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Study of the periodic thermal contact between exhaust valve and its seat in an internal combustion engine

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Highlights

- Heat flux increases with increasing contact frequency.
- Thermal diffusivity greatly affects conductive transfer.
- Manufacturers can use this model to assess the cylinder head's temperature field.
- Automotive industry can use this model to improve the heat transfer of internal combustion engine.

Abstract

The focus of internal combustion engine development for urban vehicles is shifting towards reducing materials by making them lighter. In order to maintain thermal and flow levels, a model was developed to study the thermal behavior of valve seats during periodic contact, which can also help improve engine performance and fuel efficiency. The model, composed of two cylindrical bars in periodic contact, takes into account the evolution and topography of the contact surface. The model's performance was evaluated through various experimental studies and showed a maximum difference of 5.05% with experimental values, in good agreement with previous literature. The results showed that heat flux increases with increasing contact frequency and thermal diffusivity affects conductive transfer. This model can be used by manufacturers to evaluate cylinder head temperature and by the automotive industry to improve heat transfer in engines.

Keywords

seat thermal behavior, contact surface evolution, contact surface topography, thermal diffusivity

1. Introduction

Periodic thermal contact has numerous practical applications, such as heat transfer in sliding solids [8, 51], regenerative heat exchangers [8], solar heating systems [17], and heat production between the workpiece and matrix in repetitive forming and rolling processes and between valve seat and valve in internal combustion engines which generate hot gases. The most popular application is the seat-valve systems of internal combustion engines. Industrialists are faced with the problem of cooling these systems since their thermal behavior depends on temperature fields distributed within the equipment. The heat transfer in valve- seats takes place through the periodic contact of two materials of the same or different nature [18, 19]. During a period, the duration of contact and the duration of non-contact are not equal [2, 7]. These systems' heat transfer is governed by the thermal resistance at the contact interface. The goal of research in urban vehicles is to reduce engine weight and increase efficiency while ensuring durability [1, 21–23, 47, 52]. To achieve this, accurate thermal models are necessary to understand and control heat transfer within the engine system. By reducing engine weight and mass, the overall performance and durability of the vehicle can be improved, making it lighter and more environmentally friendly. The literature on engine performance improvement is extensive and includes research studies, academic publications, and industry reports. Numerous studies have focused on developing models to regulate thermal behavior, both theoretically and experimentally. Some of the main areas of focus include the use of new materials and lightweight design solutions [24, 25, 48] optimization of valve-seat components, and modeling of heat transfer and combustion processes. Many researchers have used advanced numerical simulations [13], such as finite element analysis and computational fluid dynamics [4], to gain a deeper understanding of the complex phenomena involved in internal combustion engines. Other studies have focused on

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experimental methods, including testing of different engine configurations and components, in order to validate and refine the numerical models [5].

Among the earliest were those of Moses et al [28] who were interested in the prediction of the periodic contact conductance. The contact time τc has a direct influence on the temperature distribution at the end of the separation part of the cycle, but the change in temperature distribution during contact is not significant; this was confirmed by Dodd et al. [9]. Shojaefard et al. [15] conducted an experimental study with a real seat-valve configuration for different engine speeds. Goudarzi et al. [38] and Bi et al. [10] experimentally discussed the effect of pressure and contact frequency on the thermal contact conductance between two coaxial cylinders, like the exhaust valve and its seat. They concluded that the conductive heat transfer was inversely proportional to the frequency and proportional to the contact pressure. Using analytical laboratory work, Popov et al. [32] were able to determine the contact heat transfer between two surfaces in periodic contact. Most experimental installations of thermal contact between the seat and the exhaust valve of an internal combustion engine [16, 34–36, 39] consist of two unidimensional bars with their ends maintained at a constant temperature. The bar tower is insulated; radiative heat transfer is neglected, so only one-dimensional heat transfer will be studied. Theoretical studies with assumptions, such as surface regularity, low contact frequency, and quasi-stationary periodic contact, have been conducted [19] to predict the heat flow rate at the contact surfaces. Under the assumption of perfect thermal contact at the interface, Reed et al. [33] and Mikhailov [26] have investigated analytically the problem of quasi-steady-state heat transfer through two surfaces in periodic and regular contact. Vick et al. [45] give complete analytical solutions to the problem of two finite regions in periodic contact with an imperfect thermal contact interface based on the method of integral transformations. The time-dependent thermal contact conductance was later predicted using the inverse heat conduction method [12] after many measurements of the medium's temperature. Orlande [30] solved the inverse thermal contact problem between two surfaces in periodic contact using the conjugate gradient method with an adjoint equation. Cheng-Hung et al. [20] used the conjugate gradient method to solve the inverse problem. Based on the quadripolar method and Fourier series time decomposition, Wang [46] performed a thermal study of periodic contacts between two flat surfaces. Fan et al. [11] introduced a new method for solving the heat transfer problem using a transfer matrix. For different roughness profiles, Zhao et al. [53] studied the contact heat transfer using a statistical study. In order to highlight the impact of the period partition coefficient, Azzouz et al. [2] conducted a theoretical investigation on periodic contact. Shojaefard et al. [37, 40] were much more interested in linear models and employed system identification methods to estimate the valve-seat temperature. Back Propagation Neural Network (BPN) was employed by Goudarzi et al. [14] to estimate the thermal contact conductance between the valve and its seat.

