Numerical Analysis of K-type, J-type and E-type Coaxial Thermocouples for Transient Measurement

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ABSTRACT

Coaxial thermocouple sensors are very effective for measuring highly transient environment due to having fast response milliseconds or less. The coaxial thermocouples are considered to be a most effective method for routine measurement of temperatures. Whenever bimetallic junctions of a given thermocouple are exposed to different temperatures, they generate a small electromotive force that can be measured and correlated to temperature by external equipment. Therefore thermocouples are called active sensors because they generate a signal without the need of any external power source rather than an output amplification device is required. The measurement of transient heat transfer rates is very important in the areas of engine measurements, advanced manufacturing, cooling devices and aerodynamics vehicles in high-speed flow environments. The robust sensors have the flexibility of mounting them directly on the surface of any geometry. Here the known step loads are applied through conduction mode of heat transfer. The numerical simulation for K-type, E-type and J-type is performed with the help of commercial software ANSYS Workbench 15 transient thermal. The heat fluxes measurement technique states that the coaxial thermocouple is rigid in construction and easy to operate and able to withstand harsh environmental conditions.

Keywords: Coaxial thermocouple, ANSYS 15, Transient Heat flux measurement.

1. INTRODUCTION

The measurement of transient temperature and heat fluxes are a very significant parameter in research programs. In many scientific and engineering applications, to make the optimise design there is a requirement to measure the precise information of time-varying short duration temperatures due to fast change in heat flux. For instant, in many research programs for devising an effective cooling system in internal combustion engines [1,2] or for typical high-speed aerodynamic reentry vehicles [3,4]. The measurements of transient temperature/heat flux can be achieved through different sensors, such as co-axial thermocouples [5-10], platinum thin film gauges [11-14], null point calorimeter [15–17], thin skin thermocouples [18,19], slug gauges [20], and nonintrusive techniques like temperature sensitive paint [21–23] and thermography [24,25]. Each technique has its own merits and demerits but coaxial thermocouple is versatile in characteristics. The coaxial thermocouple...
can able to measure highly transient temperature due to its fast response time. It can be easily and cheaply manufactured. Coaxial thermocouples can be fabricated at home by inserting one thermocouple element over the second with an insulating material (Teflon) in between with a typical thickness of about one micrometer. The sensitivity of co-axial thermocouple depends on the surface junction. A “surface junction” in the form of metallic plating is formed by grinding the front surface. Even though the surface junction of thermocouples may be during the experiment, it is usually simple and inexpensive to refurbish the device using a sharp implement or some abrasive papers. Coaxial thermocouples have multifarious advantages in terms of high resistance to shear, smaller in size, immune to ionization effects, and employability over a wide range of enthalpies. By changing the thermocouple materials, its sensitivity and temperature range of applications can be varied.

The present work involves the numerical analysis of the K-type (chromel and alumel), J-type (iron and constanatan) and E-type (chromel and constantan) coaxial thermocouple using commercial software package ANSYS 15. Here the appropriate form of one-dimensional heat conduction modeling is employed.

2. THEORETICAL BACKGROUND

Generally, co-axial thermocouple measures the transient surface temperature and surface heat flux are then predicted by using suitable one-dimensional heat conduction modeling depending on thin/thick wall gauge [26]. It’s always desirable to measure the surface temperature and used it for heat flux measurement for accurate results. Since the surface junction dimension is very less in comparison with overall dimension and experimental runtime is also very less, it is acceptable to assume a one-dimensional heat conduction semi-infinite body.

For uniform initial conditions, if a heat load $q(t)$ is applied instantaneously, the transient surface temperature for the thermocouple will be $T(t)$. So, initial and boundary condition can be written as follows:

Initial conditions: $t = 0$ and $0 \leq x \leq l$;
$T(x,0) = T_{amb} = 300 \, K$;

Top wall: $x = 0$ and $t > 0$; $q = 0$;

Interface: $x = l_1$ and $t > 0$; $q_1 = q_2 = q$;

and $T_1 = T_2 = T(t)$

Bottom wall: $x = l_2$ and $t > 0$; $T(l_2,t) = 300 \, K$
When substrate thermal properties are treated as constant, the heat flux $q(t)$ passing through the surface is calculated by using Duhamel’s superposition integral as given below [26].

$$ q(t) = \frac{\beta}{\pi} \int_0^t \frac{d(T(t))}{dt} \frac{1}{\sqrt{t-\tau}} d\tau $$

(1)

3. NUMERICAL ANALYSIS

Numerical analysis is the technique of solving real-life problems using algorithms by applying numerical methods with the help of different analysis software. It is helpful for the prediction and validation of results without conducting the experiments. In this paper, the detail transient numerical analysis conducted in ANSYS 15 Workbench on coaxial thermocouple is discussed. Firstly, the geometric 3-D model of the sensor is made in the “SolidWorks” where the thickness of the sensing area (junction) is 10µm and the length of the co-axial thermocouple is kept to be 10mm as shown in figure1. The diameter of the outer thermocouple material and inner thermocouple material is kept as 3.25 mm and 0.9 mm respectively. The thickness of the insulating material (Teflon) which is kept in between the two thermocouple material is 0.1 mm. After completing the modeling, it’s imported to the ANSYS 15 Workbench for analysis. Assigned the material thermal properties to different components of the model i.e. surface junction, inner material, outer material and insulating material as shown in table 1 and 2. For the surface thermal properties, it is appropriate to take the average of the two thermocouple material properties as it's formed by grinding the top surface.
Table 1. Materials used in K-type, J-type and E-type co-axial thermocouple

