions of one-dimensional semi-infinite concepts were followed for the substrate selection and preparation. Pyrex rods about 10 mm long with a diameter of 1.6 mm were used as substrate materials because of their highly attractive properties like low thermal conductivity and good insulation, ensuring the validity of semi-infinite assumptions. The silver conductive adhesive paste was blended with MWCNT (Multiwall carbon nanotubes) of 40-60 nm of diameter and 5-15 µm length with a different composition for the gage materials. The procedure for the preparation of thin films was followed by Kinnear et al. (1995). Functionalised CNTs prepared were mixed with the base fluid (silver and thinner) to obtain a suspension. A tip sonicator model VCX was used to disperse the carbon nanoparticles in the liquid. An ultrasonic pulse of 750W at 20 kHz was generated by the ultrasonic tip in the nanofluid. During sonication, the container of the nanofluid was cooled with a water jacket and the temperature of the nanofluid was maintained at less than 35°C. As it was confirmed from earlier studies, Hong et al. (2006) evaluated that the best sonication time for homogeneous dispersion was 60 min. CNT was added with different weight percentage (1wt%, 0. 5Wt %, 0.25wt %) with silver to obtain three different homogenous mixture of silver and CNT, hence different TFGs. The final step in the gauge construction was making the electrical connections to the metallic thin film. Aluminium wire ensured the structural stability of the leads for the electrical connection of the gauge. The primary excitation constant current of 10mA was supplied to the sensor through the voltmeter. When subjected to a change in the temperature field, the film acted as a thermometer and under some assumptions, it showed the temperature changes in the form of resistance changes, as Eq.(1).

$$R = R_0 + R_0\alpha_0 (T - T_0) \qquad \text{Eq.(1)}$$

The consistency and accuracy of the fabricated sensor were identified by the static oil bath bench calibration process, shown in Fig.1. Due to thermal excitation, the electrical resistance of the conductor varies in accordance to its temperature and this forms the resistor based thin film gauge. The effect is most commonly exhibited as an increase in resistance when the temperature increases i.e., a positive temperature coefficient of resistance (TCR), α. The calibration results in Fig.2 & Fig.3 identifies the linearity of the gauges as well as the high value of TCR when CNT is blended, ensuring the sensors best performance measures.

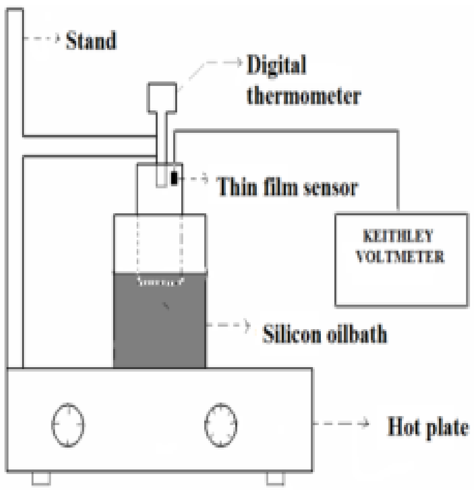

Fig.1. Schematic representation of the calibration

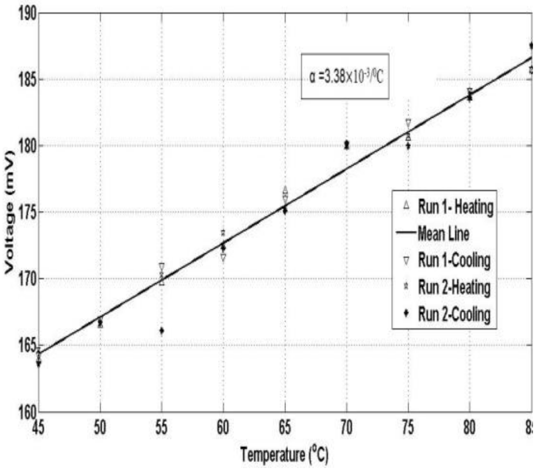

Fig.2. Calibration curve of silver gauge

Silver chemical is mixed with CNT in three different wt% (0.25wt%, 0.5wt%, 1wt %) in scientific methods and the TCR value is calculated for different wt% is shown in the Fig.3. There is found to be an increment in TCR values for the corresponding % wt of CNT increment. With respect to the basic TCR value of the Silver thin film, the blended combinations exhibit a performance improvement in TCR values for different wt% (0.25wt%, 0.5wt%, 1wt %) respectively as 17.15%, 20.192%, 24.14%, shown in table 1.

