EFFECT OF CONTACT PRESSURE AND FREQUENCY ON CONTACT HEAT TRANSFER BETWEEN EXHAUST VALVE AND ITS SEAT

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Abstract The hot gases produced by the internal combustion engines passes through the exhaust valve and causes high temperatures in the exhaust valve and its seat. To avoid damaging the exhaust valve, heat must be transferred from the valve to its seat during the contact they make at the opening and closing cycle. Heat transfer rate from the exhaust valve to its seat is a function of many factors. One of the most important factors is the thermal contact conductance (TCC) between the exhaust valve and its seat. Very few researches have been done about estimation of the TCC between the exhaust valve and its seat in the past. An experimental study has been conducted to determine the TCC between two co-axial cylinders, as the exhaust valve and its seat. Furthermore, the influence of contact pressure and frequency of contact upon the TCC is studied. The results show that the TCC decreases as the frequency of contact increases. The experimental results obtained from the present work are in good agreement with the previous published data.

Keywords Thermal Contact Conductance, Exhaust Valve, Contact Pressure, Frequency of Contact

چکیده خروج گازهای حاصله از احتراق در موتورهای احتراق داخلی سبب می‌شوند سوپاپ دود و نشیمن گاه آن به دماهای بالایی برسند. به منظور جلوگیری از آسیب دیدن سوپاپ دود در طی سیکل باز و بسته شدن، گرما بایستی از سوپاپ دود به نشیمن گاه آن منتقل شود. عوامل مختلفی بر نرخ انتقال حرارت سوپاپ دود به نشیمن گاه تاثیر می‌گذارند؛ یکی از مهمترین آنها ضریب هدایت حرارتی تماس (TCC) می‌باشد. تاکنون تلاش‌های اندکی برای تخمین TCC میان سوپاپ دود و نشیمن گاه انجام گرفته است. یک مطالعه تجربی به منظور تعیین TCC میان دو سیلندر هم–محور همچون سوپاپ دود و نشیمن گاه انجام گرفته است. به علاوه اثر فشار تماس و فرکانس تماس بر TCC مورد بررسی قرار گرفته است. نتایج نشان می‌دهد که با افزایش فرکانس TCC کاهش می‌یابد. نتایج آزمایشگاهی حاصل از این تحقیق در مقایسه با داده های قبلی دیگر محققان سازگاری خوبی نشان می‌دهد.

1. INTRODUCTION

Internal combustion engines generate hot gases. When these gases exit through the exhaust valve, the valve and its seat reach high temperatures. To keep it from being damaged, heat is transferred from the exhaust valve to its seat as they come into contact during the opening and closing cycle. The determination of heat transfered from the exhaust valve to its seat and the online temperature estimation of engine component such as exhaust valve offer a chance for better engine control. The importance of this work is the investigation of periodic heat transfer through contact, using the simplified test setup. Also identifying the critical factor TCC, for different pressure and frequency, which is effective in designing engines' cooling system.

In the past years, the experimental study of thermal contact was of increasing interest to researchers and industrial engineers [1-6]. A few numbers of these researches are related to periodic thermal contact problems.

A theoretical study was made by Howard, et al [7]. Considering heat transfer in a mathematical model comprising of two identical bars in material and length, l, whose longitudinal axes were in line and whose adjacent ends could be brought into contact and separated cyclically. An inverse heat conduction method for determining the periodic time-varying contact conductance between two periodic contacting surfaces is presented by Flach, et al [8]. The technique is based on solving two single-regions' inverse problems for the contact surface temperature and heat flux of each solid. Vick, et al [9] utilized the finite integral transform technique to obtain quasi-steady-state solutions for the problem of two periodic contacting finite regions with imperfect thermal contact at the interface. This study is focused on the effects of contact duration, TCC, thermal conductivity, and thermal diffusivity on the temperature distribution across two contacting surfaces. Moses, et al [10] experimentally examined the problem of periodically contacting similar metal surfaces and obtained results that are comparable in both form and magnitude to those of Vick and Ozisik. Moses, et al [11] also experimentally examined the approach to the quasi-steady-state condition for similar metallic surfaces in periodic contact, focusing on the behavior of the TCC during the contact portion of a cycle and on the number of cycles required to reach a quasi-steady state condition. The experimentally obtained temperature distributions from Moses and Johnson also were examined by Beck as an example of a parameter and function estimation technique for the inverse heat conduction problem. Dodd, et al [12] extended this set of experiments to consider periodic contacts between aluminum and stainless steel. Results for this single case of periodic contact between dissimilar metals indicated that the same transient behavior of the TCC exist for all metal pairs.

