The Investigation of the Effect of Contact Frequency upon Thermal Contact Conductance

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Abstract

Thermal Contact Conductance (TCC) between an exhaust valve and its seat is one of the important parameters to be estimated in an internal combustion engine. An experimental study presented here to acquire temperature in some interior points to be used as inputs to an inverse analysis. An actual exhaust valve and its seat are utilized in a designed and constructed setup. Conjugate Gradient Method (CGM) with adjoin problem for function estimation is used for estimation of TCC. The method converges very rapidly and is not so sensitive to the measurement errors. Contact frequency is one the factors which have a significant influence on TCC. The results obtained from current inverse method as well as those obtained from linear extrapolation method show that the thermal contact conductance decreases as the contact frequency increases. The results obtained from both sets of results are also in good agreement.

***Keywords**: Thermal contact conductance, conjugates gradient method, contact frequency, exhaust valve, seat*

1. Introduction

The temperature distribution in the combustion engine components is highly influenced by the thermal contact resistance, which typically is expressed either as thermal contact resistance or as thermal contact conductance. For the prediction and optimization of the thermal behavior of modern combustion engines knowledge about the contact heat transfer is crucial. One of the practical applications is the estimation of thermal contact conductance between the exhaust valve and its seat in an internal combustion engine.

Microscopic and macroscopic irregularities are present in all practical solid surfaces. Surface roughness is a measure for the microscopic ones. Therefore, two solid surfaces apparently in contact touch each other only at a few individual spots. The entrapped gas represents an additional thermal resistance and causes a temperature drop ΔT at the interface. Radiation in the gas gaps will affect the heat transfer only under high temperature conditions ($T > 600$ K).

Experimental efforts as well as theoretical analysis have been done for estimating the thermal contact conductance. The estimation of this prior parameter has been carried out while the heat transfer was either in a steady-state [1,2] or transient condition [3,4]. Some parts of the researches are related to estimation of periodic thermal contact conductance [5-7]. Components in many rotary devices and in automated processes transfer heat periodically across the contact surfaces. Example includes heat transfer between a soldering iron and work piece on an assembly line. A few of them include constant or fixed contacting surfaces [8] usually applied in heat rejection from electronic components. Experiments were conducted using setups that contained two specimens [9,10]. Commonly, two hot and cold rods were used in those setups.

The thermal contact conductance can neither be measured nor calculated directly, so an inverse method should be applied to solve this problem. One of the techniques using for solving the inverse problem is Conjugate Gradient Method (CGM) with adjoin problem for function estimation which is a powerful and straight forward method. The Conjugate Gradient Method by utilizing the ideas based on perturbation principles [11-13] transforms the inverse problem to solution of three simple problems called the direct problem, the sensitivity problem and the adjoin problem together with the gradient equation. The advantage of the present method is that no a priori information is needed on the variation of the unknown quantities, since the solution automatically determines the functional form over the domain specified.

In this study, an actual exhaust valve of an internal combustion engine and its seat are utilized in a setup. This will allow the experiments to simulate the thermal behavior of the exhaust valve and its seat more properly. In addition, the application of CGM of function estimation is demonstrated to the estimation of the thermal contact conductance between the valve and its seat under periodic contact.

2. Experiment Circumstance

In order to acquire desired data for estimating the thermal contact conductance between two contacting surfaces, a setup is designed and built. Unlike the previous apparatuses, which usually used two hot and cold rods as the exhaust valve and its seat, in this study, an actual exhaust valve and its seat are utilized. This lets the experiment to simulate the thermal behavior of the exhaust valve and its seat more properly. A photo of the constructed setup and its schematic view are shown in Figures 1 and 2, respectively. Different components of the experimental apparatus are illustrated in Figure 2. A brief description of the test apparatus will be given later.