Table.1. TCR percentage performance improvement

Material	TCR [/ºC]	Enhancement of TCR (%)
Ag+ 0 wt% CNT	*3.38× 10-3*	-
Ag+ 0.25 wt% CNT	*3.95× 10-3*	*17.15*
Ag+ 0.5 wt% CNT	*4.06× 10-3*	*20.19*
Ag+ 1.00 wt% CNT	*4.19× 10-3*	*24.14*

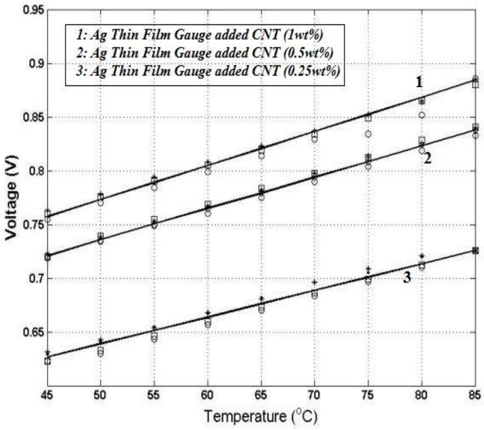

Fig.3. Calibration results of CNT added Ag thin film

3. Theoretical investigations

Most of the metal-based thin film shows linearity in resistance-temperature characteristics, according to Eq(1). The relation between the resistivity and temperature using for different gauge materials were evaluated using Lacy's [2011] 2D model for FCC Crystal structure.

3.1 XRD characterisation and analysis

The nondestructive XRD diffraction technique is used to monitor the phases, structure lattice parameter, strain and texture present in the film. The input parameters for the theoretical evaluations were taken from XRD characterisation studies. Lattice parameter constant 'a' of the face-centered cubic system (FCC) can be calculated from the equation standard miller indices values obtained correspondingly. The electrical resistivity for the materials is calculated from the model according to Eq. (2).

$$\rho = \rho_0 \left[\frac{1}{\frac{\left[2\sqrt[\delta]{\gamma / kT} - b \right]\left(\frac{\tau_1}{\tau_2} - 1 \right)}{2a+b} + 1} \right] \qquad \text{Eq. (2)}$$

Fig.5 and Fig.6 show the XRD spectrum from a micrometer thick crystalline Ag and CNT blended Ag thin film. The Ag and Ag+ CNT XRD diagrams compared and the small peak shift identified for the Ag + CNT thin film, inferring the presence of 1% wt addition of CNT on to the Ag thin film. The value of lattice parameter and crystal size calculation from the FCC structure is noted in Table 2.

Table.2. Comparison of lattice parameter values and Crystal size

Material	Lattice parameter (×10-10) [m] (From XRD data)	Crystal size(m)
Ag thin film	$3.23A^0$	2.33610^{-8}
Ag+ CNT thin film	$3.4509\ A^0$	$2.669*10^{-8}$

The peak shift in the Fig.6 infers the presence of CNT composition in silver. The crystallite size is calculated from XRD developed Paul Scherrer Eq.(3), the values infers the improvement of size with 1% wt added CNT.

$$B(2\theta) = \frac{k\lambda}{L\cos\theta} \qquad \text{Eq.(3)}$$

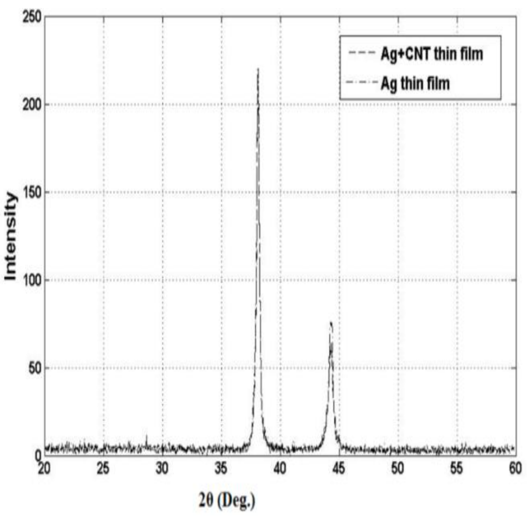

Fig.5. XRD spectrum comparison

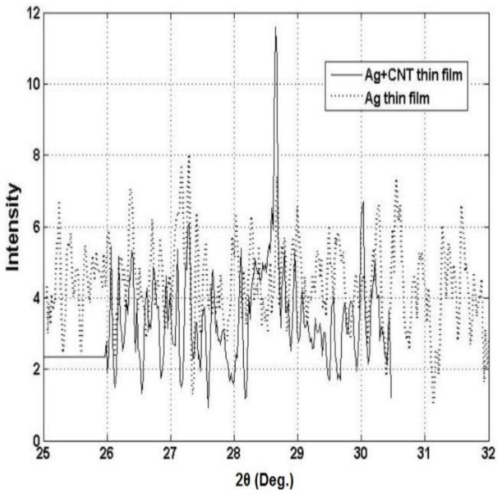

Fig.6. XRD spectrum for CNT peak on Ag-CNT thin film.

