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Numerical investigation into thermal contact conductance between linear and curvilinear contacts

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Abstract. Heat transfer has considerable applications in different industries such as designing of heat exchangers, nuclear reactor cooling, control system for spacecraft, and microelectronics cooling. As the surfaces of two metals make contact with each other, this issue becomes so crucial. Thermal Contact Resistance (TCR) is one of the key physical parameters in heat transfer of the mentioned surfaces. Measuring the experimental value of TCR in laboratory is highly expensive and difficult. As an alternative, numerical modeling methods could be engaged. In this study, inverse problem method solution is utilized as a proper method for estimation of TCR value. To that end, three different configurations, namely, flat-flat, flat-cylinder, and cylinder-cylinder, were utilized in two steady and unsteady state conditions to predict the value of TCR. A comparison between the measured and obtained values from the simulation shows that the errors for flat-flat, flat-cylinder, and cylinder–cylinder configurations after 10 minutes from starting the experiment are 4.6074%, 0.1662%, and 0.5622%, respectively. For steady state condition, the corresponding errors are 6.06e-3%, 1.506%, and 0.846%, respectively. In conclusion, the final results establish the fact that the inverse problem method solution can predict TCR values between contacting surfaces.

1. Introduction

Heat transfer is a key issue for metallic bodies in contact in the designing of heat exchangers, nuclear reactor cooling, control system for spacecraft, and microelectronics cooling. The most important parameters affecting heat transfer across the interface are contact loading, surface roughness, thermo-physical properties, and mechanical properties. When two solid bodies are in contact, their physical contacts are limited to the finite number of separated points at their interface [1]. The real contact area is in microscopic scale, which is very small compared to the apparent contact area. Macro-contact is created due to the surface curvature of contacting bodies. The relatively high temperature difference occurs between the interfaces, because after heat flows through the macro contact, it must pass the micro-contacts to be conducted from one surface to another [2]. A constriction at the contact surfaces in the heat transfer is created by this phenomenon, named TCR, defined as follows [2,3]:

$$R_c = \frac{\Delta T}{q}, \tag{1}$$

where ΔT denotes temperature drop between two contacting surfaces and q is the heat flux, defined as follows [2]:

$$q = \frac{d}{dA}\left(\frac{dQ}{dt}\right), \tag{2}$$

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where Q and t are heat transfer between surfaces and time, respectively.

There are experimental, analytical, and numerical models developed for TCR prediction, but these models are not general and are suitable for specific cases [2].

It is found that several parameters such as the type of contaminant or the lubricant used, temperature and interfacial pressure, the geometry of contacting surfaces in both micro and macro scales, and the type of contacting materials are the most important factors. TCR can be measured while the system is in steady state or transient condition [2].

Clausing and Chao proposed a model for TCR in a vacuum environment and their results showed that the macroscopic constriction was the dominating parameter. They studied the impact of material properties, the degree of conformity of mating surfaces under load, surface films, surface roughness, creep, additional interstitial material, and mean interface temperature. Their model predicted TCR quite well [4]. The assumption of most prediction models of TCR is flat surface due to its simplicity. Marotta et al. developed a thermo-mechanical model including both microscopic and macroscopic thermal resistances for non-flat roughened surfaces with non-metallic coatings. Their model forecasted TCR of several non-metallic coatings deposited on metallic aluminum substrates in a satisfactory way [5]. Mikic and Rohsenow proposed a theoretical model to predict the conductance of cylinders and spheres [6]. Thomas and Sayles studied the relationship between roughness, flatness deviation, and contact resistance [7]. Kumar et al. studied TCC of flat-flat and curvilinear metallic contacts by carrying out experiments and implementing inverse analysis of transient state. Their results showed a good agreement between the values of TCC in stabilized transient and steady state when the steady state values were calculated based on the actual interfacial temperature drop [1]. They investigated TCC of flat-flat, cylinder-flat, and cylinder-cylinder contacts made of brass by carrying out experiments using liquid crystal thermography. In contact region, where separation occurs, a difference in thermal conductivity exists, so the region was subdivided into the sub-regions based on distinct temperature zones in their study. This made a good estimation of thermal conductivity, so the precise temperature in the adjacent interface could be determined by extrapolation and then steady state TCC was predicted with a good agreement [3]. Burghold et al. investigated time-dependent TCC by an experimental method using IR-thermography. They measured the heat transfer between contacts by using a high-speed infrared camera. This method could help to understand the transient heat transfer phenomena due to its visualization and quantification. Their results showed that instantaneous load was proportional to the heat transfer coefficient [8]. A new method for solving this problem is inverse problem method. In this study, the solution to the inverse problem used to find TCR in contacting surfaces for the cylinder-cylinder, cylinder-flat, and flat-flat contact surfaces in both steady state and transient conditions is presented. The contact surface is an alloy made of brass. The length of all specimens is 30 mm with the diameter of 25 mm. Each specimen has four holes with the depth of 12.5 mm and diameter of 0.8 mm, and diameter of all curved surfaces is 25 mm.

