Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

Simulation of Fast Response Thermocouple for the Nuclear Reactor Core

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Abstract: Thermocouples have been used for measurement of temperature ever since the discovery of Seebeck effect. They have been used for measurement of temperature in a number of industrial processes. The fact that the output is in terms of electrical voltage makes them quite suitable for interfacing them with electronic control circuits. Though the voltage output of a given type of thermocouple is a function of the temperature difference between the hot and the cold junctions, the response time and the magnitude of voltage depends on the geometry and material of the thermocouple also. The selection of a particular type of thermocouple depends upon the application or the process requirement. This report deals with the study of the mineral insulted stainless steel thermocouples which are used in fast reactors for measurement of temperature in various locations. Some of these installation locations like the outlet of the fuel subassemblies require that the response time of the thermocouple should be less so that better control and safety can be achieved in a fast reactor. Since it is time consuming to fabricate thermocouples of different dimensions and materials and to obtain their response time experimentally, a numerical modelling approach has been followed in this report. Various designs of thermocouples have been analyzed and their response time has been calculated using a finite element based software COMSOL. Based on this analysis a design of the thermocouple having a fast response has been selected.

Keywords: Mineral-insulated-thermocouple, COMSOL multi physics, Response time.

1. Introduction

Temperature measurement has been of prime importance in almost all the industrial plants, be it chemical processing, boiler operations or a nuclear power plant. Various methods have in use for measurement of temperature like variation in resistance with temperature, measurement of infra-red radiation and the Seebeck effect. Of these thermocouples working on Seebeck effect have been utilized quite successfully for temperature measurement in a wide range of temperatures and also in a vast number of applications.

1.1) Description of Thermocouple

Thermocouples work on the principle called seebeck effect. When two dissimilar metals or metallic wires are kept in contact with a temperature difference between the two junctions, an electromotive force (EMF) proportional to the temperature difference is produced. A thermocouple works on the same principle and consists of two dissimilar metals joined together in one end.

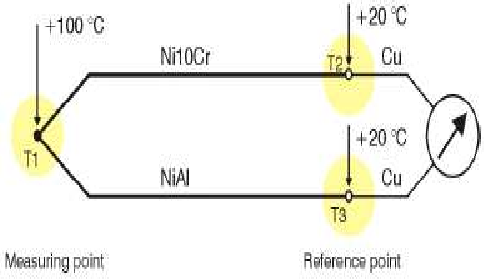


Fig1.1: K Type-Thermocouple measuring circuit

The magnitude of the EMF depends not only on the temperature difference but also on the type of the materials used for making the thermocouples. Based on the application different types of thermocouples like J, K, S, N, etc are available commercially.

1.2) Description of a Fast Reactor

Fast reactors or Fast Breeder reactors are used to effectively utilize the natural Uranium resources, especially in countries like India. Fast reactors utilize a mixture of uranium and plutonium as fuel in the reactor. Energy produced as result of fission of fuel in mainly in the form of heat. Liquid sodium which is having good neutronic and thermal properties is utilized to transfer heat from the fuel to finally the steam generator for production of steam which is used to run the turbine and produce power.

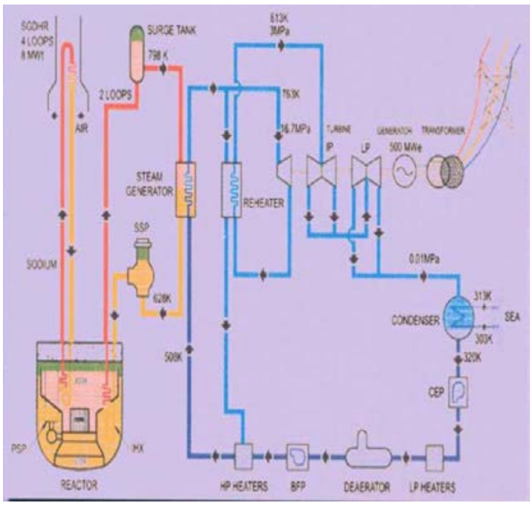


Fig: 1.2 Schematic of a Fast Breeder Reactor

FBR is a 500 MWe, sodium cooled, pool type, mixed oxide (MOX) fuelled reactor with two secondary loops located at Kalpakkam[8]. Figure 1.2 shows the schematic diagram of fast breeder reactor. The heat generated inside the reactor due to the fission process is captured out through the liquid sodium.