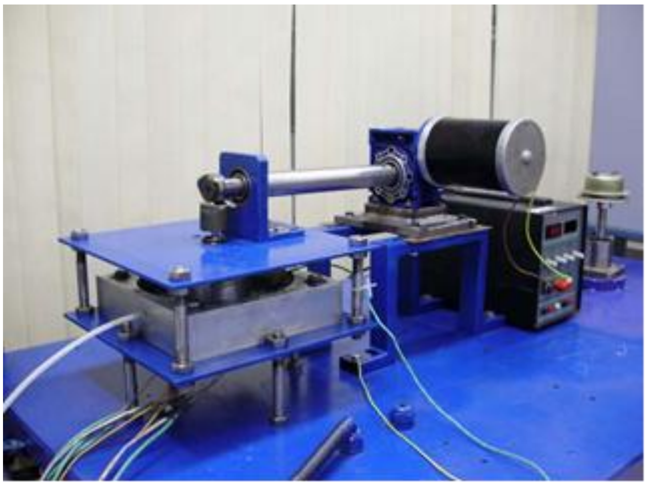

Fig1. A photo of the test apparatus

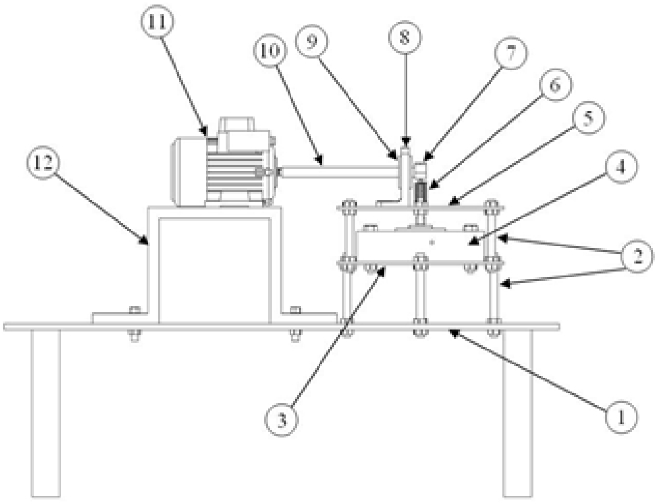

Fig2. Different components of the experimental setup: 1-main plate, 2-supporting rods, 3-lower supporting plate, 4-seat, 5-upper supporting plate, 6-valve spring, 7-cam, 8-camshaft support, 9-bearing, 10-camshaft, 11-electromotor-gearbox, 12-electromotor support

In order to carry out the experiment in the dynamic state and to investigate the effect of the contact frequency upon the thermal contact conductance, a DC electromotor-gearbox (KORMAS model), with the minimum speed of 1 rpm and the maximum speed of 300 rpm is utilized. The maximum power of the electromotor-gearbox is 400 Watts. In addition, to control the speed of the electromotor, a converter is used.

A 55 mm long interior heater with 4 mm diameter is located within the valve stem to generate heat. The maximum power of the heater is 110 Watts and it operates with 230 Volts. The supplied heat flux magnitude is controlled by a three-phase power control unit.

The temperatures of the valve and its seat are controlled by using the ice and water mixture. An Aluminum reservoir is used to hold the mixture. Ice is continuously added to the reservoir in order to compensate the amount of the ice melted. The mixture surrounds the seat to keep its temperature around 0 °C.

An insulator, made up of Alumina Silicate, is used to minimize the amount of heat transfer through the valve stem and the upper and lower sides of the seat. The insulation thick layers around the seat ensured the one-dimensional radial heat transfer through the valve head.

The actual exhaust valve and its seat are made from steel. The roughness of the valve and the seat at the contact interface is about 0.3 to 0.4 μm. The surface roughness is measured by a high-resolution profile-meter. The thermo-physical properties of the valve and the seat are tabulated in Table 1. It should be noted that with increasing the temperature up to 600 K, these properties do not vary significantly [10]. Thus, the properties at 300 K are used for the calculations.

The thermocouples with 1 mm diameter and with the measurement accuracy of ± 0.1 °C for the range of -65 to +400 °C are used for all of the temperature measurements. The thermocouples are mounted in the holes drilled in the valve head and the seat. The locations of the thermocouples and the geometry of the problem are shown in the Figure 3. The thermocouples are mounted into the holes with a multi-metal epoxy which its properties is close to the steel used in the valve and seat. It can preserve its properties up to 280 °C. Six thermocouples are located in the valve head and the seat. One additional thermocouple is located in the ice and water reservoir to measure the mixture temperature. These thermocouples are calibrated with a physical technique under steady-state condition. All thermocouple ends are terminated at a junction box connected to an A/D card through coaxial cables. The data acquisition system is composed of 8 channels and interfaced to a PC. The data acquisition system included a C# code. The time interval duration for data acquisition can be set in the program. The program will automatically log the temperature data into an Excel file for sorting and analysis.