3.2 Modification of Lacy's Resistivity- Temperature relationship model

The analytical model equation is compared with experimental result comparison for the resistance-temperature relationship. The lattice constants a and b of Eq.(2) is obtained from XRD spectrum, shown in Table 3. Lattice parameter values are varied, γ and time constant ratios are adjusted to produce the best-fit equation. The graph is plotted of electrical resistivity as a function of temperature for Silver and CNT blended Silver thin film gauge shown in Fig.6. The linear response is expected from Eq.(2), there is a very good match with the general linear equation (1) and Fig.6. The temperature coefficient of resistance (TCR) of sensors and their comparison was plotted in Fig.7 and Fig. 8.

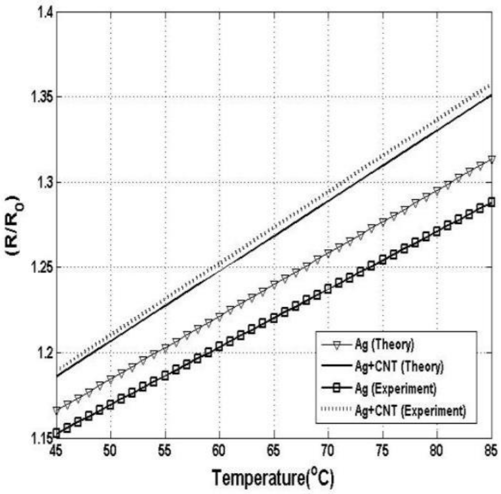

Fig.7. Plot showing the TCRs of different sensors

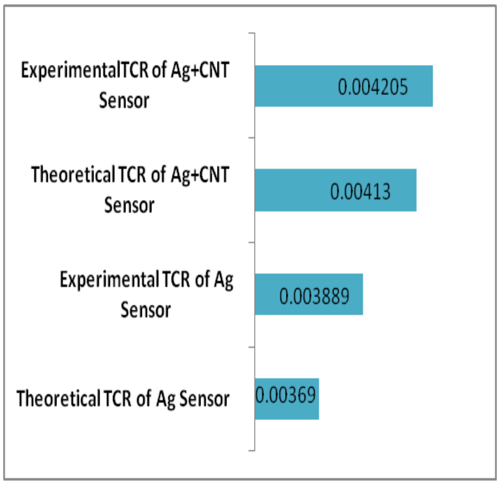

Fig.8. Comparison of TCRs obtained from different sensors

Silver TFGs and Silver–CNT nanofluid TFGs were successfully developed and calibrated in the laboratory for the use of short duration facilities. The initial resistance of Ag-CNT thin film gauge was found to increase with the concentration of CNTs.

Thin Film	Parameter	Characterized Relationship	Experimental Relationship
Silver film	δ=1;a=1×10^{-12}m; b= 3.23×10^{-10}m; (τ1/τ2)= 2.0584	$R=R_0\left[1+3.69\times10^{-3}T\right]$	$R=R_0\left[1+3.3889\times10^{-3}T\right]$
Ag-CNT film	δ=1;a=1x10-12m; b= 3.059x10^{-33} *m;* *(τ1/τ2)= 2.0084*	$R=R_0\left[1+4.13\times10^{-3}T\right]$	$R=R_0\left[1+4.205\times10^{-3}T\right]$

Fig.9 Correlation comparison

The temperature coefficient of resistance of Silver- CNT nanofluid TFG was increased by 17.2%, 20.2% and 24% when the CNT wt concentration was increased by 0.25%, 0.5% and 1% respectively. The concentration of CNT in silver thin film gauges increased the overall TCR of the thin film gauges. Crystallite size and Lattice parameter of thin films were increased for the nanofluid based thin films gauges. Theoretical investigation of resistance – temperature relationship is found to be a very good agreement with the experiment results. The correlation comparison is The enhancement of TCR of Ag and Ag+ CNT nanofluid based thin film was found to be 21% and 12% by experimental and theoretical investigation respectively.

4. Conclusion

The reliability of the next generation heat transfer fluids i.e. CNTs on the heat flux and temperature measurement performances have been investigated. The technical conclusions identified from the experimental as well as theoretical assumption based interpretations. Specifically, the temperature coefficient of resistance of nanofluid-based temperature sensor was increased with the concentration of CNT on the base metal and the static calibration of TFGs showed an adequate linear behaviour.

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