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Eigendecomposition model of resistance temperature detector with applications to S-CO_2 cycle sensing

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HIGHLIGHTS

- Developed eigendecomposition model of resistance temperature detector (RTD) in a fluid.
- Showed that RTD time constant primarily depends on the rate of heat transfer from the fluid to the outer wall of RTD.
- Showed that RTD time constant can be calculated as the sum of reciprocal eigenvalues of the heat transfer matrix.
- Calculated time constant of thermowell-mounted RTD sensor at the hot side of the precooler in the S-CO_2 cycle.

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ABSTRACT

Super-critical carbon dioxide (S-CO_2) is a promising thermodynamic cycle for advanced nuclear reactors and solar energy conversion applications. Dynamic control of the proposed recompression S-CO_2 cycle is accomplished with input from resistance temperature detector (RTD) measurements of the process fluid. One of the challenges in practical implementation of S-CO_2 cycle is high corrosion rate of component and sensor materials. In this paper, we develop a mathematical model of RTD sensing using eigendecomposition model of radial heat transfer in a layered long cylinder. We show that the value of RTD time constant primarily depends on the rate of heat transfer from the fluid to the outer wall of RTD. We also show that for typical material properties, RTD time constant can be calculated as the sum of reciprocal eigenvalues of the heat transfer matrix. Using the computational model and a set of RTD and CO_2 fluid thermophysical parameter values, we calculate the value of time constant of thermowell-mounted RTD sensor at the hot side of the precooler in the S-CO_2 cycle. The eigendecomposition model of RTD will be used in future studies to model sensor degradation and its impact on control of S-CO_2.

1. Introduction

Super-critical carbon dioxide (S-CO_2) is a promising thermodynamic cycle for advanced nuclear reactors and solar energy conversion applications (Ahn et al., 2015; Iverson et al., 2013). Before S-CO_2 cycles can be implemented in large -scale applications, a number of studies are currently conducted on various aspects of the cycle, including efficient strategies for S-CO_2 control. We have previously investigated the performance of proportional-integral (PI) controller of S-CO_2 cycle, designed to respond to change in the demand of electrical power generation (Heifetz and Vilim, 2015). In the PI controller in our studies, set point was taken as the temperature measurement on the hot side of the pre-cooler. Our studies were performed under idealized conditions of instant measurements. In reality, temperature sensors have time constants, which depend on heat transfer properties of the process fluid and senor materials. In nuclear power applications, temperature measurements which require higher accuracy are usually performed using resistance temperature detectors (RTD) (Hashemian and Jiang, 2009; Montalvo et al., 2014; Vilim et al., 2012; Yun et al., 2012). One of the challenges in practical implementation of S-CO_2 cycle is high corrosion rate of components and sensor material due to toxic nature of the working fluid. In this paper, we develop a computational model of resistance temperature detector (RTD) sensing, which is based on eigendecomposition computation of radial heat transfer in a long cylinder. This model allows for estimating RTD time constant for given geometrical and thermophysical parameter values of the sensor and CO_2 fluid. The advantage of this RTD model is that it allows for modeling changes in sensor response time due to material degradation in a computationally efficient manner. The RTD model we have developed will be integrated into custom plant simulation software to allow real-time computation of sensor response time for given material

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and fluid parameters. Modeling the changes of RTD performance due to material degradation, and the impact of these changes on S-CO_2 cycle control will be pursued in our future work.

This paper is organized as follows. In Section 2, we describe the basis properties of RTD and develop sensing model using eigendecomposition model of heat transfer. In Section 3, we develop the model of heat transfer coefficient from the process fluid to the RTD inserted into stream. In Section 4, we obtain numerical estimates for the time constant of thermowell-mounted RTD measuring CO_2 temperature in the regime close to the fluid critical point. Conclusions of the study in this paper are presented in Section 5.

