THERMAL ANALYSIS OF SLIDING CONTACT IN SYSTEMS WITH ROTARY MOTION

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ABSTRACT
Many devices involve sliding contact where a rotating component slides over a stationary component. Examples include disk brakes, cam/valve lifters, and laboratory pin-on-disk machines. An essential feature of these devices is that a wear track forms on the rotating component that is cyclically exposed to frictional heating, temperature fluctuations, and enhanced chemical film formation. The objective of this paper is to develop a theoretical model and solution methodology to examine the thermal effects produced by friction between sliding contacts in systems with rotary motion.

A new methodology based on a combination of control volume finite difference and the cellular automata concepts is developed. The method involves a cascading sequence of simple, explicit rules of evaluation, rather than complicated partial differential equations.

Results using the general model developed in this study are presented in dimensionless form to show the importance of critical operating parameters. Implications for applications such as disk brake and cam/valve lifters are suggested.

INTRODUCTION
Surface temperatures in tribological processes are important, not only in influencing mechanisms of friction and wear, but as a controlling factor in the failure of lubricant films and the formation of protective antitrust films. For example, it has been shown in automotive engine valve train wear studies by one of the authors that the thermal instability of the additive zinc dialkyl dithiophosphate (ZDDP) plays a key role in its antitrust action. Engine tests using P-32 tagged ZDDP showed heavy (high P-32 content) film formation in the region of the cam nose—the region of highest expected surface temperature. But the question arises whether there is enough time for a film-forming reaction to occur as the cam nose sweeps by. The temperature at the cam nose is high but the time is short. Is it possible that the important reactions occur after contact when, although the temperatures are lower, there is more time for a surface reaction to occur? That is part of the rationale for the present study and the basis of this paper.

Conventional surface temperature analyses often assume one solid body sliding over an infinite plane as a simple but sometimes unrealistic model [1,2]. But many tribological systems involve unidirectional, repeated traverse contact and motion, including a variety of elements with rotary motion (e.g., disk brakes and cam/valve lifters) as well as laboratory test devices (e.g., pin-on-disk machines).

The objective of this paper is to develop and implement a general model to analyze the thermal effects produced by friction between sliding contacts in systems with rotary motion.

In order to attain this goal, a rule-based solution method is developed that combines fundamental ideas from control volume finite differencing with those from cellular automata.

PHYSICAL MODEL
The physical model used in this study is shown schematically in Fig. 1. A disk rotating at angular speed \( \omega \) is exposed to a frictionally generated heat source over a portion of the surface of dimensions \( 2a \)-by-\( 2a \). The surface is cooled by a fluid at temperature \( T_\infty \) with heat transfer coefficient \( h \). As long as the heated area is not too close to the disk center, a computational model consisting of a plate with similar dimensions, shown in the lower portion of Fig. 1, can be used to simulate the thermal processes over the rotating disk. The boundary conditions in the \( x \)-direction must be cyclic, that is, the surfaces at \( x = 0 \) and \( x = L_x \) are actually the same physical location, as if the disk shown in Fig. 1 had been cut along section A-A and spread open.

With respect to a reference frame attached to the heat source, the thermal energy equation corresponding to the physical model is,

\[
\frac{\partial T}{\partial t} + V \frac{\partial T}{\partial x} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{q_{fr}'}{(\rho C_p L_z)} T - T_\infty \]

where \( T = \) temperature, \( t = \) time, \( x,y = \) position, \( V = \) sliding speed, \( \alpha = \) thermal diffusivity, \( \rho = \) density, and \( C_p = \) specific heat. We have assumed that the dimensions in the \( x \)-direction are small enough to neglect temperature gradients, thus the effects of frictional heating and convective cooling are lumped directly into the energy equation. The frictional heat source is specified mathematically as,
The boundary conditions in the $x$-direction are cyclic and the boundaries in the $y$-direction are taken as insulated.

### SOLUTION USING CELLULAR AUTOMATA

The energy equation, with appropriate boundary conditions and initial condition, is solved using a new methodology based on a combination of cellular automata [3] and control volume finite difference concepts, as described in the companion paper by Vick [4]. The unique feature of this solution methodology is that rather than attempting to develop equations for entire complex processes, *computationally explicit*, yet *numerically stable* rules for elementary physical processes are developed individually. These elementary rules are then assembled in a cascading sequence at each time step to form a complete process. The cascading sequence of explicit rules is applied to the state variables to transform them from one state to the next over a typical time interval. In addition to significant modeling flexibility, the cellular automata environment lends itself to extremely efficient computational algorithms and hardware implementation due to its inherent use of local rules and potential for parallel computation.

### NUMERICAL STUDIES

The energy equation and associated boundary conditions contain a total of 8 independent parameter groups and have 4 independent dimensions ($K$, sec, m, J). In order to concentrate on the interactions between sliding speed, convective loss, and geometry, the mathematical formulation is normalized in terms of the following dimensionless variables and parameters,

$$q_f(x, y) = \begin{cases} 
q_f^* , & -a \leq x \leq a, \quad -a \leq y \leq a \\
0 , & \text{elsewhere}
\end{cases}$$

Variables: $\theta = (T - T_0)/T_0$, $x^* = x/a$, $y^* = y/a$, $t^* = ta/a^2$

Parameters: $Pe = Va/\alpha$, $Bi = ha/kl$, $L_x^* = L_x/a$, $L_y^* = L_y/a$

In dimensionless variables, the frictional heat flux is equal to 1 in a square of area 2-by-2 centered at (0,0) on the x-y surface.

Some representative results are shown in Figures 2-4 in the form of contour maps of steady state surface temperature distributions using geometry $L_x^* = 20$ and $L_y^* = 8$. Figure 2 shows that for a relatively high Peclet number, $Pe$ (or high sliding speed) and low Biot number, $Bi$ (or low heat transfer coefficient), the effects of the heat source sweep over the entire surface and the thermal wake is felt all the way back at the source itself. The cyclic nature of the motion is important to consider for accurate thermal predictions in this case. Figure 3 is for a high $Pe$ and moderate $Bi$. Although elevated temperatures are felt over a high percentage of the surface, significant thermal effects have not quite swept back into the contact zone. Finally, for a combination of relatively moderate $Pe$ and $Bi$, the thermal effects are confined to the contact zone and the region immediately downstream of contact. Conditions such as those in Fig. 2 would typically be found in disk brakes and complete analysis including the rotary, cyclic motion is necessary for accurate predictions.

### SUMMARY AND CONCLUSIONS

A theoretical model and solution methodology to examine the thermal effects produced by friction between sliding contacts in systems with rotary motion has been described. A new methodology based on a combination of a control volume finite difference and the cellular automata concepts has been successfully used to solve the model equations.

Results using the general theoretical model developed in this study are presented in dimensionless form. Case studies reveal that the effects of the rotary motion are important for a combination of relative high $Pe$ number and low $Bi$ number. Conversely, the combination of medium to low $Pe$ and medium to high $Bi$ produce a temperature field only in the local area of the contact zone; thus simpler traditional analyses using infinite bodies could be used in these cases.

### REFERENCES