It is important to note that the transfer of heat between two surfaces in periodic contact, such as the valve seat in an internal combustion engine, is highly dependent on the pressure at the contact surfaces. The greater the pressure at these surfaces, the higher the contact conductance will be, leading to a decrease in the contact resistance and a more efficient transfer of heat. However, the traditional models used to predict the thermal behavior of these contact surfaces have limitations and weaknesses. Some models consider the contact resistance to be a constant value during the contact period, assuming that the intermittency of the contact generates a pseudo-resistance and that the resistance does not change significantly during the contact period. However, this model, which is commonly used in literature, may not provide an accurate representation of the actual contact resistance, as it does not take into account the pressure at the contact surfaces, which can have a significant impact on resistance. Other models consider the contact resistance to be a periodic function, or impedance, that takes into account the variation of the resistance over time and its relationship to frequency. While these models may provide a better understanding of the variation of resistance over time, they may still have limitations in accurately predicting the thermal behavior of the contact surfaces. The relationship between pressure and contact resistance is non-linear, and these models may not account for this non-linearity, resulting in an inaccurate representation of the actual contact resistance and limitations in covering a wide range of frequencies.To overcome these limitations, a new model was proposed in a study. This model takes into account the pressure at the contact surfaces and integrates the Yovanovitch model [50], considering the influence of the period's partition coefficient and contact frequency on heat transfer. This results in a more comprehensive model that provides a better understanding of the thermal behavior of the contact surfaces during periodic contact, which is crucial for ensuring the proper functioning of internal combustion engines

2. Mathematical model

The model is presented as two cylindrical rods made of homogeneous and isotropic material of length L with an equal circular cross section, in established periodic contact. The lateral surface of the two solids thermally insulates along its entire length. In valve seat applications, the valve and seat contact each other during a fraction of the engine cycle, and the contact time is shorter than the non-contact time. This is due to the valve's motion, which causes it to open and close periodically, resulting in intermittent contact between the valve and seat. The partition coefficient γ represents the ratio of contact time to the total period τ, and it is typically less than one($\gamma<1$) [2]. The period's partition coefficient is integrated to account for the variable contact and non-contact times during a period, making it easier to model the behavior of the valve-seat contact in the engine.

The ends that are not in contact are maintained at constant temperatures $T(x_1,t)$ and $T(x_2,t)$, but different from each other. It is assumed that enough contacts have been made to achieve a quasi-steady state for the temperature distribution in the solids, meaning that the temperature distribution within each period remains consistent from one period to the next.

The chosen one-dimensional cylindrical model's schematic diagram is illustrated in (figure1).

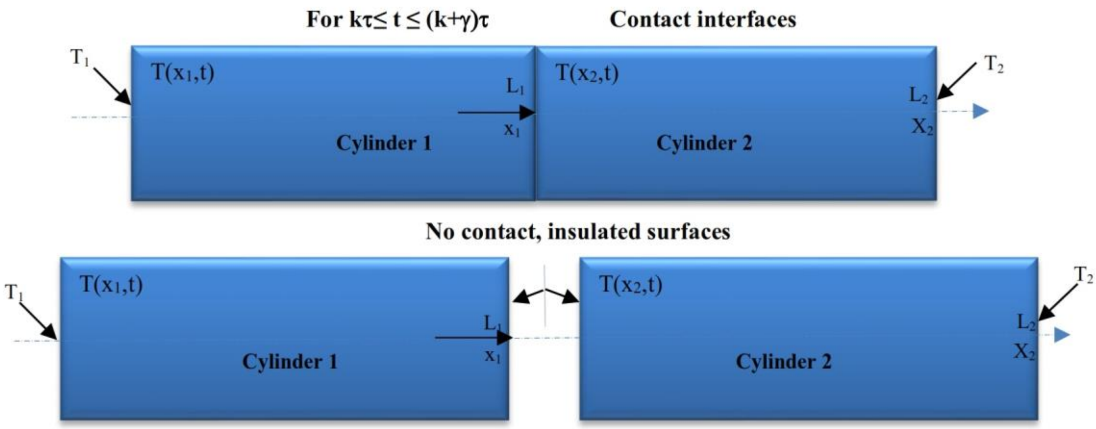

Fig. 1. Schematic representation of cylindrical model.

