form a wake. This is further support of the Kelvin-Helmholtz mechanism of vapor film instability.

Liquid-solid contact data reported by Chang[3] showed that for the velocities in our experiments the liquid-vapor interface separating the liquid wake from the vapor wake probably experiences a Taylor-like instability. That is, the liquid above the vapor wake can fall through the interface and touch the heater surface. Thus film boiling heat transfer analyses for upflowing liquids over cylinders should include this type of analysis of the vapor wake.

Acknowledgments

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Heat Transfer Across Aluminum/Stainless-Steel Surfaces in Periodic Contact

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Introduction

DURING the past forty years, the primary emphasis in the study of heat transfer across contacting surfaces has been focused on steady-state contacts. In the area of dissimilar surfaces across the contact, most of the research activity has been devoted to the problem of thermal rectification—the phenomenon of the dependence of the thermal contact conductance h_c on heat flux direction. Studies of dissimilar steady-state contacts involving aluminum/stainless steel have been reported by several investigators, as summarized by Dodd and Moses.[1]

A wide variety of engineering problems are also of interest that involve intermittent loading conditions across contacting surfaces, including aircraft braking systems, thermal control of electronic components, and a variety of manufacturing processes. Although the problem of periodically contacting dissimilar metals is not addressed in the literature, the problem of periodically contacting similar metallic interfaces has received some attention. Since the temperature during any cycle is always a function of time for these problems, a true steady-state condition is never attained. However, as a reference condition, the quasisteady state will be defined as the condition where the temperature distribution for cycle n is the same as that for cycle $(n+1)$ (and succeeding cycles).

The problem of the quasisteady-state heat transfer across two surfaces coming into regular, periodic contact has been examined analytically for perfect thermal contact[2,3] and with the effects of the thermal contact conductance at the contact interface.[4,5] Experimental results for periodic contacts in similar metal surfaces are given by Howard[6] and Moses and Johnson.[7,8]

The objective of this Note is to extend the study of heat transfer across periodically contacting surfaces to include observations on the effects of dissimilar metals across the contact interface. The inclusion of these effects on the behavior of the thermal contact conductance and the temperature distributions across such interfaces should provide insight into these parameters for a wider range of material characteristics than is currently addressed.

Experimental Apparatus

The mathematical model of the experimental problem is the same as that considered by Vick and Ozisik[5] for finding $T(x,t)$ for one-dimensional heat transfer through two specimens with thermal conductivity k, and thermal diffusivity α, each of length L, heated at $x=0$ and cooled at $x=2L$, with the contact interface at $x=L$. The experimental apparatus consists of two test cylinders—each held at one end in a thermal reservoir—the supporting frame, and the equipment required to bring the test specimens uniformly into and out of contact. Details of the apparatus are provided by Moses and Johnson.[7,8] The test specimens are nominally flat and free of coatings or surface oxidation. Surface profilometer measurements show the CLA roughness to be 0.71 μm for the aluminum (alloy 2024) specimen and 2.54 μm for the stainless steel (ANSI 303).

Procedure and Data Acquisition

Since the purpose of the experimental program is to examine the influence of periodic contact on the heat transfer across the contact interface, both apparent interface pressure and mean interface temperature are controlled to reduce the number of parameters influencing the thermal contact conductance. After allowing the test specimens to come to a steady-state condition while separated, the air-pressure regulator is set to provide an applied load at the contact interface of 85 kPa and the experiment is activated. The mean interface temperature for the test specimens is 48.5°C. Heat transfer during the experimental series is directed from the aluminum specimen to the stainless-steel specimen.

Experimental measurements are made in two phases. First, measurements are conducted to determine the length of time for the problem to come to a nondimensionalized quasisteady-state condition. Temperature measurements are made at different intervals for each experiment in this phase. Sampling intervals of 3, 6, 12, and 24 s are used for contact/separation intervals of 15, 30, 60, and 120 s, respectively. Once the number of cycles required to attain the quasisteady state has been determined, the experiments are rerun to collect data over one cycle in the quasisteady state. During this second phase, data records over all contact/separation ranges are made at 3-s intervals.

Of the two quantities of interest, the temperature distribution is available from the experimental output. Computation of the thermal contact conductance is accomplished by the use of a parameter estimation technique for solution of the inverse conduction heat-transfer problem.[9] Using the method of Kline and McClintock, the overall uncertainty for the experiments is computed to be ±20.6%.

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Results

The results presented are for the case of dissimilar materials contacting with equivalent times for length of contact and length of separation t_c in any cycle. The dimensionless variable, $T^* = [T(x,t) - T(2L,t)]/[T(0,t) - T(2L,t)]$, where $T(x,t)$ is the local temperature distribution and t is the time from the initiation of the cycle, is introduced for comparison with the results of Ref. 5. For the experiments themselves, the value of L is fixed and the value of t_c may be chosen, subject to the thermal properties of the material. However, both T^* and h_c are observed results of the experiment. Although either of these parameters may be influenced by manipulation of the reservoir temperature, the contact pressure, or the surface preparation, it is not possible to effectively preselect the values of these quantities. Furthermore, since the experimental evidence for similar materials[7] and these experimental results for dissimilar materials indicate that the thermal contact conductance varies with time, the computation of h_c used for comparison with other results is based on the last value of h_c obtained during contact in the quasisteady state.