It is obvious that one of the significant applications of periodic thermal contact is in heat transfer calculation between the exhaust valve and its seat. In internal combustion engine, Huang, et al [13] employed the conjugate gradient method to solve the inverse problem to determine the periodic TCC as a function of time between the exhaust valve and the seat. Couedel, et al [14] conducted an experimental study, which measured the temperature in situ field under periodic contact for an actual valve-seat configuration. The results from experimental setup indicated that the TCC was highly dependent on the rotational frequency of the internal combustion engine and that the mean (time-averaged) and periodic temperature field can be measured by the use of an integrating voltmeter and extremely fast (response time) instrumentation. In addition, the thermocouples must be positioned close to the valve-seat interface to obtain efficient measurement of the oscillating temperature. Shojaeefard, et al [15] used a new method to estimate valve temperature and the TCC. They estimated the TCC with linear models of system identification method.

So far, a comprehensive model to predict the heat transfer between the exhaust valve and its seat has not been developed due to its complex dynamic system and real contact surfaces. Therefore, it is clear that heat transfer between the exhaust valve and its seat can play a great role in improving engine performance and fuel efficiency. In addition, integration of this thermal information for an online estimation of ECU-based calculation, for the in-cylinder temperatures will help to regulate the cooling system better, for enhanced operating temperatures without damage.

In this study, an experimental apparatus has been designed and constructed for the estimation of the TCC between the exhaust valve and its seat, using inverse heat transfer method. This method is very rapid and is not very sensitive to measurement errors. The other advantage of the present method is that no prior information is needed on the variation of the unknown quantities [16].

2. EXPERIMENTAL SETUP

The test apparatus is designed and developed for the identification of the TCC between two periodic contacting surfaces such as the exhaust valve and its seat. The TCC is measured by passing heat flux through two contacting cylindrical specimens. All experiments are performed in an environment at a pressure close to 1 bar. The insulating thick layers ensured no radial heat loss due to convection. Additionally, the specimens are kept at relatively low temperature, so the radiation heat transfer across the interstitial gap is negligible. Low temperatures are also necessary to prevent extreme creep in specimens, or melting of specimens. The only significant type of heat transfer across the interface is conduction through the solid contacts. Figure 1 shows the test apparatus.

2.1. Loading System A compressive load is exerted on the specimens by a simple mechanical system including a free disk and several dead weights. In order to avoid moments and lateral forces, the compressive load is exerted on the specimen through a ball bearing. Since the ball is free to roll, it does not transfer moments or lateral forces to the specimen. In order to carry out experiment in dynamic state and to investigate the effect of frequency of contact on the TCC an electromotor gearbox (ANTRIEBSTECHNIK GEFEG), model M32-1018236H 30/1, with maximum speed of 500 rpm and maximum power of 300 Watts is utilized. To control the speed of the electromotor, a converter is used.