2. Numerical method

In the contact surface, heat flow is a result of applying a heat source and a heat sink to the upper and lower specimens, respectively [9]. The temperature difference and heat flux are calculated by using the temperature distribution along the specimens. The temperature difference across the contact surfaces is defined as follows [2]:

$$\Delta T = T_{C_{\text{hot}}} - T_{C_{\text{cold}}}, \tag{3}$$

where $T_{C_{\text{hot}}}$ and $T_{C_{\text{cold}}}$ are the temperature of hot and cold specimens, respectively, and can be estimated by the least squares method.

Thus, combining Eq. (1) and Eq. (3) yields [2]:

$$R_c = \frac{T_{C_{\text{hot}}} - T_{C_{\text{cold}}}}{q}. \tag{4}$$

Eq. (4) can be used to calculate TCR.

First, we must know the difference between direct problem and inverse problem. In direct problem, the physical properties of the system are known and there is a deterministic method for calculating the outcome (response) of the system. An inverse problem is a kind of problem in which some physical properties are unknown, but the response of the system to some stimulus is known and the problem is to find the unknown properties [10].

2.1. Direct problem

Two specimens are in contact and TCR at their interface is $R_c(t)$. Dimensionless partial differential equation for this problem is shown by the following equation:

Specimen 1:

$$87 \times 10^3 \times 401.9328 \frac{\partial T_1}{\partial t} = 116 \frac{\partial^2 T_1}{\partial x^2}, \tag{5}$$

$$x = -19.049 \text{ mm} \Rightarrow T_1 = 45.57^\circ \text{ C}, \tag{6}$$

$$x=0 \Rightarrow -116 \frac{\partial T_1}{\partial x} = \frac{44.34 - 43.49}{9.10790036047978 \times 10^{-5}}, \tag{7}$$

$$t = 0 \Rightarrow T_1 = T_{\text{ambient}}. \tag{8}$$

Specimen 2:

$$87 \times 10^3 \times 401.9328 \frac{\partial T_2}{\partial t} = 116 \frac{\partial^2 T_2}{\partial x^2}, \tag{9}$$

$$x = -19.049 \text{ mm} \Rightarrow T_2 = 42.04^\circ \text{ C}, \tag{10}$$

$$x=0 \Rightarrow -116 \frac{\partial T_2}{\partial x} = \frac{44.34 - 43.49}{9.10790036047978 \times 10^{-5}}, \tag{11}$$

$$t = 0 \Rightarrow T_2 = T_{\text{ambient}}, \tag{12}$$

where the ambient temperature is 25°. The direct problem for this case occurs when the thermo-physical properties, boundary conditions at the outer ends, and TCR of the specimens are known and the problem is to find the temperature profile in the specimens.

2.2. Inverse problem

The solution method to the inverse problem for this case is as follows.

The assumption is that there is no prior information on the functional form of $R_c(t)$. The function $R_c(t)$ is defined in the whole time domain and is the property of the Hilbert space integrable time functions [10].