Where,

T_1 , T_2 : The imposed temperatures, C

L: Specimen length, m

T(x,t) : Generalized temperature distribution, C

X : Spatial variable, m

The equation system is built around the linear heat conduction equation, with appropriate boundary conditions, especially at the interface:

The mathematical formulation of the heat conduction problem is expressed mathematically in the manner shown below:

$$\frac{\partial^2 T_j}{\partial X^2{}_j} = \frac{1}{a_j}\frac{\partial T_j}{\partial t} \qquad 0 < x_1 < L_1; 0 < x_2 \langle L_2 \qquad j = 1,2 \qquad t \rangle 0 \quad (1)$$

With the following boundary conditions

$$\lambda_1 \left(\frac{\partial T_1(0,t)}{\partial x_1}\right)_{x_1=0} = h[T_{2\infty} - T_{1\infty}] \quad (2)$$

$$\lambda_2 \left(\frac{\partial T_1(L_2,t)}{\partial x_2}\right)_{x_2=L_2} = h[T_{1\infty} - T_{2\infty}] \quad (3)$$

Periodicity conditions

$$T_j(x,t) = T_j(x,t+\tau) \quad (4)$$

With $\tau = \tau_c + \tau_{\kappa c}$

Initials conditions

$$T_1(x,0) = T_{1\infty} \quad (5)$$

$$T_2(x,0) = T_{2\infty} \quad (6)$$

Open contact (no flow)

∀t where: κτ+τc≤ τ ≤ (κ+1)τ:

$$\lambda_1 \left(\frac{\partial T_1(L_1,t)}{\partial x_1}\right)_{x_1=L_1} = \lambda_2 \left(\frac{\partial T_2(0,t)}{\partial x_2}\right)_{x_2=L_2} = 0 \quad (7)$$

Close contact

∀t where: kτ≤ t ≤ (k+γ)τ:

$$\lambda_1 \left(\frac{\partial T_1(L_1,t)}{\partial x_1}\right) = \lambda_2 \left(\frac{\partial T_2(0,t)}{\partial x_2}\right) \quad (8)$$

$$R_c \lambda_1 \left(\frac{\partial T_1(L_1,t)}{\partial x_1}\right) = [\Delta T_{interface}] \quad (9)$$

h: Convective coefficient at x = 0, x = 2L, W/m^2C

R_c: Resistance model that takes into account the evolution of contact that will be developed later

When using dimensionless system, the change of variable will look like this:

$$\begin{cases} x^* = x/L_1 \\ h^* = hL_1/k_1 \\ \tau = (a_1 \tau c)/(L_1^2) \\ a^* = a_2/a_1 \end{cases} \quad (10)$$

2.1. Choice of theoretical model

Imperfect thermal contact occurs due to the existence of asperities that do not promote the transfer of the full heat flow between two bars in contact. As the contact pressure increases, the deformation of the asperities during contact increases and additional asperities may also come into contact. This leads to an increase in the actual contact area, which in turn leads to an increase in the heat flux lines and thermal contact conductance. In the past and in recent years, several correlation and prediction models have been developed to gain a better understanding of thermal contact conductance. Some of these models are found in references [6, 27, 41–43, 49, 50, 53].

However, despite these efforts, there are still not many satisfactory models available for the study of the effect of surface topography on the heat flow transmitted during periodic contact. The problem of conductive heat transfer involves three main factors: geometry, mechanics, and thermal aspects. These factors are highly interdependent, making it challenging to accurately model the complex interactions between them.

The need for a better understanding of the effect of surface topography on heat transfer during periodic contact is further highlighted by the widespread use of various materials in industrial and technological applications[24, 25, 48] . The surface topography and roughness of materials can significantly impact the heat transfer characteristics and it is crucial to be able to predict and quantify these effects in order to optimize the design of heat transfer systems.

In this study, a resistance of the form Yovanovitch model [50] is introduced at the interface of two surfaces in periodic contact under two moderate pressures (pressurized/low-pressure non-contact). This model expresses the constriction resistance for plastic deformation, taking into account the contact pressure (where the thermal resistance is pressure-dependent), the microhardness and the evolution of the contact surface. The Yovanovitch model, which has been validated for conformal surfaces, has been extensively studied both theoretically and experimentally for cylindrical thermal contact conductance [6, 27, 42, 43, 49, 50, 53].

In addition to the Yovanovitch model, other models and correlations have been developed to better understand the problem of conductive heat transfer during periodic contact [6, 27, 42, 43, 49, 50, 53]. However, there is still a need for further research in this area to fully understand the interplay between geometry, mechanics, and thermal aspects and to develop more comprehensive models that take into account the complex interactions between these factors. The Yovanovitch model is presented in the following format.

$$R_s = 11{,}25\sigma m\lambda_s(H_c/p)0{,}95 \quad (11)$$

Where,

σ is the quadratic roughness.

m is the slope of the asperity.

λ_s is the equivalent conductivity of the two materials in contact $\lambda_s = (2\lambda_1.\lambda_2)/(\lambda_1 + \lambda_2)$

H_c is the effective hardness.

P is the applied pressure.