2.2. Heat and Cooling System The temperatures of the specimens are controlled by using circulating cooling water at the bottom and a heater at the top of the specimens. The stainless steel plate base, is applied to hold the cooling system. Cooling water from a constant temperature bath of (0°C) is re-circulated for removing heat from the specimens. A centrifugal pump with the power of 100 Watts is used to pump the circulating water through the copper tubes in the end region of the bottom specimen. An 80.0 cm long flexible wire heater is wrapped around the end of top specimen to generate heat. The supplied heat flux magnitude is controlled by a variable transformer. An insulator, made up of glass-wool and fiberglass, is used to minimize the amount of heat transfer through the load system, heater, cooling system and the specimens. The heat meter is used in order to measure the actual heat flow rate through the specimen.

2.3. Temperature Measurement System The type K thermocouples are used for all of the temperature measurements. The thermocouples are mounted in holes drilled perpendicular to the axis similar in all specimens. The thermocouples are mounted into the holes by epoxy with conductivity which can resist high temperature. The temperature distribution along the specimens, measured by 3 0.5 mm thermocouples in each specimen, is used to calculate the heat flux and the temperature drop at interface. Thermocouples are fixed in 1.0 mm diameter holes drilled on the test specimens. Two K-type thermocouples are located on the centerline of each specimen at 2.0 cm intervals for 4.0 cm of each specimen adjacent to the contact surface. One additional K-type thermocouple is located on each specimen centerline at 1.0 cm from the contact surface (Figure 2). These thermocouples are calibrated with a physical technique in the steady-state condition. All thermocouple ends are terminated at a junction box, which is connected to an A/D card (The data acquisition set-up was

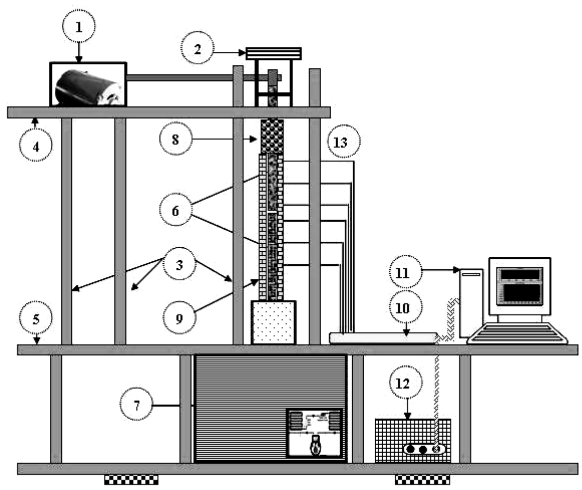

Figure 1. Experimental setup.

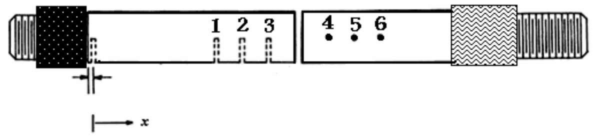

Figure 2. The test specimens.

composed of 8 channels and interfaced to an Intel PC/Pentium II computer) through an interface cable. This will automatically log the temperature data into the files.

2.4. Specimens Properties The test specimens are cylindrical in shape with a diameter of 0.8 cm and a length of 20 cm. Three holes are drilled perpendicular to each specimen's axis of symmetry. They are located on the center line of each specimen at 0.02 m intervals for the 0.01 m of each specimen adjacent to the contact surface. Two additional holes are drilled on the specimen centerline, one at 0.03 m from the contact surface and the other at 0.05 m from the contact surface. Extreme care is taken during the preparation of the contacting surfaces. The surfaces of the cylindrical test specimens are machined in order to obtain surfaces having small roughness about 4.7 μm for steel and 5.9 μm for aluminum. The surface roughness was measured by a high-resolution profile-meter (surfscan 200). Thermophysical properties of specimens are shown in Table 1 at 300 K. It should be noted that with increasing the temperature to 800 K, these properties do not vary significantly. Thus, properties of specimens at 300 K were used for calculations [17].

2.5. Data Acquisition System All the thermocouples are connected to a data acquisition system through the feedthroughs. The data acquisition set-up is composed of 8 channels and interfaced to an Intel PC/Pentium II computer. The data acquisition system includes a SCSI board and MATLAB software, used for collecting data, storing data and data analysis.