For solving the mentioned problem, the following function must be minimized:

$$S[R_c(t)] = \int_{t=0}^{\tau} \left[\sum_{j=1}^{N_1} (T_{1j} - Y_{1j})^2 \right] dt + \int_{t=0}^{\tau} \left[\sum_{j=1}^{N_2} (T_{2j} - Y_{2j})^2 \right] dt, \tag{13}$$

where T_{1j} and T_{2j} are the predicted values at the measurement locations for temperatures of Specimens 1 and 2, respectively, and Y_{1j} and Y_{2j} are the corresponding measured values.

The idea based on the perturbation principles is combined with conjugate gradient method to change the presented inverse problem to three problems, namely, sensitivity problem, direct problem, and the adjoint problem, which are added to the gradient equation.

This method has a great advantage in that there is no need to have prior information about the variations of the unknown quantities, because the solution itself can automatically determine the functional form over the domain specified.

3. Experimental data used

The experimental data used in this study were collected from the paper published by Kumar and Tariq [3]. The experiments were carried out by Kumar and Tariq with three configurations for the specimens: (1) flat-flat, (2) cylinder-flat, and (3) cylinder-cylinder contact surfaces made of brass in both steady state and transient conditions. All of the specimens were 30 mm in length with the diameter of 25 mm. Each specimen included four holes with the depth of 12.5 mm and diameter of 0.8 mm. All curved surfaces were 25 mm in diameter (see Figure 1). The ambient temperature was 25°C.

4. Results and discussion

The intention of this study is to predict TCR of the cylinder-cylinder, cylinder-flat, and flat-flat contact surfaces in both steady state and transient conditions by the use of inverse problem solution for heat transfer method. In this method, the heat transfer inverse problem will be remodeled to three equations for sensitivity problem, direct problem, and adjoint problem to which conjugate gradient is added. After obtaining the predicted values of TCR, percentage of errors of the

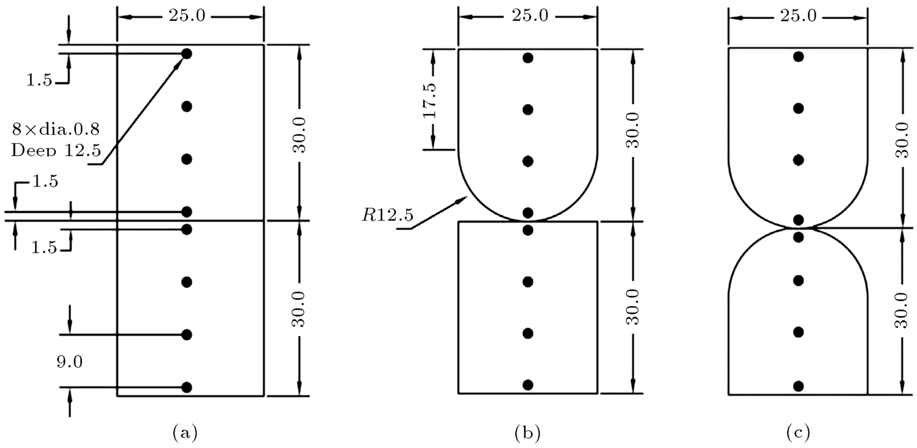

Figure 1. Schematic of different contact configurations.

prediction model is calculated from the formula below:

$$\mathrm{ER}\% = \left(\sum \frac{T_{1,\exp} - T_{1,\mathrm{cal}}}{T_{1,\exp}} + \sum \frac{T_{2,\exp} - T_{2,\mathrm{cal}}}{T_{2,\exp}} \right) \times 100. \tag{14}$$