Measurement and monitoring of sodium temperature is of prime importance both from the operational and safety point of view [1]. Stainless Steel Sheathed Mineral Insulated Thermocouples are used for measurement of temperature in a fast reactor. Sodium may react with the material of the thermocouple and thus to protect the material of the thermocouple, it is enclosed in a Stainless Steel (SS) sheath since SS is compatible with liquid sodium.

But since liquid sodium is also a conductor of electricity it is necessary to provide an electrical insulator so that the EMF produced does not get grounded via liquid sodium. Magnesium Oxide (MgO) is used as the electrical insulator since it is electrically insulating but has got acceptable thermal conductivity. Figure 1.3 shows the photograph of some of the commercially available SS Sheathed Mineral Insulated Thermocouple. But this arrangement leads to increase in response time of the thermocouple since it will take some time for heat to reach the junction. This necessitates a study on the behavior of the thermocouple and methods to reduce the response time of thermocouple.

Fig 1.3 Mineral Insulated Thermocouples

Since it is time consuming to fabricate thermocouples of different dimensions and materials and to obtain their response time experimentally a numerical modeling approach has been followed in this report. Various designs of thermocouples have been analyzed and their response time has been calculated using a finite element based software COMSOL. Based on this analysis a design of the thermocouple having a fast response has been selected.

2. Factors Determining the Response time

The response time of a thermocouple is affected by several factors.

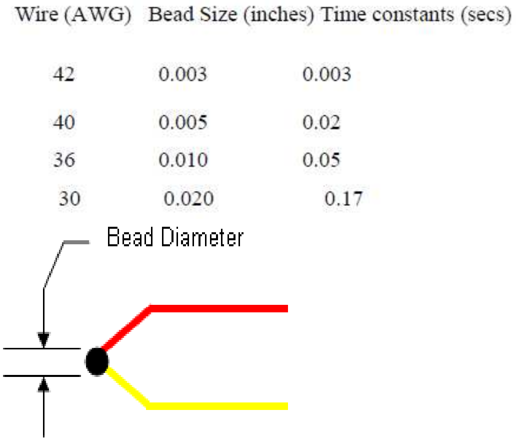
The main factors affecting thermocouple response time are:

1) The conducting medium including attachment method.

2) Thermocouple bead size.

3) Insulation and sheath of the Thermocouple.

Thermocouples response time is expressed in terms of its “time constant.” The time constant is defined as the time required for a thermocouple’s voltage to reach 63.2% of its final value in response to a sudden change in temperature. Thermocouples having bead of heavy mass will respond much slower than one that is left free standing because its value is governed by the temperature of the large mass. A free standing (exposed or bare wire) thermocouple’s response time is a function of the wire size (or mass of the thermocouple bead) and the conducting medium.Some standard bead sizes (bead size is typically 2 times the diameter of the wire) and time



Wire (AWG)	Bead Size (inches)	Time constants (secs)
42	0.003	0.003
40	0.005	0.02
36	0.010	0.05
30	0.020	0.17

Fig: 2.1 Thermocouple Bead

The standard commercial sensor available in the market has got different time constants according to standard dimension as mentioned below. The figure 2.2 shows the graphical form of thermocouples time constants with respect to wire diameter and sheath. Tabulated time responses of thermocouple with sheath variation given in table 2.1.

Table: 2.1 Commercial Thermocouple sheath response times[6]. Table: 2.1 Commercial Thermocouple sheath response times[6].