All experiments are performed in an environment at a pressure close to 1 bar. Additionally, the specimens are kept at relatively low temperature, so the radiation heat transfer across the interstitial gap is negligible. The experiments are carried out for both constant and periodically contacting surfaces. Two valve springs with different stiffness of K1 and K2 (K2>K1) are applied to investigate the effect of the valve spring stiffness upon the thermal contact conductance. In addition, the experiments are done for various speeds of 20 rpm, 40 rpm and 60 rpm. For periodically tests, for 2/3 of the period duration the vale and its seat are in contact and for 1/3 of the period duration, they are separated.

Table 1 the thermo-physical properties of the valve and the seat

	Vale	Seat
Material	Steel (X53CrMnNiN21-9)	Steel (X20Cr13)
Roughness (e)	03-0.4 (μm)	03-0.4 (μm)
Density (ρ)	7800 (kg/m^3)	7700 (kg/m^3)
Specific Heat (c_p)	0.5 (kJ/kg K)	0.46 (kJ/kg K)
Conductivity (k)	14.5 (W/m K)	30 (W/m K)

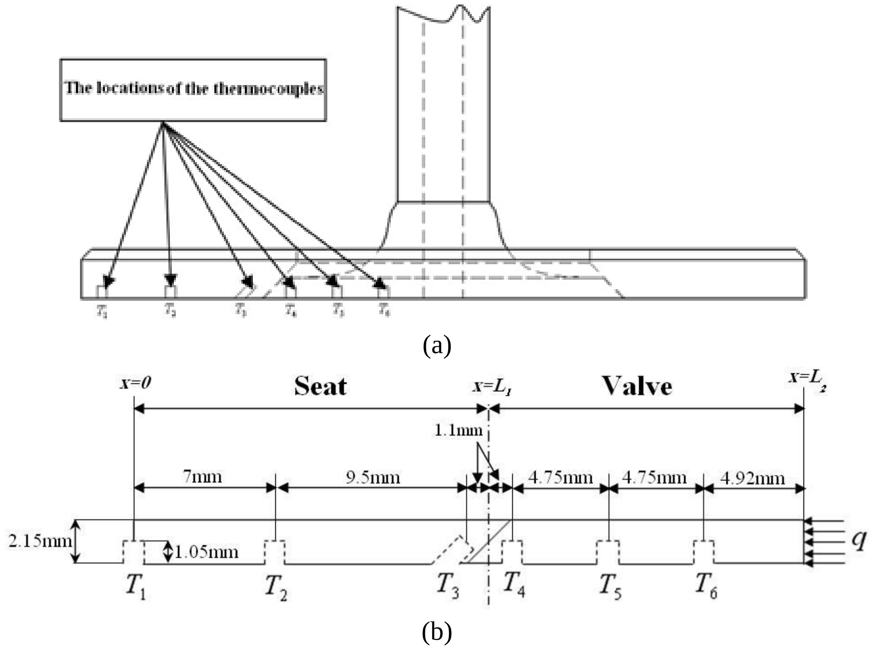

Fig3. The locations of the thermocouples and the geometry of the problem

3. The Inverse Method

The geometry and the coordinates for the one-dimensional physical problem considered here is shown in Fig. 3.The mathematical formulation of the direct heat conduction problem is given in as:

Seat ($0 \le x \le L_1$):

$$\frac{\partial^2 T_1}{\partial x^2} = \frac{1}{\alpha_1}\frac{\partial T_1}{\partial t} \qquad 0 < x < L_1 \text{ for } t > 0 \qquad (1.a)$$

$$T_1(0,t) = T_0 \qquad \text{for } t > 0 \qquad (1.b)$$

$$k_1 \frac{\partial T_1}{\partial x} = h(t)[T_2 - T_1] \qquad \text{at } x = L_1, \text{ for } t > 0 \qquad (1.c)$$

$$T_1(x,0) = T_i \qquad 0 < x < L_1 \qquad (1.d)$$

Valve ($L_1 \le x \le L_2$):

$$\frac{\partial^2 T_2}{\partial x^2} = \frac{1}{\alpha_2}\frac{\partial T_2}{\partial t} \qquad L_1 < x < L_2, \text{ for } t > 0 \qquad (2.a)$$

$$k_2 \frac{\partial T_2}{\partial x} = h(t)[T_2 - T_1] \qquad \text{at } x = L_1, \text{ for } t > 0 \qquad (2.b)$$