3. TEST PROCEDURE

To start an experiment, the test specimens are first cleaned with alcohol. Then the test specimens are placed in the experimental apparatus including a compressive testing system, which exerts an initial load of 50 kPa. Afterwards, the apparatus is insulated from the surroundings with glass wool. The variation of effective quantities such as temperatures, pressure and frequency are measured when the system reaches the steady state condition. As it is discussed before experimental procedure is repeated for experiments with 2 pairs of test specimens. All experiments are conducted with dry interfaces. Friction between the two specimens is assumed negligible in order to eliminate heat generation due to friction. The lateral surfaces of the specimens are insulated with glass wool as an insulator. The ambient temperature is about 23˚C. The lower surface of the bottom specimen is retained at a constant temperature of 0.0˚C.

Initial results on hot stainless steel indicate that, the heat transfer down the specimen is one-dimensional. A Selection of these temperature measurements is given in Table 2 for the case of measurements at a distance of 3.0 cm from the contact surface. At this location on the test specimen, it is seen that the maximum difference between the center line temperature (T_{CL}) and the surface temperature (T_{Surf}) is 4.8 (˚C) on the heated specimen. This difference represents up to 1.74 % of any single temperature measurement used in the computation. Therefore, the heat flow in the test specimen is nearly one-dimensional and the radial conduction heat losses are negligible.

The temperatures differences observed in Table 2 are shown to investigate one-dimensional heat transfer. The next calculations are based on the assumption that heat transfer is one-dimensional and none of those parameters in Table 2 are relevant to the calculation of the TCC.

The temperature distribution obtained from thermocouples, which is located in each specimen, is used to calculate the heat flux and temperature difference at the interface. It is assumed that the temperature drop on both contact surfaces of the specimens is defined by

$$\Delta T_C = T_{C1} - T_{C2} \quad (K) \tag{1}$$

Thus, the TCC is determined using the following equation:

$$h = q/\Delta T_C \quad (W/m^2.K) \tag{2}$$

Where q is the heat flux through contact surface. T_{C1} and T_{C2} are the temperatures of contact surfaces and they are estimated by the temperature distribution in specimens using Least Square Method.

TABLE 1. Thermophysical Properties of Specimens at 300 K.

Material	Aluminum	Steel
Conductivity ($W/m^2.K$)	177	37.7
Density (kg/m^3)	2770	7822
Heat Capacitance (j/kg.K)	875	444
Surface Roughness (μm)	5.9	4.7
Length (m)	0.20	0.20
Reservoir Temperature (˚C)	0.0	---

TABLE 2. Measured Temperatures.

Time (min)	T_{CL} (˚C)	T_{Surf} (˚C)	ΔT (˚C)	$\Delta T/T_{CL} \times 100$
20	41.3	40.4	0.9	2.18
40	156.1	153.6	2.5	1.6
60	208.9	205.7	3.2	1.53
80	224.2	221.9	2.3	1.02
100	275.9	271.1	4.8	1.74

The heat flux values can be calculated using the temperature gradient and the thermal conductivity of the material. Fourier’s law of heat conduction is used to determine the thermal conductivity of the test specimens from the measured heat flux and the known specimen dimensions. The top heat flux indicates the heat supplied to the test specimen and the bottom heat flux indicates the heat removed from the test specimen. It is observed that the heat flux in the top specimen is more than that in the bottom specimen. This is due to the nature of periodic thermal contact; as the hot specimen is not always in contact with the cold one, the whole of passing flux in hot specimen is not transfered to the cold specimen. Then, the average heat fluxes on the hot and cold side cross the contact interface is used for calculations.