The results of this model are shown in Figures 2-4 for the unsteady state model state condition (Figure 2 is for the flat-flat, Figure 3 is for the flat-cylinder, and Figure 4 is for the cylinder-cylinder configurations of contact surfaces). For the flat-flat case, the measurements are done at the times of 10, 20, 50, 60, and 65 minutes after the experiment starts; the predicted values of TCR are 4.54e-5, 5.40e-5, 6.2665e-5, 7.92e-5, and 7.92e-5, respectively; and the corresponding errors are 4.6074, 3.3791, 0.6782, 1.0675, and 1.0675. For the flat-cylinder case, the measurements are carried out at the times of 10, 16, 50, 60, and 65 minutes after the experiment begins; the predicted values of TCR are 5.03e-4, 1.84e-4, 2.15e-4, 1.34e-4, and 1.34e-4, respectively; and the corresponding errors are 0.1662, 4.4178, 3.7212, 2.7079, and 2.7079. For the cylinder-cylinder case, the measurements are carried out at the times of 10, 16, 50, 60, and 65 minutes after the experiment begins; the predicted values of TCR are 4.25e-4, 1.87e-4, 1.97e-4, 1.97e-4, and 1.97e-4, respectively; and the corresponding errors are 0.5622, 1.8719, 1.3832, 1.0695, and 1.0695. The predicted values are the same for the times of 60 and 65 minutes in all cases.

The results also show that in the separation region of the two specimens, a temperature drop occurs. The

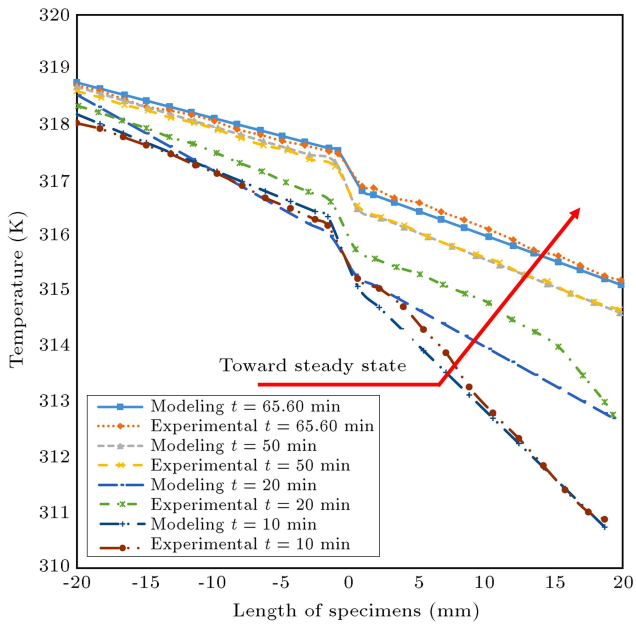

Figure 2. Temperature versus length of specimens for flat-flat surface, unsteady state condition.

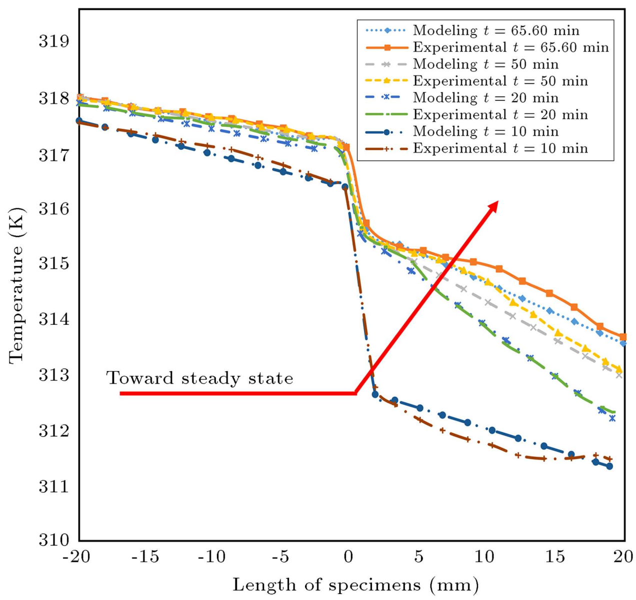

Figure 3. Temperature versus length of specimens for flat-cylinder surface, unsteady state condition.