The expression for the pressure p in equation (11) is given as follows:

$$p = 0.79. H\left[\frac{(h_c)^{1{,}052}\sigma^{1{,}052}}{\lambda_s^{1{,}052}m_c^{1{,}052}}\right] \quad (12)$$

Where:

R_C: contact resistance

At the interface, the evolution and distribution of the contact resistance during the passage of heat flow from one solid to another will depend on the contact conditions, both topographic and periodic; we will be in a situation at the interface where the contact resistance Rc will be variable, a situation corresponding to the evolution of the contact surface. For this reason, the extreme values of Rc retained for the situations of moderate and non-moderate pressure are respectively, 10^{-3}, 10^{-4} ($m^2.K.W^{-1}$) [3], these resistances corresponding respectively to the situation where the couple of materials will be pressed against each other until a maximum contact pressure P_1 and then the contact load decreases until a contact pressure P_2, when P increases, the deformation of the asperities during the contact increases, this deformation decreases with the decrease of P. In this case, the model that we retain will correspond to a parabolic evolution of the pressure, which will be determined by identification.

$$P = a\,t^2 + bt + c \quad (13)$$

The boundary conditions $\forall\ 0 \le t \le \tau\gamma$

$$\begin{cases} if\ t = 0\ \ R_c = 10^{-3}\ \ P = P_1 \\ if\ t = \tau\gamma R_c = 10^{(-3)} P = P_2 \\ if\ t = \tau\gamma/2 R_c = 10^{(-4)} P = P_2 \end{cases}$$

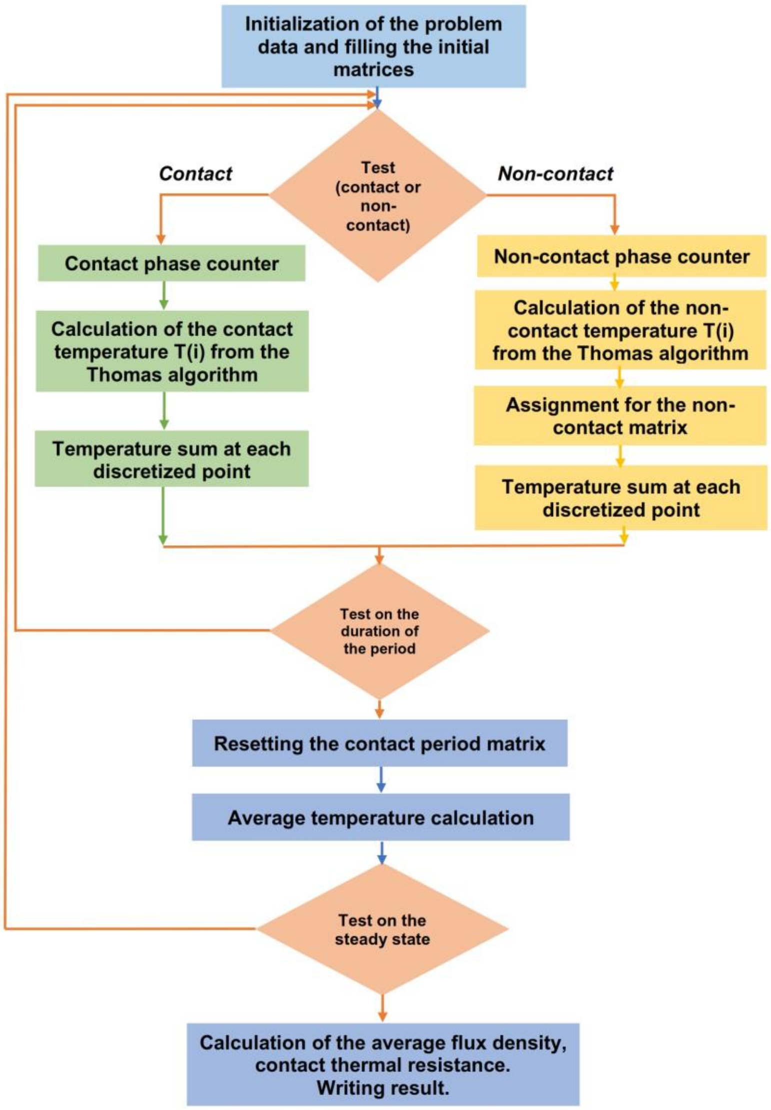

Fig. 2. Algorithm computational procedure to solve periodic problem.

By identification the values of the constants a and b can be found.

The beginning of the solution is ignored, corresponding to the unsteady state, to consider only the case of very long times, illustrating the steady state solution. The analytical solution is difficult to obtain, and it presents a problem of implementation for the understanding of the involved phenomena. A numerical model is used to solve the problem; we used the finite difference method (Crank-Nicolson scheme). This method is suitable for complex problems of this non-linear type and has many advantages, including ease of programming and a low demand on CPU resources.The algorithm computational procedure to solve periodic problem is shown in Figure 2.