Sheath Thickness(mm)	Measuring junction	Response time (seconds)
0.063	grounded	0.09
	ungrounded	0.28
0.125	grounded	0.34
	ungrounded	1.6
0.188	grounded	0.7
	ungrounded	2.6
0.250	grounded	1.7
	ungrounded	4.5

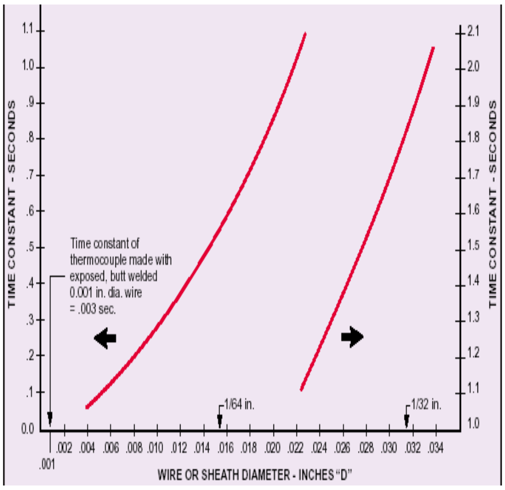


Fig: 2.2 Time constants variation with respect to wire and sheath diameters

3) Thermocouple Response Time

In a large FBR plant, for the reason of preventive maintenance for the plant, a fast response thermocouple is be required for monitoring the core exit. In addition to quick response to temperature change, there is a possibility of detecting the core anomaly sensitively which might be easily missed by a slow response sensor. Because the fast response sensor could detect the temperature fluctuation due to core anomaly, the state of the core will be diagnosed effectively.

3.1) Response of thermocouple

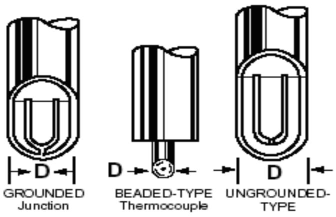
Response time is defined as the time in which the output of the thermocouple attains 90% of its steady state value. Response time is mainly governed by the heat transfer characteristics of the thermocouple body especially for the SS sheathed thermocouple. Response time becomes critical in many applications where the variation in system temperature in quite fast and the system requires fast control. One such application requiring fast response thermocouple is temperature measurement in a fast reactor particularly at the outlet of fuel subassemblies.

This section should contain a mathematical description of the problem being solved in the current study. Governing equations, initial and boundary conditions and any other pertinent information can be included. A description of how COMSOL was used/ will be used in this study should be listed. Information should include the different application modes being used and any other information which the authors deem of value to the COMSOL modeling community.

4) Modeling of Thermocouple

In order to evaluate the performance of the thermocouple and to obtain the geometrical dimensions of a fast response thermocouple a finite element modeling of the heat transfer problem has been done using the commercial code COMSOL. Both two dimensional and three dimensional models have been developed to solve the problem.

The effects of the various parameters on the response time of the thermocouple has been analyzed and presented in this chapter.



Simulation Models

The response time of the thermocouple depends upon a number of parameters. A parametric analysis has been done with respect to these parameters and its effect on the response time has been obtained. The parameters varied in the analysis are:

1. Diameter of the thermocouple wire (a)
2. Thickness of the sheath (b)
3. Position of the hot junction (h)
4. Insulation thickness (c)
5. Bead diameter.

Since a number of combinations are possible out of these 4 parameters, a coding representation (a-b-h-c) to refer to each configuration has been used. e.g. (Ex: 0.5-2.5-2-5 refers to a thermocouple having 0.5mm conductor diameter, 2.5mm sheath thickness, 2mm hot junction position from base level, and 5mm as Thermocouple MgO insulation.

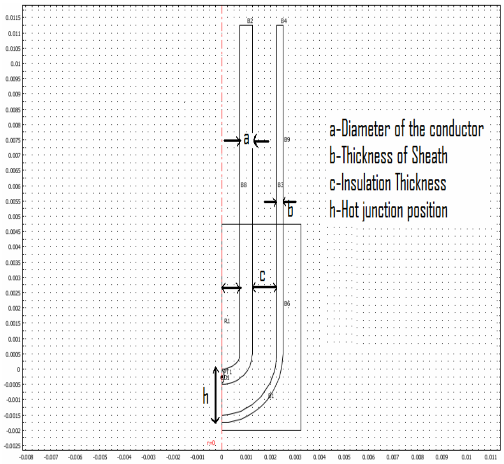


Fig 4.1 Reference dimensions of the thermocouple model

All the simulations for the models designed in this session are done at the input temperature of 600 degrees (which is the nuclear core temperature) and the responses for each model studied at 90% of the input temperature.

Model geometries

The figure 4.2 shows the simulation model. The cross sectional view gives the thermocouple interiors. Number 1 in figure shows the two colored structures which are the two thermocouple wires. Number 2 gives the insulation space and number 3 gives the sheath of the thermocouple.