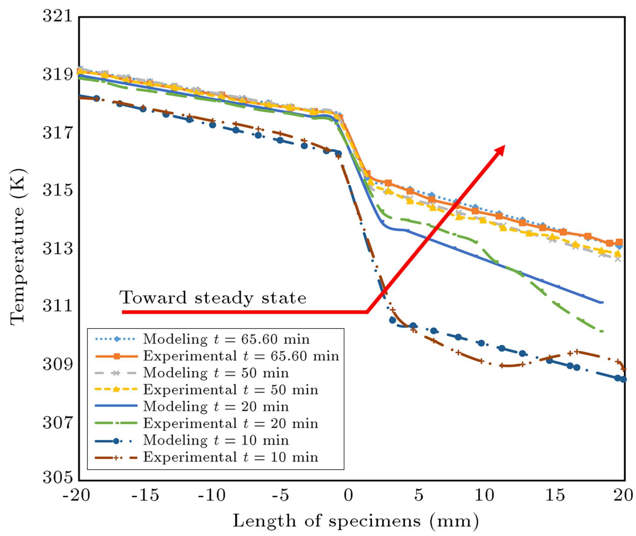

Figure 4. Temperature versus length of specimens for cylinder-cylinder surface, unsteady state condition.

slope of temperature drop in flat-flat configuration is less than that in cylinder-cylinder configuration. Also, this slope in flat-cylinder configuration is more than the other cases (Figures 2 to 4).

Values of TCR in transient state and the corresponding errors are presented in Table 1.

The results for the steady state flat-flat, cylinder-flat, and cylinder-cylinder geometries of contact surfaces are shown in Figure 5, Figure 6, and Figure 7, respectively, and the corresponding predicted values are 9.11e-5, 5.28e-4, and 5.32e-4 with the errors of 6.06e-3, 1.506, and 0.846. The results show that the best estimates are for the steady state condition and among them, the flat-flat case has the lowest error.

Table 1. TCR values in transient state and the corresponding errors.

Contact type	10 (min)		16 (min)		50 (min)		60 (min)		65 (min)	
	TCR	Error%	TCR	Error%	TCR	Error%	TCR	Error%	TCR	Error%
Flat-flat	4.54e-5	4.6074	5.40e-5	3.3791	6.2665e-5	0.6782	7.92e-5	1.0675	7.92e-5	1.0675
Flat-cylinder	5.03e-4	0.1662	1.84e-4	4.4178	2.15e-4	3.7212	1.34e-4	2.7079	1.34e-4	2.7079
Cylinder-cylinder	4.25e-4	0.5622	1.87e-4	1.8719	1.97e-4	1.3832	1.97e-4	1.0695	1.97e-4	1.0695

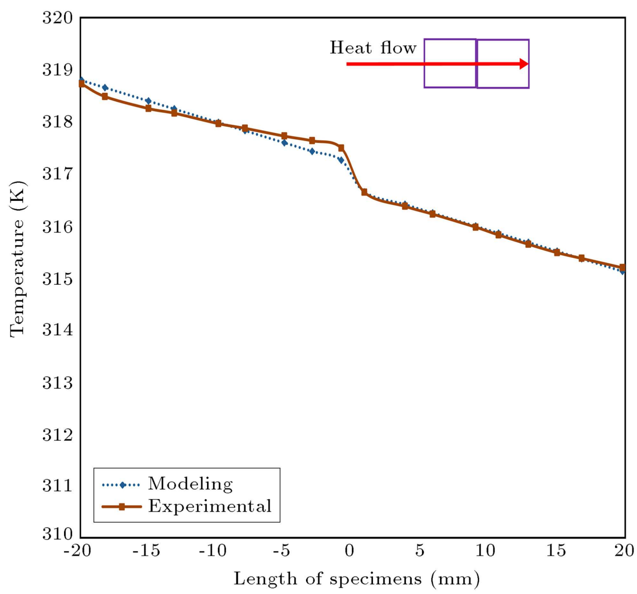

Figure 5. Temperature versus length of specimens for flat-flat surface, steady state condition.