3. Results and discussion

3.1. Validation of model

The robustness of the model will be measured by comparing model results with experimental results obtained by other researchers. These references were chosen for comparison because they are among the most well-known and widely cited studies in the field of thermal contact conductance. These studies have been conducted using rigorous experimental methods, and their results have been widely accepted and used as a basis for further research and analysis. Additionally, these studies have provided valuable insights into the key factors that influence thermal contact conductance, such as surface roughness, pressure, and temperature. Furthermore, the studies by Dodd and Moses [9], Moses and Johnson [29], and Vick and Ozisik [45] have been conducted using similar materials and under similar conditions, making it easier to compare the results of the developed model to the experimental results. In addition to these well-known references, the model is also compared to experimental results from Tariq and Asif [44] and Parikh et al [31].

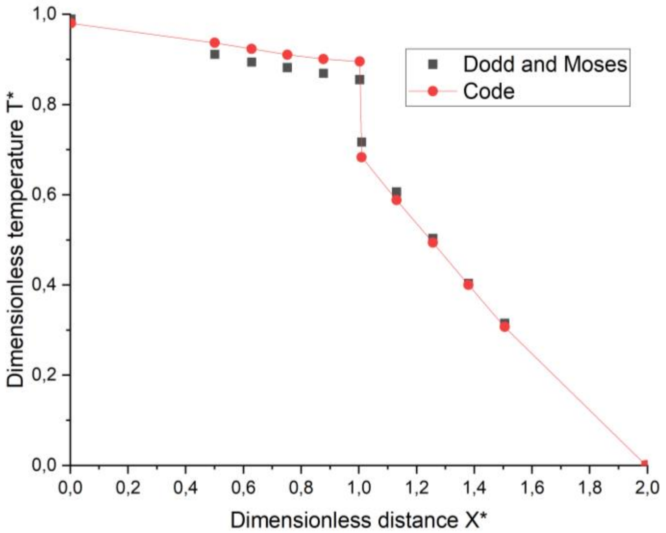

Fig. 3. Dimensionless temperature distribution at the end of the contact cycle in the quasi-steady state by numerical code and published experimental results (Dodd and Moses [9]) for validation.

This allows for a more robust and meaningful comparison, which is essential for validating the model. Overall, these references were chosen because they are considered to be the most authoritative and relevant sources for comparison, and they provide a comprehensive picture of the state of the field and the key factors that influence thermal contact conductance. By comparing the developed model to these well-established studies, the validity of the model can be determined and its accuracy can be confirmed

In Figure 3, the temperature field obtained at the end of the cycle in the two connected rods is compared to the experimental results obtained by Dodd and Moses [9]. The chosen materials in this study are, respectively, aluminum with a thermal conductivity of k = 166.51 W/m.C. in bar 1 and stainless steel with a thermal conductivity of k = 23.10 W/m.C. in bar 2 for a contact period τ=120s in a steady periodic state. It shows a good agreement between the model and experiment; hence, we can consider that the model is validated.

Figure 4 represents the temperature field's comparison at the end of the contact cycle between model results and Moses and Johnson's [29] experimental results. The study is carried out for two copper bars of conductivity k = 385.4 W/m.C. in contact for a period τ= 0.55 and a biot number Bi = 0.98. The two plots are in good agreement.

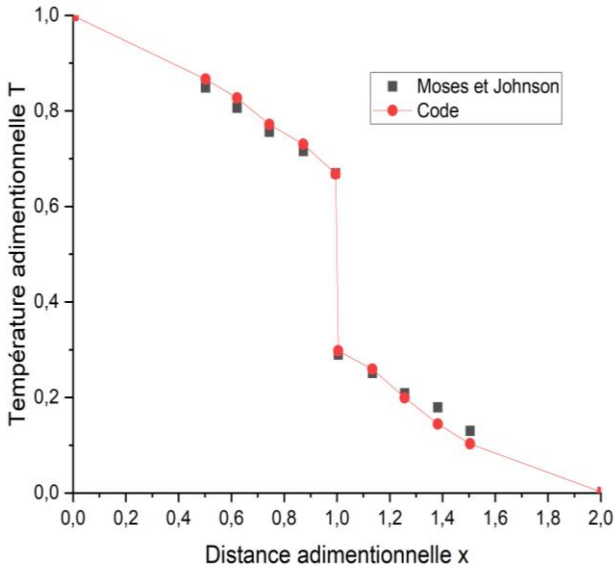

Fig. 4. Dimensionless temperature distribution at the end of the contact cycle by numerical code and published experimental results (Moses and Johnson [29]) for validation.

Figure 5 shows that the results obtained in this study are similar to those of Vick and Ozisik [45] . Specifically, when considering the case of τ = 0.1 and Bi = 3.21, with brass-brass contact (k = 106.1 W/m.C.) at the end of the contact period, the developed code showed an average deviation of 5.05% from the experimental results reported by Moses and Johnson [29]. In addition, the difference between the dimensionless temperature distributions obtained from the developed code and the analytical results from Vick and Ozisik [45] was found to be 3.81%. These findings demonstrate that the developed code is able to accurately model the heat transfer during periodic contact and is in good agreement with previous experimental and analytical results.