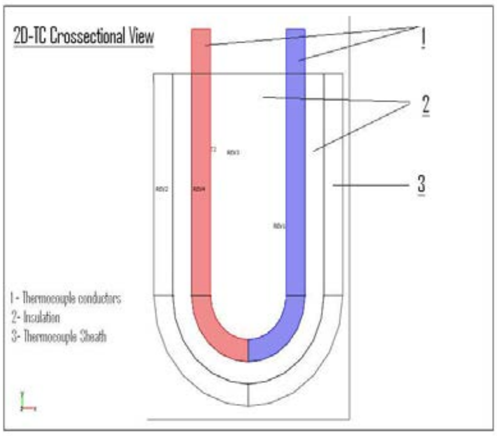


Fig: 4.2 2-D Cross-sectional view of thermocouple

The intersection of the two colored wires forms the junction of the thermocouple where the simulation results are interested. The figure 4.3

gives the 3-dimensional view of the simulated model thermocouple. It a prototype of mineral insulated thermocouple which has conductors surrounded with the insulation over which sheath is placed.

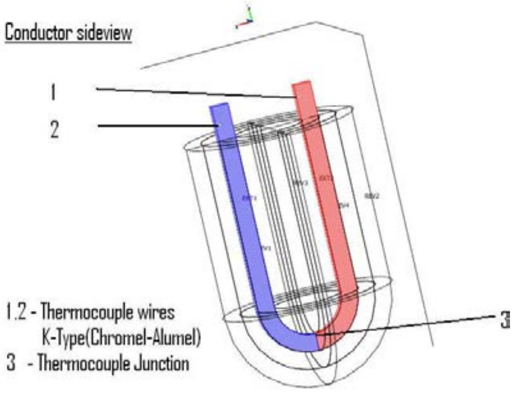


Fig: 4.3 3-D view

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Model analysis

The heat transfer from the outer surface of the thermocouple to the junction tip of the thermocouple is basically by conduction and depends on the thermal conductivity and heat capacity of the materials present. Since inside the thermocouple there is no fluid so convective heat transfer is not there inside the thermocouple and so it has not been considered in the analysis. Heat transfer by radiation is small and negligible compared to heat transfer by conduction and so has not been taken into account in the model.

Model Equation:

The mathematical model for heat transfer by conduction is the heat equation

$$\rho c \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = Q \_\_\_\_\_\_\_\_ (4.1)$$

Where
- T is the temperature,
- ρ is the density,
- C is the heat capacity,
- Cp is the heat capacity at a constant pressure,
- Cv is the heat capacity for a constant volume,
- k is the thermal conductivity,
- Q is a heat source or heat sink.

For a steady-state model, temperature does not change with time, and the first term containing ρ and C vanishes.

Model equation for Thermo well:

In a thermo well besides heat transfer by conduction, heat is also transferred by convection in the fluid inside the thermo well. To model heat conduction and convection through a fluid, the heat equation also includes a convective term. COMSOL Multi physics represents this formulation in the General Heat Transfer application mode as

$$\rho c_p \frac{\partial T}{\partial t} + \nabla.(-k\nabla T + \rho c_p T u) = Q \_\_ (4.2)$$

where u is the velocity field. This field can be provided as a mathematical expression of the independent variables or can be calculated within COMSOL Multiphysics by coupling a momentum-balance application mode such as Incompressible Navier-Stokes or Non-Isothermal Flow. Equation 5-2 defines the heat flux vector. For transport through conduction and convection this equation yields

$$q = -k\nabla T + \rho c_p T u \_\_\_\_\_\_\_\_\_\_\_\_ (4.3)$$

Where q is the heat flux vector. If the heat transfer is by conduction only, q is determined by $q = -k\nabla T$.

The boundary conditions for two dimensional model, the temperature is implicitly defined in terms of a gradient:

Here COMSOL Multiphysics uses two types of boundary conditions, the Dirichlet type and the Neumann type . The Dirichlet type has been used to set a temperature on a boundary

$$T = T_o ,$$

and use the Neumann type to set the heat flux on a boundary .

$$-n.q = q_0 \_\_\_\_\_\_\_\_\_\_\_\_ (4.4)$$

where:
- q is the heat flux vector,
- n is the normal vector of the boundary,
- q_0 is inward heat flux, normal to the boundary.