As test samples are perfectly insulated and the steady-state conditions are satisfied, a significant difference between passing heat flux in both specimens isn't noticed. Additionally, the magnitude of the radiative heat transfer can be neglected due to the relatively low temperatures. Then, the heat loss from the test specimens to the surrounding air can be neglected.

In order to study the effect of applied contact pressure on TCC, the load in steps of 0.5-2.5 MPa are utilized. The temperatures values are recorded for each load when they reach the steady-state condition. Therefore, the TCC value is obtained for contact pressure of 0.5, 1.0, 1.5, 2.0 and 2.5 MPa. The effect of the frequency of contact on the TCC is studied by increasing the electromotor speed from 50 to 300 rpm. The temperatures values are recorded for each frequency when they reach the steady-state condition. Therefore, the TCC value is obtained for frequency of 50, 100, 150, 200, 250 and 300 rpm.

4. RESULTS AND DISCUSSION

Temperature variations with time at different points of test specimens are obtained by data acquisition system. Three thermocouples are placed at different distances from the interface in any specimens (Figure 2). The measurement time step is 0.267 second. The measured temperatures in both specimens are shown in Figure 3. The surface temperature at the contact surface is obtained by using least squares method. Figure 4 shows the contact surface temperatures for similar contact (steel-steel). In this case, the contact pressure is 1.5 MPa.

The values of TCC are computed using Equation 2. We know that thermal contact conductance is proportional to temperature drop (T_{C1}-T_{C2}) in interface. At the beginning of the test, the value of temperature drop is very small and it has little influence upon the TCC. When the test proceeds, the value of temperature drop becomes greater and therefore the effectiveness of the TCC becomes pronounced. According to this reason, the measured value of the TCC is more accurate as the number of cycles is increased.

The effect of contact pressure and frequency of contact on TCC is investigated and results are shown in Figure 5 and 6.

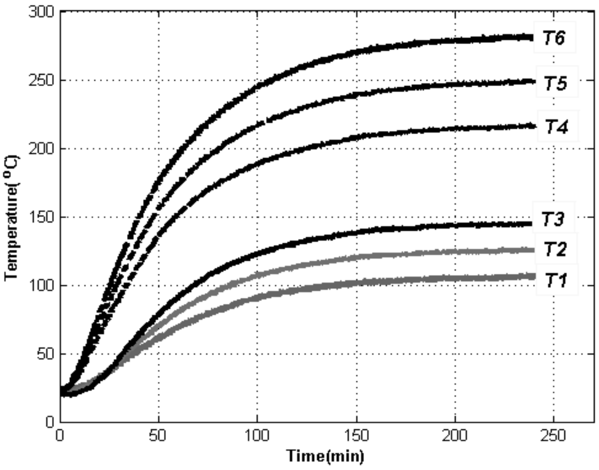

Figure 3. Measured temperatures in both specimens.

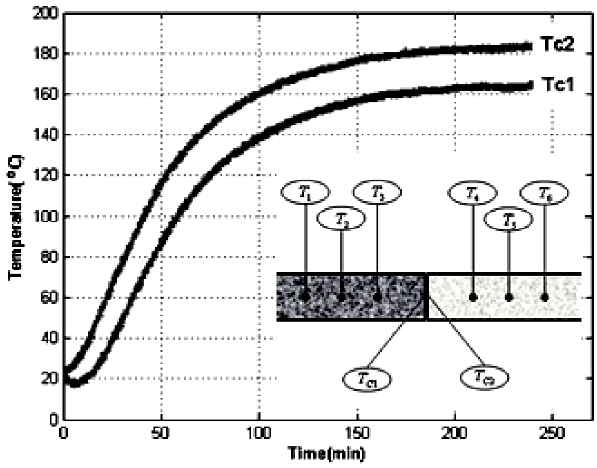

Figure 4. Contact surface temperatures.