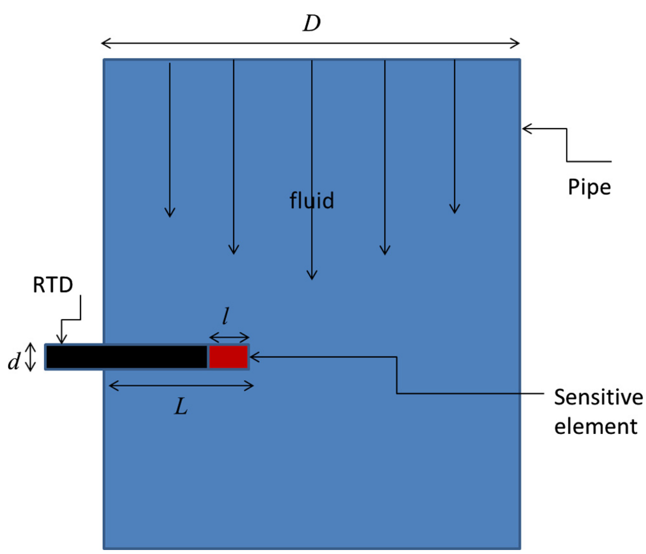

Fig. 1. Schematic of thermo-well mounted RTD insertion into a process fluid pipe.

Table 1
Geometrical dimensions of RTD insertion into process fluid pipe.

Geometrical quantity	Symbol	Value (m)
Pipe diameter	D	1
RTD outer diameter	d	0.01035
RTD immersion length	L	0.05–0.1
RTD sensing element length	l	0.01–0.03

2. Resistance Temperature Detector (RTD) model

2.1. RTD basic properties

A typical RTD is a long and narrow cylindrical metallic structure with a diameter 0.6–1 cm, which is inserted into a plant cooling system pipe to an immersion depth of 5–10 cm in the process fluid (Hashemian and Jiang, 2009). Heat sensing element is the bottom 1–3 cm long section of the RTD. Fig. 1 depicts temperature sensing with RTD inserted into a process fluid. Typical dimensions are presented in Table 1. Nomenclature for thermo-physical material properties of RTD and process fluid is listed in Table 2.

The heat sensing element is a cylindrical layered structure, at the core of which is a thin platinum wire wounded on a grooved cylinder called mandrell. The basis of temperature measurements is that resistivity of platinum wire changes with temperature. Change in resistivity can be detected in real time with external circuit. The mandrell, which is made of an insulation material, such as Alumina (Al_2O_3), is enclosed by a concentric cylinder of insulation material of the same type. The insulation, in turn, is enclosed by a concentric cylinder of stainless steel called sheath. Depending on the installation mode, RTD's are either direct immersion (wet-type) or thermowell mounted (well-type). A wet-type RTD is installed into a transverse hole in the cooling system pipe, so that the sheath is in direct contact with the process fluid. A well-type RTD is installed into a thermowell, which had been previously mounted in the cooling system pipe. A thermowell is a hollow stainless steel cylinder with an average outer diameter of 1–2 cm, which is in direct contact with the process fluid. This paper considers the performance of well-type RTD. From the point of view of heat transfer in the sensor, thermowell is considered as an integral component of RTD. It is assumed that the sheath is in direct contact with the thermowell, i.e. there are no air gaps. A schematic drawing of transverse cross-section of well-type RTD is shown in Fig. 2. Note that mandrell is an inner part of the insulation, and therefore no material boundary is drawn around mandrell. Radial dimensions and material regions of the RTD in this report are presented in Table 3. Radius of mandrell indicates the location of the sensing wire. Although surfaces of RTD are slightly slanted, in this paper we make straight cylinder approximation of the RTD shape.

2.2. Model of heat conduction in RTD

In general, heat conduction in RTD is a 3-D problem, described by Rohsenow and Choi (1961)

Table 2
Nomenclature for thermos-physical RTD and process fluid properties.

Thermophysical material properties	Description		Symbol	Units
RTD	Alumina (aluminum oxide)	Density	ρ_A	kg/m^3
		Specific Heat	c_A	J/kg K
		Thermal Conductivity	k_A	W/m K
	Stainless steel-316	Density	ρ_S	kg/m^3
		Specific Heat	c_S	J/kg K
		Thermal Conductivity	k_S	W/m K
Fluid	Heat transfer coefficient		h_f	W/m^2 K
	Reynolds number		Re	none
	Prandtl number		Pr	none
	Viscosity		μ	kg/m s
	Thermal conductivity		k_f	W/m K
	Density		ρ_f	kg/m^3
	Specific heat		c_f	J/kg K
	Free stream velocity		v	m/s
	Mass flux		G	kg/m^2 s
	Pipe diameter		D	m