As expected, the general results demonstrate that the stainless-steel specimen with its lower values of k and α determine the rate at which the problem is driven to quasisteady state. For all of the contact times considered, T^* in the aluminum specimen is approaching its quasisteady-state value by the tenth cycle, whereas the stainless-steel specimen demonstrates a much stronger dependence on t_c for the attainment of quasisteady state. Quasisteady behavior is observed in fewer cycles as the contact/separation interval is increased. The number of cycles required for T^* to reach the quasisteady value is 33, 25, 21, and 10 for t_c equal to 15, 30, 60, and 120 s, respectively.

Additionally, as shown by Fig. 1, T^* at the end of the contact cycle appears to be driven to the same distribution for all contact intervals. The temperature distribution at the end of contact in the aluminum specimen is the same for all contact/separation intervals. At the same time, the temperature distribution in the stainless-steel specimen is changing from the 15-s to 30-s intervals, but appears to have attained a characteristic value for the 60-s and 120-s intervals.

Figure 2 shows the temperature distributions at the end of the separation period for each contact/separation interval. This figure indicates that t_c appears to have a more significant effect on the temperature distribution at the end of the separation interval than on the distribution at the end of contact. This observation is in agreement with the results of Moses and Johnson[7,8] for similar metallic interfaces.

Figure 3 indicates actual values of h_c plotted against the time from the initiation of the contact interval in the quasisteady state. This figure indicates the dependence of h_c only on the contact/separation interval for a particular cycle. For larger values of t_c, the contact conductance attains a uniform value before the end of the contact interval.

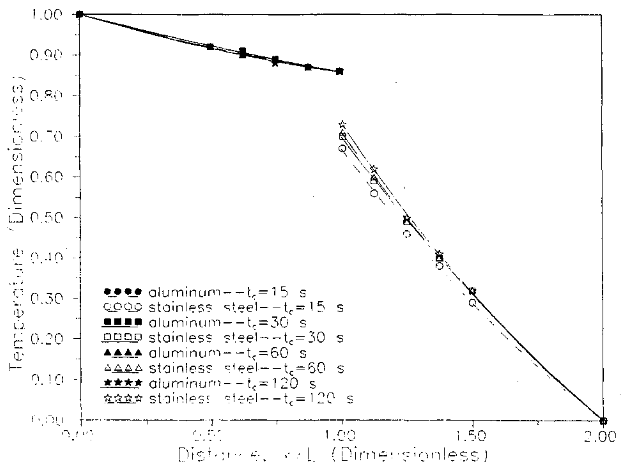

Fig. 1 Quasisteady-state temperature distribution at the end of contact.

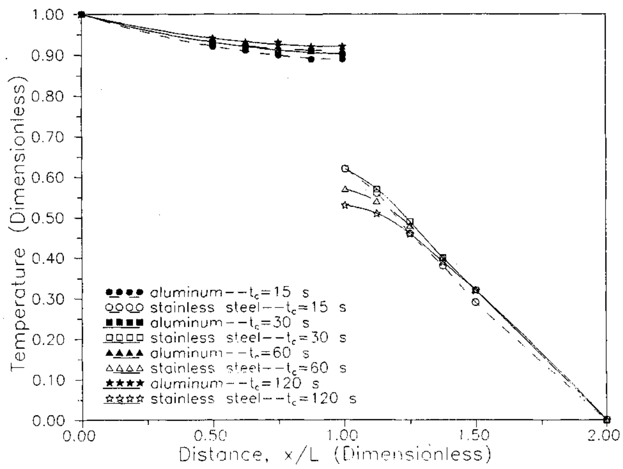

Fig. 2 Quasisteady-state temperature distribution at the end of separation.

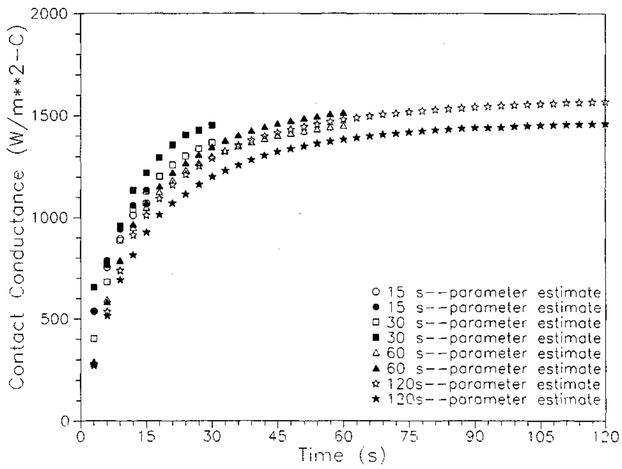

Fig. 3 Thermal contact conductance during the quasisteady state.

