of 10 atm and with $\Theta_i = 5\%$ would be expected. The final porosity for this case is in excess of 40%.

This theoretical treatment of this laser material interaction could be tested by measuring the distribution function in a sample of material made from quartz fibers and then measuring macroscopic quantities like porosity after laser irradiation. The foaming of the surface of the material can also be measured and used to deduce the frozen-in pressure in the bubbles.

Acknowledgments

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Experimental Results for the Quasisteady Heat Transfer Through Periodically Contacting Surfaces

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Introduction

QUASISTEADY-STATE heat transfer across two surfaces coming into regular, periodic contact has been examined analytically by Howard and Sutton[1] and Mikhailov[2] under the assumption of perfect thermal contact at the interface. Howard and Sutton[3] and Vick and Ozisik[4] have extended this analysis to include the effects of thermal contact resistance at the contact interface, with Howard[5] undertaking an additional experimental study. Moses and Johnson[6] experimentally examined the behavior of thermal contact resistance during the quasisteady state and the time required to approach the quasi-steady-state condition. This paper experimentally examines the influence of the cycle contact and separation times and the thermal contact conductance on the quasi-steady-state temperature distribution across periodically contacting surfaces.

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Experimental Apparatus

The mathematical model of the experimental problem is the same as that considered by Vick and Ozisik[4] for finding the temperature distribution, $T(x,t)$, 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 (detailed by Moses and Johnson[6,7]) 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. The contact mechanism consists of two main plates. A thermal reservoir is suspended below the upper plate, with an alignment ball and a spring-loaded alignment mechanism to maintain the proper alignment of the test surfaces. The second thermal reservoir is attached to the lower plate, which slides along the four PVC rods forming the supporting frame. This plate is made of Teflon to reduce binding in the sliding contact. The specimens are caused to contact and separate by driving the lower plate with a pneumatic cylinder.

The test specimens are 0.0254 m in diameter and 0.1397 m in total length. On each cylinder 0.0381 m on one end is threaded to fit into the fluid reservoir. Copper-constantan thermocouples are located on the centerline of each specimen at 0.0127-m intervals for the 0.0508 m adjacent to the contact surface. Two additional copper-constantan thermocouples are on the specimen centerline—0.005 and 0.1011 m from the contact surface. The lateral surface of the test specimens is insulated with a Teflon sleeve, cut for thermocouple access and to allow the thermocouples to move freely in a vertical direction as the surfaces move into and out of contact. Separate experiments indicate that the heat flow in the test specimens is one-dimensional.[7] Thermal properties and surface characteristics of the test specimens are listed in Table 1. The test specimens are nominally flat and free of coatings or surface oxidation.

Procedure and Data Acquisition

After the test specimens come to steady state while separated, the timer is activated to start the experiment. To reduce the number of variables influencing the thermal contact conductance, the air-pressure regulator is set to provide an applied load at the contact interface of 85–90 kPa and the mean temperature of the interface at the end of the contact interval is kept at 33°C. Temperature measurements are made at 10-s intervals.

The temperature distribution is available directly from the experimental output. The thermal contact conductance, h_c, is computed from the apparent temperature drop, ΔT, and the heat flux, q'', across the interface, according to the definition $h_c = q''/\Delta T$. The apparent temperature drop across the interface is obtained with a least-squares quadratic regression to curve fit independently the experimental data from each test specimen. The heat flux at the contact interface is computed from Fourier's law using the least-squares curve fit of the temperature distribution. The overall uncertainty for these experiments is 21% for aluminum, 14% for brass, and 11% for copper.[7]

Table 1 Properties and surface roughness of test specimens

Specimen type/designation	k, W/mC	$\alpha \times 10^5$, m^2/s	Length, m	Roughness, CLA, μm
Aluminum 1	167.2	6.7	0.1016	5.207
Aluminum 2	167.2	6.7	0.1016	4.750
Brass 3	106.1	3.4	0.1016	0.439
Brass 4	106.1	3.4	0.1016	0.635
Copper 1	385.4	9.5	0.1016	2.134
Copper 2	385.4	9.5	0.1016	2.413

Results

The results presented are for identical materials contacting with equivalent times, t_c, for length of contact and length of separation in any cycle, and are presented in terms of dimensionless variables $T^* = [T(x,t) - T(2L,t)]/[T(0,t) - T(2L,t)]$, $Bi = h_c L/k$, $\tau = \alpha t_c/L^2$, and $L^* = x/L$. Since the problem is periodic, a true steady-state condition is never attained. Quasisteady state is defined as the condition where $T(x,t)$ for any cycle n is the same as $T(x,t)$ for cyle $n+1$, where t is the time from the initiation of the cycle. Since the experimentally measured h_c is a function of time from the start of a cycle,[6] the computation of Bi is based on the value of h_c at the end of the contact period.