The Heat Transfer Module uses the following more general formulation of Equation 5-4:

$$-n.q = q_0 + h(T_{\inf} - T) \_\_\_\_\_ (4.5)$$

This formulation allows to specify the heat flux in terms of an explicit heat flux, q0, and a heat transfer coefficient, h, relative to a reference temperature, $T_{\inf}$.

The thermal insulation condition is obtained by setting $q_0 = 0$.

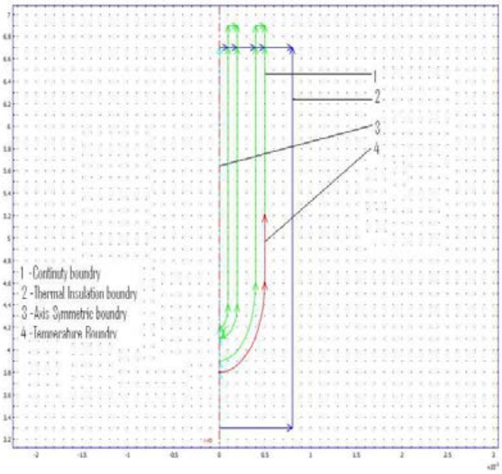


Fig: 4.4 Thermocouple model Boundaries

Material Properties:
The model geometry shown in figures 4.2, 4.3, to distinguish the model sub domains for solving have to specify the physical properties. The table 5.1 gives the different materials used in simulations and their properties [5].

Table 5.1 Material properties of thermocouple:

Material	Density (ρ) Kg/m^3	HeatCapacity(C_p) $j/(Kg.K)$	Thermal conductivity(k) $W/(m.K$
Chromel	8730	448	19.2
Alumel	8610	523	29.7
Liquid sodium	860	1280	107
Dry Air	0.4412	1110	0.0515
MGO(Magnesium oxide)	2848	940	1.44
SS 316 stainless steel	8030	475	21.4

5) Simulations:

2D simulations:
Ungrounded thermocouple: In ungrounded thermocouple the junction of the thermocouple is not in contact with the SS sheath.

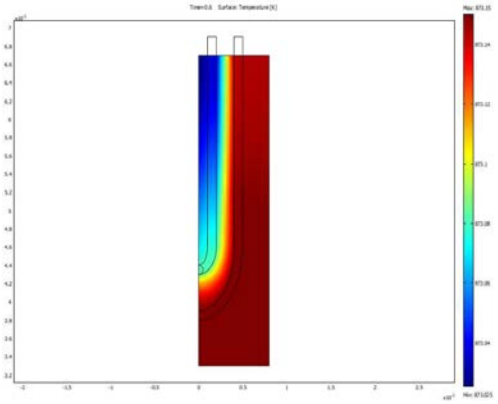


Fig: 5.1 Post processed 0.1-0.1-0.6-1 mm thermocouple

Time response curve of grounded thermocouple for 0.1mm-0.1mm-0.6mm-1mm is

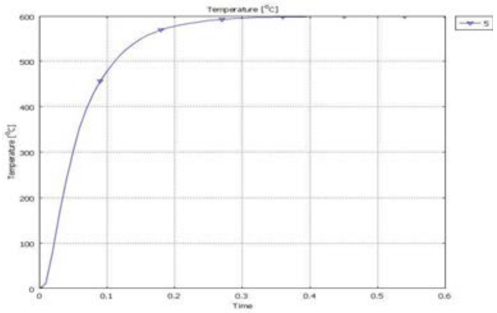


Fig: 5.2 Time response at hot junction of 0.1-0.1-0.6-1 mm thermocouple

Grounded thermocouple: In grounded thermocouple the junction of the thermocouple is in contact with the SS sheath