<table>
<thead>
<tr>
<th></th>
<th>Inner material</th>
<th>Outer material</th>
<th>Insulating material</th>
<th>Surface Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-type</td>
<td>Chromel</td>
<td>Alumel</td>
<td>Teflon</td>
<td>Chromel and Alumel</td>
</tr>
<tr>
<td>J-type</td>
<td>Iron</td>
<td>Constantan</td>
<td>Teflon</td>
<td>Iron and Constantan</td>
</tr>
<tr>
<td>E-type</td>
<td>Chromel</td>
<td>Constantan</td>
<td>Teflon</td>
<td>Chromel and Constantan</td>
</tr>
</tbody>
</table>

Table 2. Thermal properties of the materials used in K-type, J-type and E-type co-axial thermocouple[27]

<table>
<thead>
<tr>
<th></th>
<th>Specific heat (J/kgK)</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constantan</td>
<td>390</td>
<td>8885.6</td>
<td>21.2</td>
</tr>
<tr>
<td>Iron</td>
<td>460</td>
<td>7874</td>
<td>79.5</td>
</tr>
<tr>
<td>Chromel</td>
<td>300</td>
<td>8730</td>
<td>19</td>
</tr>
<tr>
<td>Alumel</td>
<td>110</td>
<td>8600</td>
<td>30</td>
</tr>
<tr>
<td>Teflon</td>
<td>1010</td>
<td>2160</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The mesh generation for this dimension has been the important task as the thickness of sensing part (junction) is too thin as compared to the substrate material. Here the auto-mesh option is used and sizing method is employed for the meshing of the sensing area-surface junction. There are total 1359 mesh elements on the model.

The boundary conditions applied to various surfaces include a top wall (surface junction) exposed to sudden heating load, bottom surface as isothermal wall kept at 300K, adiabatic wall for side surfaces of the coaxial thermocouple. As the simulation is to be performed for two seconds, it is acceptable to assume side wall as adiabatic and bottom surface as isothermal.

Figure 2. Meshing of coaxial-thermocouple model
Uniform temperature of 300 K is considered as the initial condition in the computational domain. Here the runtime for the simulation is set as two seconds.

4. RESULTS AND DISCUSSIONS

The heat flux signals recovered from the temperature data (Fig. 4(a–c)) using the semi-infinite method discussed in the section 2 are as shown in Fig. 5(a–c). The nature of the heat flux and temperature traces obtained from present investigations compare well with the same reported in the literature [27] for short duration testing.
Figure 3. Nodal contours of different co-axial thermocouples for different heat fluxes

When input heat flux is 30 kW/m$^2$, the temperature of sensing surface (junction) of K-type thermocouple varies from 300 K to 308.35 K, J-type thermocouple varies from 300 K to 305.2 K and that of E-type varies from 300 K to 306.03 K. When input heat flux is 50 kW/m$^2$, the temperature of sensing surface (junction) of K-type thermocouple varies from 300 K to 313.93 K, J-type thermocouple varies from 300 K to 308.76 K and that of E-type varies from 300 K to 310.02 K. When input heat flux is 70 kW/m$^2$, the temperature of sensing surface (junction) of K-type thermocouple varies from 300 K to 319.49 K, J-type thermocouple varies from 300 K to 312.26 K and that of E-type varies from 300 K to 314.03 K.
Figure 4. Temperature v/s Time plots for different input heat loads

These results show excellent agreement between the applied and recovered heat signals in terms of trend and magnitude. The agreement is quite good and results are satisfactory within an accuracy of 2.05%. This observation reconfirms the uni-directionality of heat transfer and semi-infinite thickness of the thermocouple material.
The following hypotheses have been made in improving the model for estimation of heat flux deviation from the temperature records; (i) temperature measured by sensing component is identical to the temperature of surface of the substrate; (ii) no lateral heat conduction through the substrate and heat is conducted only in the direction normal to the surface; (iii) thermal properties of the substrate are constant; (iv) substrate is of infinite length so that the temperature rise at infinity is zero, then using Eq. (1) heat flux has been recovered from transient temperature shown in graph 5(a)-(c).
Measurement of transient heat flux has been performed numerically with K-type, E-type and J-type coaxial thermocouples using ANSYS thermal transient v.15 by finite element method. Three-dimensional geometry has been generated with the help of SolidWorks to estimate transient heat flux applying heat at sensing terminal. The transient temperature history has been recorded numerically for two second with K-type, E-type and J-type coaxial thermocouple for three different inputs one by one. The transient heat flux has been recovered using one-dimensional heat conduction model for a semi-infinite body from transient temperature data which is obtained from the numerical analysis. The heat flux estimated from these coaxial thermocouples and input flux is measurable and seems good for short duration heat transfer problem. So these coaxial thermocouples can measure heat flux in a quick time-varying application such as internal combustion engine, cooling system, etc. As these coaxial thermocouples are made of two metals, these are strong, easy in fabrication, low production cost and can be fabricated at home.

Figure 5. Surface heat flux recovered from the temperature histories for the heat transfer

5. CONCLUSION
REFERENCES