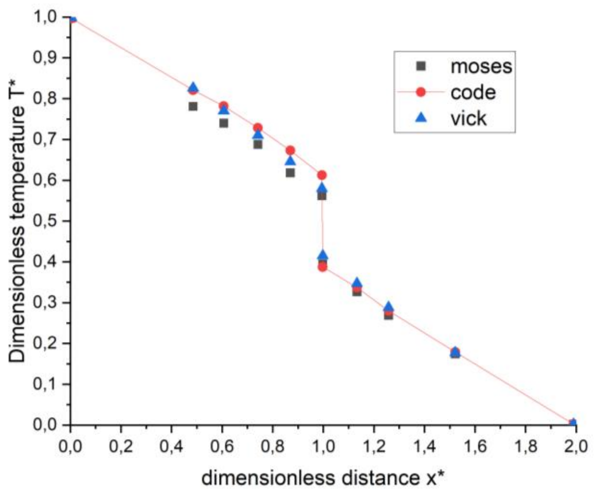

Fig.5. Comparison of analytical and experimental dimensionless temperature distributions for brass; τ= 0.10, Bi = 3.21

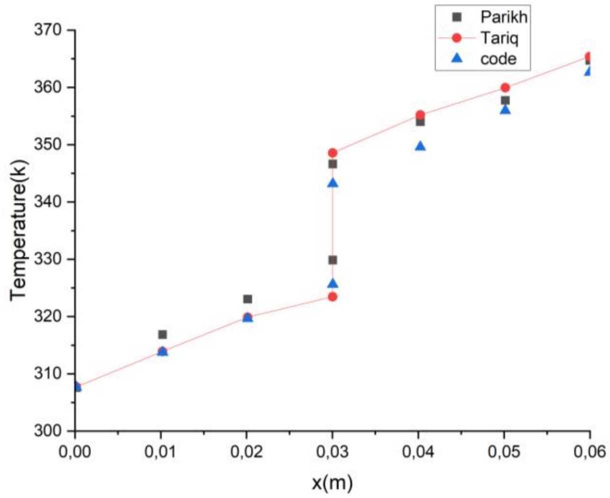

Fig.6. Validation of centreline temperature of rods under steady-state conditions using numerical code and published experimental results.

In Figure 6, the validation results of the developed code are presented, including comparison with published results by Tariq and Asif [44]and Parikh et al [31] for SS 304 (k = 16.05 W/mK) contact material at a nominal pressure of P=5 MPa and surface roughness of Ra=1.83 µm. The comparison of temperature profiles generated by the code and experimental results[44] showed an average percentage error of only 0.81%. Moreover, the code has undergone validation through comparison with published results by Parikh et al.[31] , where it demonstrated an average percentage error of 0.88%.

These results provide further validation for the performance of the developed code, and demonstrate its capability in accurately modeling heat transfer.

The model developed in the study was validated by comparing it with the results of previous experiments conducted by Dodd and Moses [9], Moses and Johnson [29], and Vick and Ozisik [45], as well as Tariq and Asif [44] and Parikh et al[31]. These experiments were used as a benchmark for the accuracy of the model. After a thorough analysis of the comparisons, the model was found to be in good agreement with the experimental results.

The findings of these experiments were used to refine and improve the model, ensuring that it accurately predicts the various situations and phenomena that occur during periodic thermal contacts such as the valve seat in an internal combustion engine.

3.2. Influence of the period's partition coefficient and contact frequency on heat transfer

For the seat valve application in internal combustion engines, the selection of materials is crucial as the thermophysical properties of these materials play a determining role in their performance. In this regard, four metallic materials commonly used in industry, each with distinct differences in their thermophysical properties, have been selected and presented in Table 1. The range of contact frequency values considered in the numerical application ranges from 1 to 20 Hz.

The selection of the appropriate material is based on thermal diffusivity values, which play a critical role in conductive heat transfer when two solids are in contact. The seat valve in internal combustion engines must be able to quickly transfer heat away from the hot combustion gases to prevent damage and ensure proper functioning.

Table.1. Materials thermophysical properties

Material	λ(W/m.K)	ρ(kg/m^3)	Cp (J/kg.K)	a(m²/s)	b(W.s$^{1/2}$.K^{-1}.m^{-2})
Cu	393	8930	384	1,2.10^{-4}	36715
Al	209	2700	885	8,8.10^{-5}	22350
Ac	50	7850	456	1,4.10^{-5}	13380
Ti	16.7	4500	522	7.1.10^{-6}	6265

In this study, the effect of the period's partition coefficient on the heat flux density through a periodic contact interface is examined. The range of values considered for the period's partition coefficient covers the entire domain of]0,1[. In the numerical equation (9), the imposed temperatures are set as T1 = 100 °C and T2 = 0 °C.