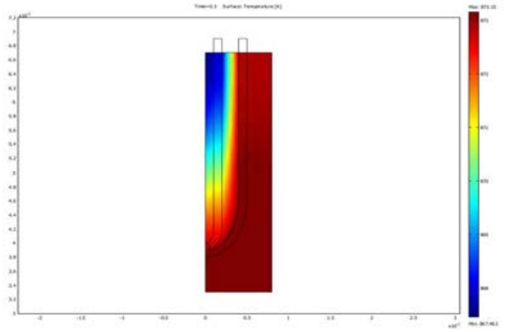


Fig: 5.3 Post processed grounded 0.1-0.1-0.2-1mm thermocouple

Time response of grounded thermocouple for .1mm-.1mm-.2mm-1mm is

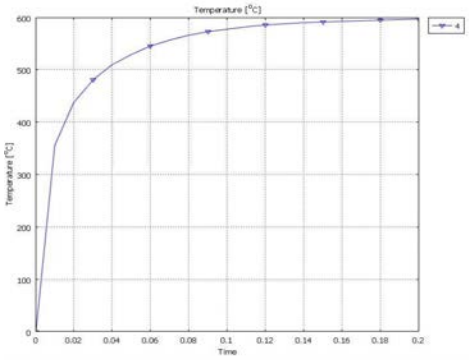


Fig: 5.4 Time response at hot junction of 0.1-0.1-0.2-1mm thermocouple

Table: 5.1 Variation of time response with sheath and insulation of thermocouple

Thermocouple	Grounded Time response (Sec's)	Ungrounded Time response (Sec's)
Sheath (inches - mm)		
0.063 1.6002	0.09	0.28
0.125 3.175	0.34	1.6
0.188 4.7752	0.7	2.6
0.250 6.35	1.7	4.5
MgO Insulation (inches – mm)		
0.063 1.6002	0.12	0.75
0.125 3.175	0.29	1.25
0.188 4.7752	0.51	2.40
0.250 6.35	1.5	4.3

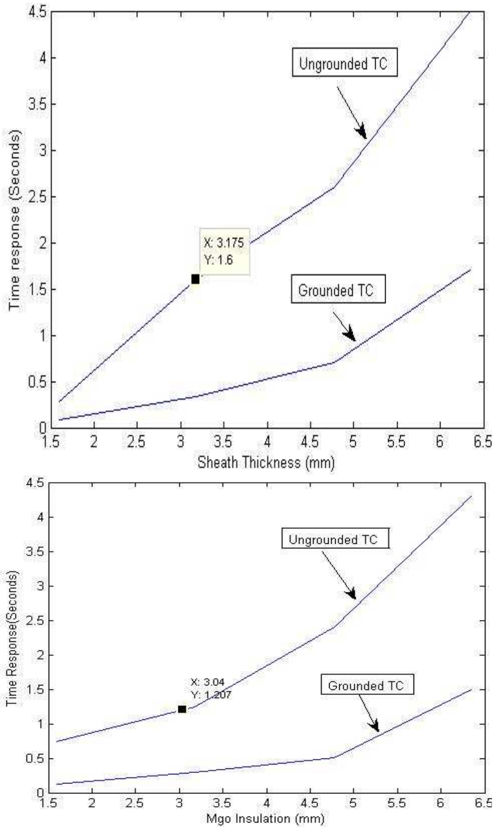


Fig: 5.5 Commercial Thermocouple response time with respect to sheath and insulation

Simulation of commercially available Thermocouple

In order to validate the finite element model, a commercially available thermocouple the response time of which is known, has been simulated in COMSOL and the simulation results have been compared. Figure 5.6 shows the time response of the COMSOL model for the commercially available t/c. From the figure the time-constant is 1.62 sec which matches fairly well with the value of 1.6 sec given in literature. The model is simulated with the SS sheath thickness of 3mm as given in literature and step change variation can be seen.

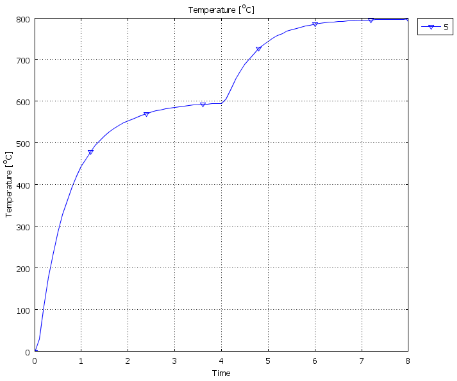


Fig 5.6 Simulated response time of commercial thermocouple with 3mm SS sheath

After validating the developed COMSOL model, the effect of various parameters on the response time was studied in order to get the dimensions of a fast response T/c for use in fast reactor. Table 5.2 below gives the specification of the t/c required for use in fast reactors.