Of the four primary parameters in the experiment, L^* and τ can be chosen, whereas T^* and Bi must be observed. Although either of these parameters can be influenced by manipulation of the reservoir temperature, the contact pressure, or the surface preparation, it is not possible to preselect these quantities effectively. The experimental values of τ and Bi are given in Table 2.

Figures 1-3 are plots of the quasi-steady-state temperature distributions. Since, for similar materials, the problem is symmetric about the interface, Fig. 3 shows results for the hot-side test specimen only. Figure 1 represents the characteristic temperature distribution in the quasisteady state obtained from the experimental observations. The results in Figs. 1 and 2 demonstrate two expected features. First, the basic symmetry expected from the form of the governing differential equation and boundary conditions is demonstated. Second, the decrease in ΔT across the contact interface with increasing h_c (increasing Bi) is shown by the figures. Figure 2 also demonstrates the similarity of the results with those of Vick and Ozisik.[4] Utilizing analytical results based on those of Ref. 4 for the case of $\tau = 0.1$ and $Bi = 3.21$, the maximum difference between the nondimensional experimental and analytical temperature distributions is 5.7% during contact and 8.2% during separation—both on the hot-side test specimen. Figure 3 demonstrates the effects of duration of contact and separation on the temperature distribution by varying the time parameter τ for similar values of Bi. For this limited range, the separation

Table 2 Time parameter, contact conductance, and Biot number for quasisteady-state contacts

Specimen type	Experiment designation	τ	h_c, W/m^{2}C	Bi
Brass	BR009	0.20	2008.7	1.92
Copper	C012	0.55	3699.4	0.98
Copper	C014	0.55	4055.2	1.07
Aluminum	AL017	0.39	1616.5	0.98
Brass	BR019	0.10	3350.3	3.21
Brass	BR020	0.40	3734.1	3.58
Brass	BR022	0.50	3935.1	3.77
Brass	BR025	0.20	3677.8	3.52

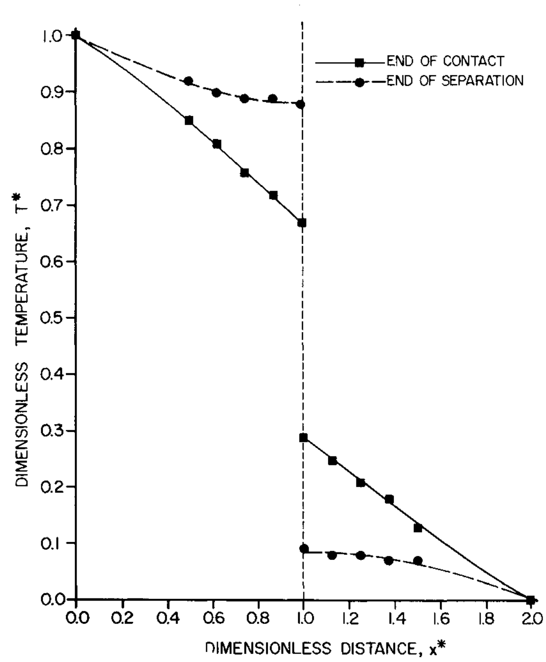

Fig. 1 Temperature distribution for copper; $\tau = 0.55$, $Bi = 0.98$.

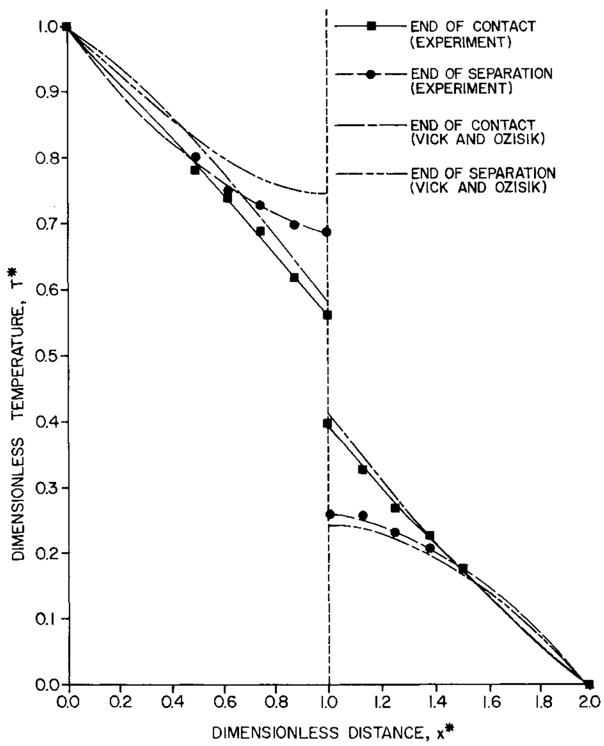

Fig. 2 Comparison of analytical and experimental temperature distributions for brass; $\tau = 0.10$, $Bi = 3.21$.