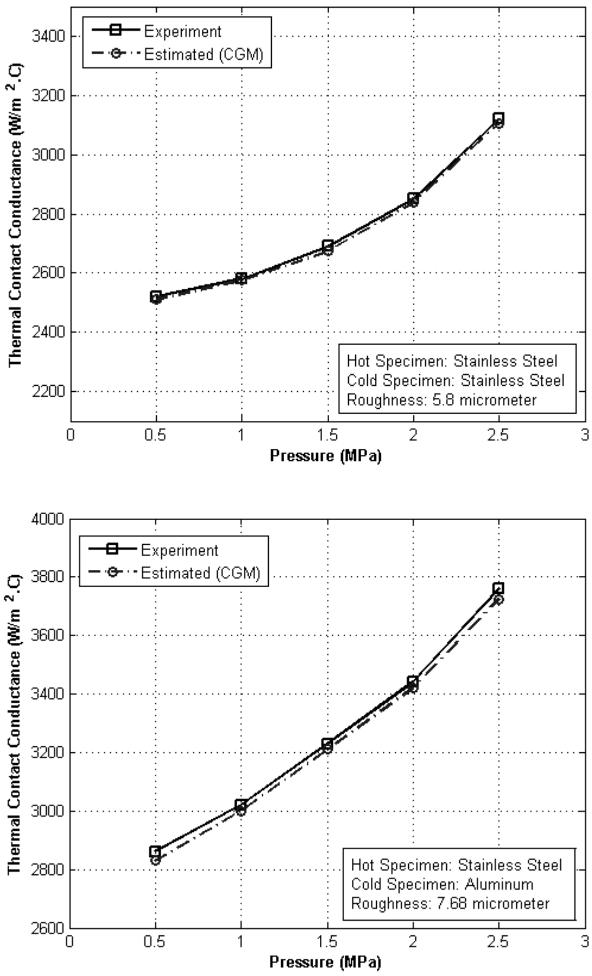

Figure 5. Thermal contact conductance for various pressures.

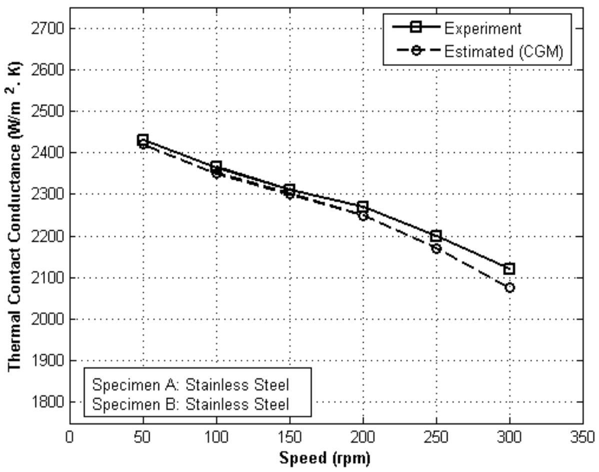

Figure 6. Thermal contact conductance for various frequencies.

4.1. Effect of Contact Pressure The contact pressure is often a more effective parameter on TCC. Further, the variation of this contact pressure has a significant influence on TCC. To observe the effect of contact pressure on TCC, 5 experiments are selected to present TCC versus pressure (Figure 5). It is obvious that TCC increases with increase in contact pressure. TCC increase is due to rising contact point distribution density with increasing contact pressure. In addition, TCC increases with increasing interface temperature at the same contact pressure.

The increase rate of TCC versus contact pressure in the similar contact is lower than the dissimilar one. This is due to the fact that in dissimilar contact, one of the surfaces is smoother than the other. Therefore, when load is applied, more contact points of contacting surfaces have conduction heat transfer.

4.2. Effect of Frequency of Contact To observe the effect of frequency of contact on TCC, 6 experiments (50, 100, 150, 200, 250 and 250 rpm) are selected to present TCC. Figure 6 shows the effects of frequency of contact on TCC. The results indicate that TCC should not be considered constant for contacts of short duration; and relatively many cycles are required for the temperature distribution in the specimen and the TCC to approach the steady-state condition. When the contact time is short or frequency of contact is high, the TCC is small and the temperature distribution in each specimen is more different. Hence, the temperature difference in the specimens at the initiation of contact is higher.