$$k_2 \frac{\partial T_2}{\partial x} = q \qquad \text{at } x = L_2, \text{ for } t > 0 \qquad (2.c)$$

$$T_2(x,0) = T_i \qquad L_1 < x < L_2 \qquad (2.d)$$

For the inverse problem, the interface thermal contact conductance, $h_c(t)$ is regarded as unknown, but everything else in the system of equations (1-2) is known and temperature readings taken at some appropriate locations within the medium are available, at times t_i, $i = 1, 2, \ldots, I$. Let the temperature recordings taken with sensors to be denoted by $Y_{1j}(t) \equiv Y_{1j}$ and $Y_{2k}(t) \equiv Y_{2k}$ for specimens 1 and 2, respectively.

It is assumed that no prior information is available on the functional form of $h_c(t)$. We are after the function $h_c(t)$ over the whole time domain $(0, t_f)$, with the assumption that $h_c(t)$ belongs to the Hilbert space of square-integral functions in the time domain [13] – denoted as $H(0,t_f)$ – in this domain, i.e., $\int_{t=0}^{t_f} [h_c(t)]^2\, dt < \infty$.

The solution of the present inverse problem is to be obtained in such a way that the following functional is minimized:

$$S[h_c(t)] = \int_{t=0}^{t_f} \left[\sum_{j=1}^{N_1} \left(T_{1j} - Y_{1j}\right)^2 \right] dt + \int_{t=0}^{t_f} \left[\sum_{k=1}^{N_2} \left(T_{2k} - Y_{2k}\right)^2 \right] dt \qquad (3)$$

where $T_{1j}(t) \equiv T_{1j}$ and $T_{2k}(t) \equiv T_{2k}$ are the estimated temperatures at the measurement locations in seat and valve, respectively.

In this work, the Conjugate Gradient Method (CGM) with adjoin problem for function estimation is used to solve the current inverse problem. The advantage of the present method is that no a priori information is needed on the variation of the unknown quantities, since the solution automatically determines the functional form over the domain specified. In this method, additional equations beyond the governing equation must be solved. It transforms the inverse problem to solution of three simple problems called the direct problem, the sensitivity problem and the adjoin problem together with the gradient equation. The set of three equations is iteratively solved using the method conjugate gradients for the corrections at the end of every iteration. For derivation of sensitivity and adjoin problem from the direct problem as well as the definition of iterative procedure and the computational algorithm of the method, the readers should consult references [13,17].

4. Results and Discussions

The thermal contact conductance was computed by means of the following expression,

$$h_c = q/\Delta T \tag{3}$$

where q is the average of the heat fluxes of the two contacting surfaces and ΔT is the temperature drop at the interface, which is computed by extrapolating the temperature profiles of each contacting specimen to the interface.

It is assumed that sufficient number of contacts has been made so that the quasi-steady-state condition is established for the temperature distribution, that is, the temperature distribution in the regions during one period is identical to that in the following period. Temperature measurements at thermocouple locations for one period and under quasi-steady-state condition are shown in Figures 4 to 6 for the speed of 20, 40, 60 rpm, respectively. The temperatures are measured by using the valve spring with the stiffness of K2 equal to 257 (N/m).

The contact frequency is one of the factors of significant influence on the thermal contact conductance. As contact frequency grows, the period duration and consequently the time of contact decreases, so the amount of the heat transfers from the exhaust valve to its seat decreases. When the temperature readings in Figures 4 to 6 are compared with each other, one can come to this conclusion that the valve becomes hotter and the seat becomes cooler as the contact frequency rises up.

The estimated thermal contact conductance determined by using the present inverse method and the linear extrapolation method, both based on the experimental data are shown in Figures 7 to 9 for the speed of 20, 40 and 60 rpm, respectively.