The seat valve in internal combustion engines (ICEs) plays a crucial role in controlling the flow of hot combustion gases and maintaining proper engine functioning. The seat valve is subjected to high temperatures and pressure, and as a result, must be able to transfer heat away from the hot gases efficiently to prevent damage. In this regard, the quality of the thermal contact between the seat valve and the surrounding materials is critical, and it is influenced by various factors such as the materials' harmonic thermal diffusivity, the quality of the thermal contact during the contact phase, and the intermittency parameters such as the contact frequency (f) and period's partition coefficient (γ). In the same way the effect of these parameters is also studied

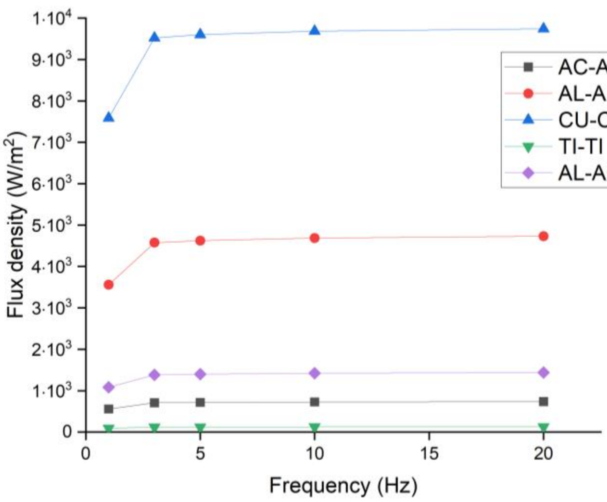

Fig. 7.Average flux density transferred as a function of frequency at γ =0.4 for different couples.

Figure 7 illustrates the impact of contact frequency f on flux density for five distinct material pairs while keeping a single value of the period's partition coefficient of γ =0.4. In advance, it is observed that the average flux density increases when f, the contact frequency, is increased.

On the other hand, the rate of increase of the heat transfer rate declines monotonically with increasing frequency, and eventually approaches zero. This trend is more pronounced for materials with lower thermal diffusivity. In the case of the three least diffusive material pairs, the average heat transfer rate becomes almost constant beyond 10 Hz. Furthermore, it is important to note that the heat transfer rate increases as the harmonic thermal diffusivity of the material pair increases. This growth rate is more pronounced for materials with higher thermal diffusivity.

First,It is clear that the thermal diffusivity of the materials plays a significant role in determining the heat transfer characteristics during periodic contact. The rate of heat transfer between two materials increases with their harmonic thermal diffusivity. This means that materials with higher thermal diffusivity, such as Copper (Cu) and Aluminum (Al), are better suited for applications that require efficient heat transfer during periodic contact.

Second, the frequency of contact also affects the heat transfer process. The average flux density increases with frequency, but the growth rate gradually decreases. This trend is particularly pronounced in materials with low thermal diffusivity, such as Titanium (Ti). It is important to consider the frequency of contact when designing engine components such as valve seats, that are subjected to periodic contact.

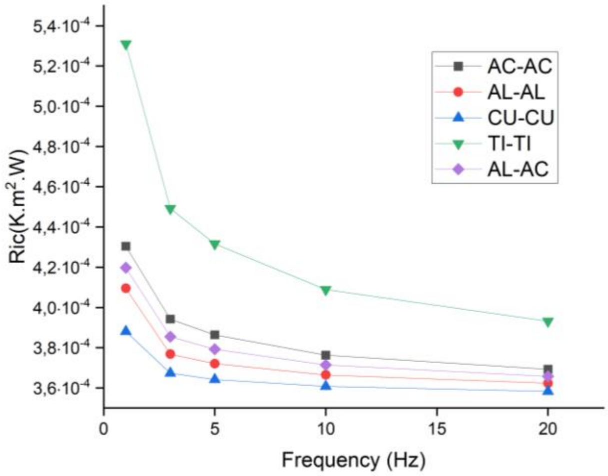

Fig.8. Ric as a function of the frequency at γ =0.4 and the couples nature.

Figure 8 demonstrates the behavior of the contact intermittent resistance (Ric) as a function of frequency and material type. The thermal contact resistance (Ric) increases as the harmonic conductivity decreases. However, the resistance ratio is not proportional to the inverse conductivity ratio. The Ric shows a monotonic decrease with increasing frequency, with a strong decrease observed at low frequencies. The rate of decrease becomes extremely slow around f = 10 Hz.

When the range of interface thermal resistance values is known, the magnitude of the Ric can be substantial. For γ = 0.4 and at f = 1 Hz, the Ric values range from 2.5 x 10^{-5} to more than 2.5 x 10^{-4} m²K/W, depending on the material pair. At f = 20 Hz, these values tend to be of a lower magnitude, but still appreciable. These results indicate the importance of considering both frequency and material type when designing components, such as valve seats in internal combustion engines (ICEs), to ensure optimal performance and longevity.