Table 5.2 Specification of the thermocouple used in reactor core monitoring:

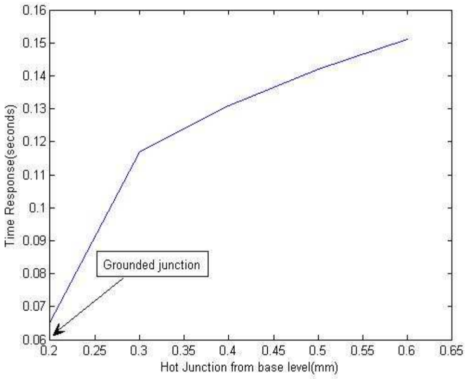
Thermocouple	Time response(Sec's)
1mm Thermocouple	0.3
2mm Thermocouple	0.3

Keeping all other parameters fixed, the position of the hot junction was varied to assess its effect on the response time for 1mm and 2mm t/c respectively. Table 5.3 below shows the effect of the variation in hot junction position for 1mm and table 6.4 for 2mm.

For 1mm thermocouple

Table 5.3: Effect of variation of position of hot junction on response time

Hot Junction position (in mm)	Response time (seconds)
0.6	0.151
0.5	0.142
0.4	0.131
0.3	0.117
Grounded Junction	
0.2	0.065



Selected Configuration

Based on the simulation done for analyzing the effect of various parameters on the response time of the thermocouple, a final configuration which yields a response time meeting the reactor requirement has been selected. The dimensions and the time response are shown below.

For 1mm thermocouple 0.14-0.05-0.6-1mm is the selected specifications of thermocouple. The steady state heat transfer, time response and step change are shown in figures 6.21,6.22 and 6.23.

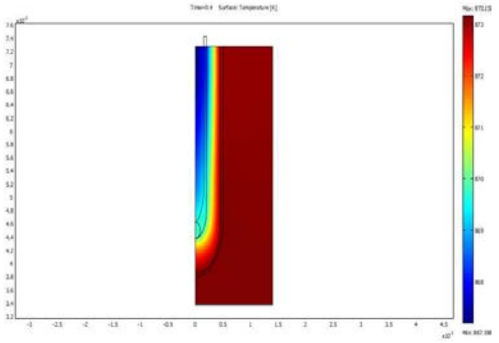


Fig: 5.7 Steady state heat transfer for selected 1mm thermocouple

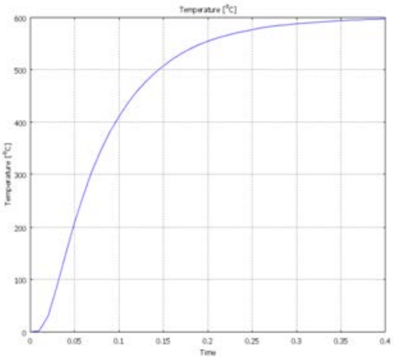


Fig: 5.8 Response time of selected 1mm thermocouple

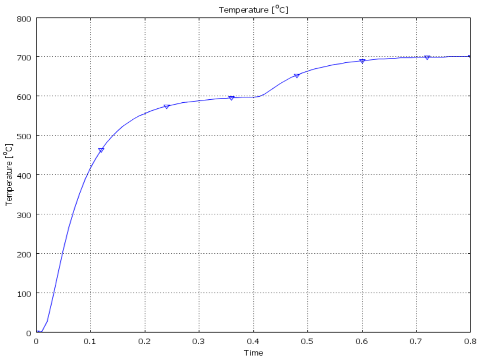


Fig 5.9 Step response time of selected 1mm thermocouple

6) Conclusion:

Since it is time consuming to fabricate thermocouples of different dimensions and materials and to obtain their response time experimentally, a numerical modeling approach has been followed in this report. Various designs of thermocouples were analyzed and their response time was calculated using a finite element based software COMSOL.

Based on this analysis a design of the thermocouple having a fast response has been selected. The selected configuration gives a response time of sec which meets the reactor requirements of 300msec response time.

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