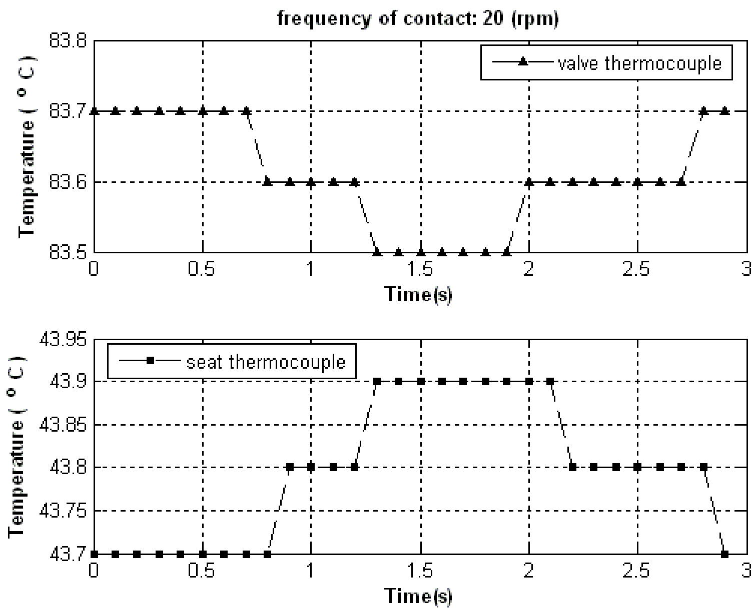

Fig4. Temperature distribution at the nearest thermocouples to the interface for the speed of 20 rpm

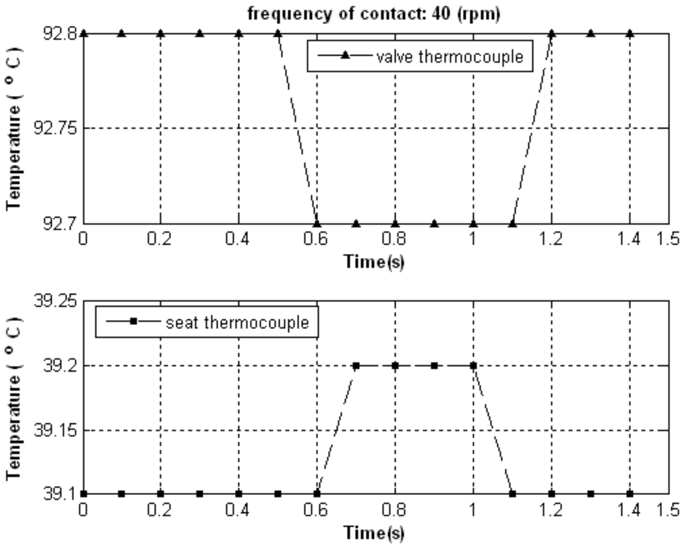

Fig5. Temperature distribution at the nearest thermocouples to the interface for the speed of 40 rpm

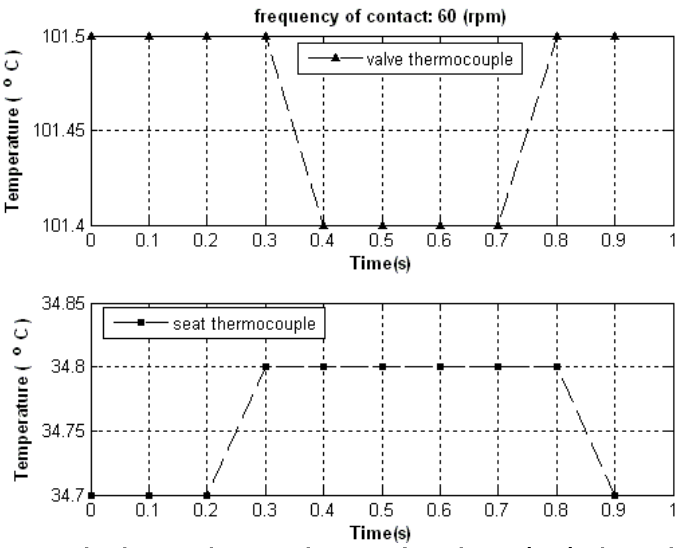

Fig6. Temperature distribution at the nearest thermocouples to the interface for the speed of 60 rpm