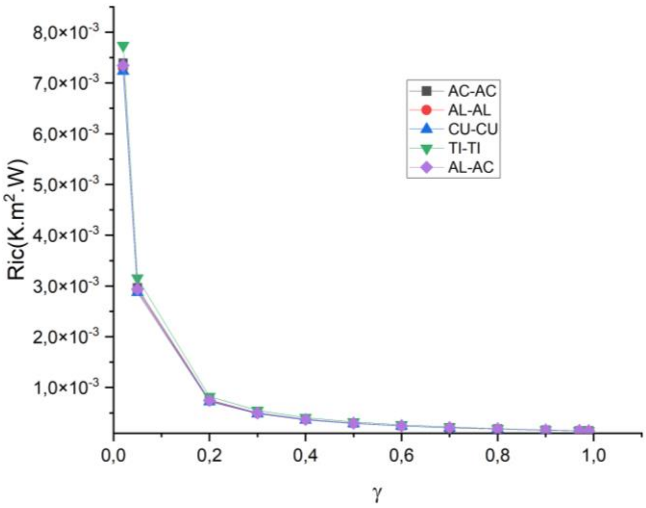

Fig.9. Ric as a function of the period's partition coefficient at f=10Hz.

Figure 9 represents the influence of the period's partition coefficient on the contact intermittence resistance (Ric). It is observed that the Ric is monotonically decreasing along γ. Although the rate of decay is increasingly small following γ, the Ric resolutely tends to zero when γ tends to one. This reflects the fact that the contact tends toward perfect static contact.

The contact intermittent resistance (Ric) also varies with both frequency and material type. The thermal contact resistance (Ric) increases in the direction of decreasing harmonic conductivity. The Ric shows a monotonic decrease along f, with a strong decrease corresponding to low frequencies. The order of magnitude of the Ric can be quite considerable and must be taken into consideration when designing engine components.

4. Conclusions

Through this study, a model for solving the problem of periodic thermal contact is developed. It differs from others in the literature in that it takes into account the evolution of the contact surface as well as the pressures exerted between the two solids in contact. Those in the literature are limited in their range of validity. Thus, the developed thermal model can predict the temperature field and the heat fluxes evacuated in the seat-valve systems for different combinations of situations based on the choice of materials, frequencies, and the used period's partition coefficient □. The □ period coefficient is defined as the ratio of the period's partition where there is contact over the period. The main objective is to understand the behavior of the intermittency contact thermal resistance for a given interface structure as a function of the contact resistance, period, and period's partition coefficient. The application is the cooling of valve heads through the seats that support them.

On this periodic contact model, the influence of the intermittency parameters and valve seat materials on the heat transfer behaviour of an internal combustion engine could be highlighted. The main conclusions can be summarized as follows:

- The results indicate that the rate of heat transfer between two materials increases with their harmonic thermal diffusivity.
- The findings suggest that selecting materials with higher thermal diffusivity can result in improved heat transfer during periodic contact.
- The results emphasize the importance of considering the frequency of contact in valve seats in internal combustion engines to ensure optimal performance and longevity.
- The thermal contact resistance (Ric) increases in the direction of decreasing harmonic conductivity, with a monotonic decrease along frequency. The values of Ric are still appreciable even at high frequencies.
- The period's partition coefficient is a key factor in valve seat applications as it helps to model the behavior of the valve-seat contact in the engine. It is important in predicting the resistance of the contact intermittence (Ric). Additionally, the period's partition coefficient helps to understand how the contact between the valve and seat evolves from intermittent to perfect static contact as the ratio approaches one. Overall, the period's partition coefficient is an essential consideration for designing and optimizing valve seat applications.
- The model provides a straightforward and understandable application for assessing temperature

distribution, heat gradient, and heat flux of the air-cooled cylinder head using various engine speeds and valve seat materials

- The results of the study showed that the heat flux transmitted from the valve to the seat is reduced with increasing frequency, resulting in an increase in valve temperature and a decrease in seat temperature. Additionally, the study showed that thermal diffusivity has a significant influence on conductive transfer.
- The comparison of the developed model with experimental results by Dodd and Moses, Moses and Johnson, and Vick and Ozisik showed that the average difference between the model and experimental results was minimal, with an average difference of 5.05% for Moses and Johnson, 3.81% for Vick and Ozisik , 0.81% for Tariq and Asif and 0.88% for Parikh et al. This confirms the accuracy of the developed model and its ability to predict the thermal behavior of periodic thermal contacts.
- The validated model will have significant applications in several fields, including the design of heat exchangers, the analysis of heat transfer in periodic thermal contacts, and the optimization of thermal processes.

The developed model's ability to accurately predict the temperature distribution during periodic thermal contacts has broad implications for understanding the thermal behavior of various materials and systems. This knowledge can inform the development of new and improved thermal management strategies for a wide range of applications, from electronics to energy storage devices and even

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