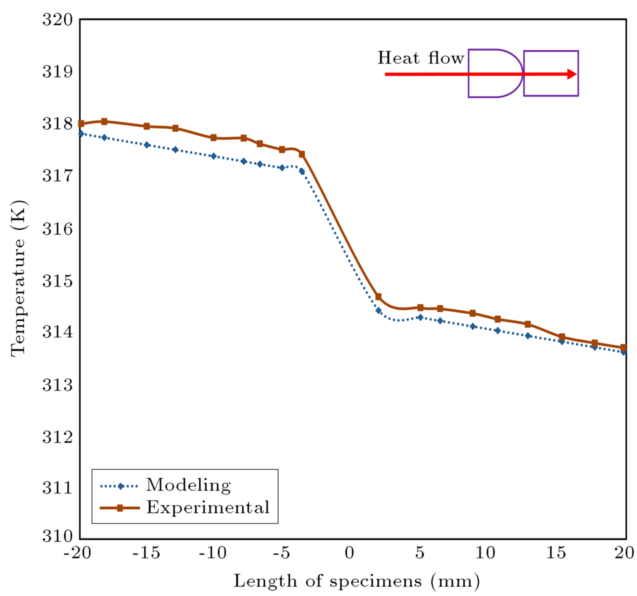

Figure 6. Temperature versus length of specimens for flat-cylinder surface, steady state condition.

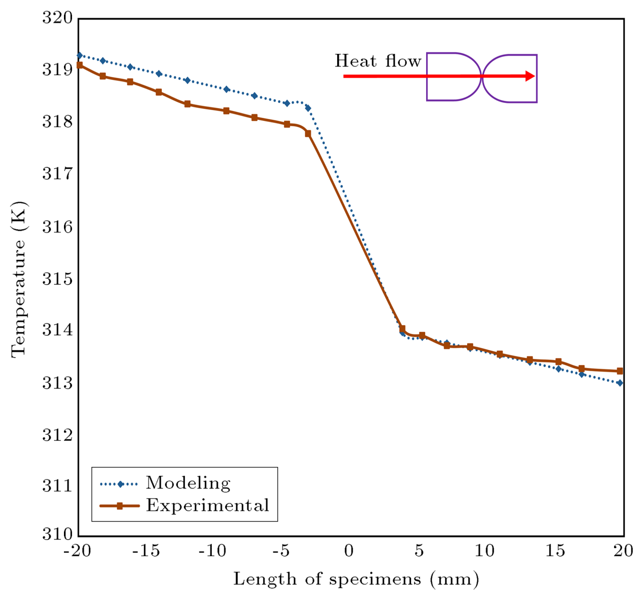

Figure 7. Temperature versus length of specimens for cylinder-cylinder surface, steady state condition.

Table 2. TCR values in steady state and the corresponding errors.

Contact type	TCR	Error%
Flat-flat	9.11e-5	6.06e-3
Flat-cylinder	5.28e-4	1.506
Cylinder-cylinder	5.32e-4	0.846

Values of TCR in steady state and the corresponding errors are presented in Table 2.

5. Conclusion

The results showed that the solution to inverse problem could predict the presented problem with a very good approximation. Also, the error in the flat-flat configuration was the lowest in both steady state and unsteady conditions compared with the other configurations. The results showed that the errors for flat-flat, flat-cylinder, and cylinder-cylinder configurations in transient state, after 10 minutes from the beginning of the experiment, were 4.6074%, 0.1662% and, 0.5622%, respectively, while the errors for flat-flat, flat-cylinder, and cylinder-cylinder configurations in steady state condition were 4.6074%, 0.1662%, and 0.5622%, respectively. The results revealed that the temperature drop slopes in flat-cylinder and flat-flat configurations had the highest and lowest values in these experiments, respectively. Considering the high cost and difficulty of TCR measurement and dependency of the value of TCR on the methods and apparatus of experiment, its prediction by numerical models is a good alternative and among such methods, the inverse problem method for heat transfer is an appropriate choice.

Nomenclature

TCR	Thermal Contact Resistance
TCC	Thermal Contact Conductance
R_c	TCR
ΔT	Temperature drop between the two contacting surfaces
q	Heat flux
Q	Heat transfer between surfaces
t	Time
$T_{C_{\text{cold}}}$	Temperature of the cold specimen
$T_{C_{\text{hot}}}$	Temperature of the hot specimen
T_{ambient}	Ambient temperature
T_{1j}, T_{2j}	Predicted values at the measurement locations for temperatures of Specimens 1 and 2
Y_{1j}, Y_{2j}	Measured values at the measurement locations for temperatures of Specimens 1 and 2

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