Favorable comparisons may be made between these experimental results and previously reported results even though actual test conditions are not the same. Barzelay et al.[10] obtained values for h_c of 1500 W/m^2°C at 170 kPa for steady-state contact between aluminum/stainless-steel specimens in air, as compared to end-of-contact cycle values ranging from 1135.7 W/m^2°C for $t_c = 15$ s to 1569.1 W/m^2°C for $t_c = 120$ s. Similarity in the form of the solution is also observed with that obtained by Vick and Ozisik,[5] while the case presented by Ref. 5 is for materials with both thermal conductivity and thermal diffusivity ratio of 5 and the aluminum/stainless-steel specimens used in the experiments have a thermal conductivity ratio of 7:21 and a thermal diffusivity ratio of 18:7; both solutions demonstrate the same characteristics in the temperature distributions.

Summary and Conclusions

Observations are presented for an experimental evaluation of the heat transfer and temperature distribution across periodically contacting surfaces. The results presented are for the case of low contact pressure, moderate interface temperature, equal contact and separation times, and dissimilar metals across the contact interface. Results may be summarized as follows:

1) Changes in either t_c or h_c influence the relative position and magnitude of the temperature distribution. In particular, it is seen that increasing either of these parameters reduces the temperature drop across the contact interface.

2) The thermal contact conductance increases with time throughout the contact portion of the cycle. For longer contact times, the value of h_c attains a peak value and remains near this value for the remainder of the contact. For the case considered here, this peak value of h_c is comparable to the values of h_c reported for steady-state contacts.

3) The ultimate value of h_c appears to be dependent only on t_c in the cycle if all other experimental parameters are constant. For all cases investigated, the values of h_c follow the same curve until the end of the cycle contact/separation interval is attained. Because of this behavior, the thermal contact conductance is not constant throughout the contact period and h_c should not be considered constant for cycles of short duration.

4) Once a quasisteady-state condition is attained, the temperature distribution at the end of the contact period in the high-thermal-conductivity material appears unaffected by the length of contact or separation. However, the temperature distribution at the end of the separation period is influenced by t_c.

5) In the material with the lower thermal conductivity, t_c influences the temperature distribution at the end of both contact and separation.

6) For the examples considered, T^* approaches within 5% of its quasisteady-state value within a maximum of 40% of the total cycles required to reach the actual steady-state condition.

The basic behavior demonstrated by the aluminum/stainless-steel specimens in periodic contact is essentially the same as that demonstrated in the similar metal contact problem investigated by Moses and Johnson.[7,8] The rapidity of the attainment of the nondimensionalized quasisteady-state temperature distribution, the time dependence of the contact conductance, and the influence of contact time on the temperature distribution during separation are all closely paralleled for periodic contact in similar and dissimilar metallic interfaces.

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Numerical Study of Two-Dimensional Freezing in an Annulus

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Introduction

In thermal energy storage applications, charging/discharging of energy into/from a phase-change medium (PCM) is usually accomplished by passing a fluid through a tube buried inside the PCM. The phase-change material may be limited to a finite annular space surrounding the tube to keep the charge/discharge time within reasonable limits. An analysis of such a situation, particularly when the PCM is initially either undercooled or superheated, is of practical importance. The charge/discharge time depends on various parameters, such as the annular ratio (annular gap/length of tube), Biot number, Stefan number, and thermophysical properties of the PCM. Because of the finite domain in the PCM, the charge/discharge time will also depend on the location of the front with respect to the boundary; i.e., if the freeze/melt front reaches the outer boundary of the annulus, sensible cooling/heating can also occur. These effects have not been given attention in earlier work reported in the literature.[2,3] The present Note discusses the result of a numerical study of two-dimensional freezing in an annulus of an initially superheated PCM. Numerical results are used to deduce a relation between the nondimensional discharge time and the other parameters referred to earlier.

Analysis

Figure 1 shows a schematic of the horizontal annular geometry considered in the present study. Initially the annular gap is full of a PCM in a liquid state and temperature T_e greater than its fusion temperature T_δ. The discharge of energy is started at time $t = 0$ by allowing a coolant to flow inside the tube at an inlet temperature T_i ($< T_e$) with an average velocity U. The thickness of the frozen layer varies along the length of the tube because of the temperature rise of the coolant in the axial direction due to energy transfer to the PCM. Assuming that the convection effects are small in the PCM [annular ratio and $(T_e - T_\delta)$ are assumed to be small], the freezing is axisymmetric.

The equation governing the problem on the PCM side (frozen/melt region) is the standard two-dimensional heat equation written in cylindrical coordinates. The energy balance at the interface between the frozen and melt region and on the coolant side are similar to the equations given in Refs. 1 and 3. The only difference is in specifying adiabatic boundary conditions on P, R, and S, as shown in Fig. 1. Nondimensionalization of these equations is done by using the nondimensional variables of Ref. 2. The boundary immobilization method[2-5] is used to solve this conjugate phase-change/convection problem. The solution of the second-order parabolic equation is carried out by using the standard finite-difference method employing an alternating-direction implicit scheme.

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