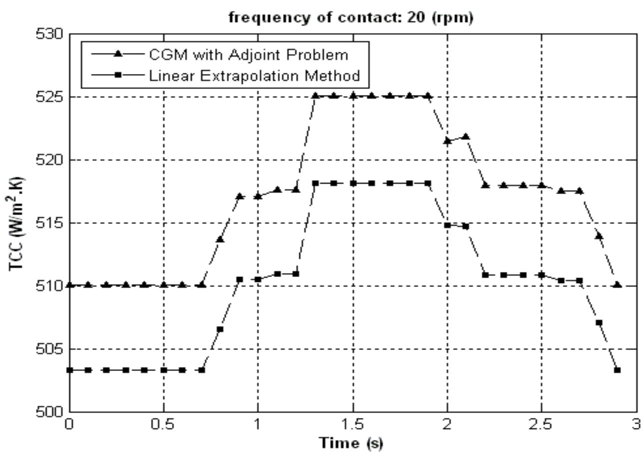

Fig7. Thermal contact conductance for the speed of 20 rpm

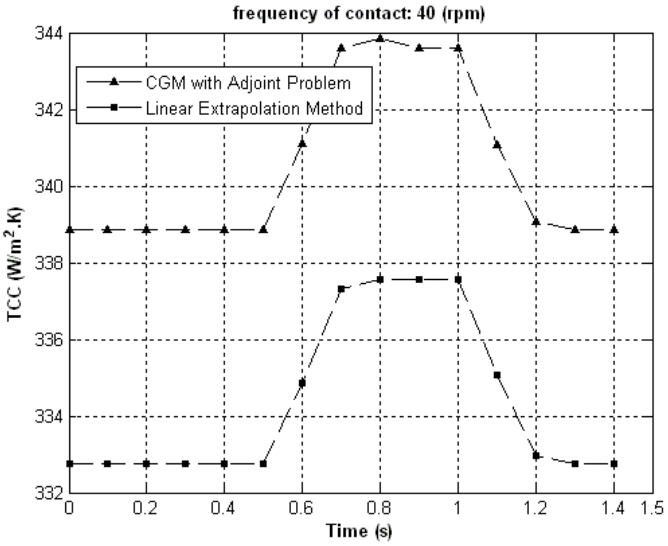

Fig8. Thermal contact conductance for the speed of 40 rpm

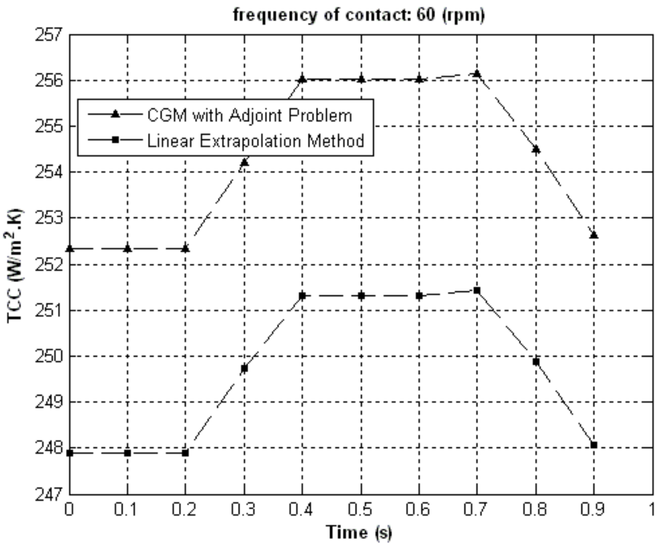

Fig9. Thermal contact conductance for the speed of 60 rpm

We expect the thermal contact conductance to be nearly zero over the non-contact segment of a period and nominally constant over the contact duration. Since the thermocouple 3 and the thermocouple 4 are extremely close to the contact surface, there is a little extrapolation from the fitted curve to determine the interface temperature. So the extrapolation result appears to show damping and lagging similar to the result obtained from CGM. The estimated thermal contact conductance computed using the present inverse analysis is somewhat improved relative to the anticipated true contact conductance.

However, the error present in any individual temperature measurement is dependent on the accuracy of the data recorder and the calibration standard. Therefore, the error introduced by temperature uncertainty into the computation of the contact surface temperatures and interface temperature drop is one of the reasons of the deviation of the extrapolation method result from the result obtained with CGM.

According to results discussed before, the thermal contact conductance decreases as the contact frequency increases. This result can easily be observed from Figures 7 to 9.

5. Summary and Conclusions

In order to acquire desired data for estimating the thermal contact conductance between two contacting surfaces, a setup is designed and built. Unlike the previous apparatuses which usually used two hot and cold rods as the exhaust valve and its seat, in this study, an actual exhaust valve and its seat were utilized. The effect of the frequency of contact on the thermal contact conductance was studied by increasing the electromotor speed.

The results show that the thermal contact conductance decreases with increasing in frequency of contact. The linear extrapolation method in addition to the CGM with adjoint problem for function estimation is applied to obtain the results. The present inverse approach is shown to be superior to the extrapolation method. Generally, the results obtained with CGM and the linear extrapolation results are in good agreement

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