Comparison of these results with the published results by Moses and Huang [11,13] shows that they are in excellent agreement.

The results show that the TCC magnitudes in lower frequencies are greater than those of the higher ones. It is known that in lower frequencies the contact time is longer and therefore, it causes TCC to become bigger.

4.3. Uncertainty Analysis The completion of uncertainty analysis for this study embodied the identification and quantification of errors. In order to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements, the method used will be explained as follows.

The experimental TCC of a particular contact is determined from the estimated heat flux and the temperature drop across the interface (Equation 2).

The heat flux through the interface is computed by the temperature gradient and the thermal conductivity. The uncertainty in the heat flux computation may be examined by comparing the differences in the computed values of heat flux for both the hot and cold specimens in the steady-state condition. This evaluation yields a maximum percentage of variation of 13.76 %. The uncertainty in the temperatures of contact interface is the result of the uncertainties associated with the thermocouple readings and the estimated temperatures. The thermocouple readings are estimated to be accurate to ± 0.1˚C. The uncertainty in the temperatures of contact interface by extrapolation of the temperature gradients is estimated; they ranged from 1.39 to 4.12 % at the seven different frequencies. The estimated maximum temperature drop was as large as 23.9˚C and the minimum value was approximately 15.2˚C. Using a simple differential error analysis [18], the estimated uncertainty in the measured thermal contact conductance can be found from

$$w_{h_c} = \left[\left(\frac{\partial h_c}{\partial q_c} w_{q_c} \right)^2 + \left(\frac{\partial h_c}{\partial T_{c1}} w_{T_{c1}} \right)^2 + \left(\frac{\partial h_c}{\partial T_{c2}} w_{T_{c2}} \right)^2 \right]^{1/2} \tag{3}$$

substituting partial derivates, it simplifies to

$$w_{h_c} = \left[\left(\frac{w_{q_c}}{\Delta T_c} \right)^2 + \left(\frac{q_c}{(\Delta T_c)^2} w_{T_{c2}} \right)^2 + \left(\frac{q_c}{(\Delta T_c)^2} w_{T_{c1}} \right)^2 \right]^{1/2} \tag{4}$$

With these parameters, the uncertainty in TCC is determined to be 7.6 %.

5. CONCLUSIONS

TCC increases with time throughout the contact portion of the cycle. For long contact times, the value of TCC in the steady state attains a peak value and remains near this value.

TCC, should not be considered constant for contacts of short duration; and relatively many cycles are required for the temperature distribution in the specimen and TCC to approach the steady-state condition.

It is obvious that TCC increases with increasing in contact pressure. For long contact times, TCC value in the steady state may be a desirable parameter. However, at short contact times, the actual value of TCC is never equal to the value of TCC at steady state conditions.

TCC, decreases with increasing in the frequency of contacts. When the contact time is short or frequency of contact is high, TCC is small and the temperature distribution in each specimen becomes more different.

Due to the nature of internal combustion engine, the contact time between the exhaust valve and its seat is very short, therefore the sample time should be further smaller than the contact time. The temperature increase during these times is very small. Therefore, if the order of the error magnitude is greater or about equal to that of rising temperature during data recording, the estimation of TCC is impossible. When the thermocouples placed too far away from the interface, accuracy of TCC estimation is reduced.

6. NOMENCLATURE

R Thermal Contact Resistance (K/W)
T Temperature (˚C)
Q Heat Flow Rate (W)
h Thermal Contact Conductance ($W/m^2.K$)
q Heat Flux (W/m^2)

Subscripts

c Contact
1,2 Specimen 1,2

Abbreviations

TCC Thermal Contact Conductance ($W/m^2.K$)

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