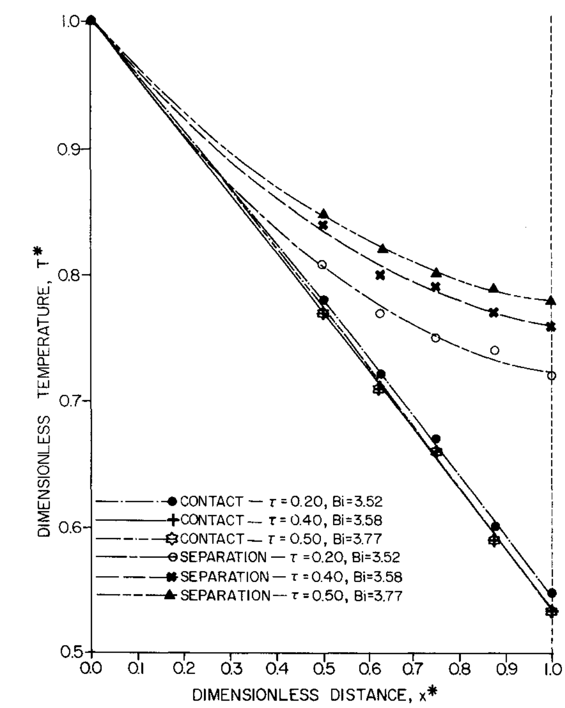

Fig. 3 Effects of the duration of contact on the quasisteady-state temperature distribution at the end of contact and separation.

Table 3 ΔT_{cycle} for quasisteady-state contacts

Specimen type	τ	Bi	ΔT_{cycle}, °C
Brass	0.10	3.21	3.50
Brass	0.20	1.92	3.99
Brass	0.20	3.52	4.78
Aluminum	0.39	0.98	4.93
Brass	0.40	3.58	6.27
Brass	0.50	3.77	5.50
Copper	0.55	0.98	5.89
Copper	0.55	1.07	6.05

temperature is affected more radically than the contact temperature by the contact and separation time. These results are in agreement with the results of Vick and Ozisik.[4]

Also apparent from Fig. 3 and Ref. 4 is the dependence of the interface temperature "envelope":

$$\Delta T_{cycle} = T_{interface,separation} - T_{interface,contact} \tag{1}$$

on τ. Less obvious, but discernible from the experimental data in Table 3, is the apparent dependence of ΔT_{cycle} on Bi. For each case of similar values of τ, larger values of ΔT_{cycle} correspond to the larger values of Bi.

Comparison of the experimental results with those of Howard[5] requires computation of three additional terms (l_c, the bar length equivalent to $\frac{1}{2}h_c$ for steady-state contact; l_i, the bar length equivalent to the resistance due to periodic interruption of the heat flow; and l_T, the bar length equivalent to the combined effects of contact resistance and periodic interruption of the heat flow) and measurement of the temperature distribution in each specimen for a fixed contact, steady-state condition. This additional measurement was made in conjunction with the periodic measurements for a set of brass and a set of copper test specimens. The quantity l_c is determined by extrapolation of a linear curve fit of the temperature distribution at steady state in the single contact measurement. The quantity l_T is determined from the periodic contact experiment by averaging the temperatures measured at each location for the entire cycle—both contact and separation—and extrapolating a linear curve fit of this time-averaged temperature distribution. The quantity l_i is then computed from the definition[1,3,5] $2l_i = l_T - 2l_c$. The results are nondimensionalized into the form of Howard and Sutton[1,3,5] by squaring the length parameter, multiplying by the cycle frequency, f, and dividing by the thermal diffusivity. This manipulation gives values of $f(l_i)^2/\alpha = 0.1592$ and $f(l_c)^2/\alpha = 0.0043$ for brass and $f(l_i)^2/\alpha = 0.3841$ and $f(l_c)^2/\alpha = 0.1192$ for copper in the current experimental results. Using the parameters ft_c and $f(l_i)^2/\alpha$, the results of Howard and Sutton[3,5] are interpolated to give $f(l_c)^2/\alpha$ of 0.0033 for the brass and 0.114 for the copper specimens.

Conclusions

Experimental observations of the heat-transfer and temperature distributions across periodically contacting surfaces are presented for low contact pressure, moderate interface temperature, identical materials across the contact interface, and equal contact and separation times in any cycle. From the results, it is seen that, for fixed values of the thermal contact conductance, changes in t_c (indicated by changes in τ) change the temperature distribution at the end of the separation portion of the cycle. For these cases, changes in τ do not significantly alter the temperature distribution during specimen contact. For fixed cycle contact/separation times, changes in h_c (indicated by changes in Bi) influence both the position and magnitude of the envelope of temperatures attained in the quasi-steady-state condition. Finally, over the range of the experiments, there is good agreement in the form and actual results with Vick and Ozisik,[4] Howard and Sutton,[3] and Howard[5]—indicating the ability of these models to accurately predict interactions for the quasisteady periodic contact phenomena.

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Mixed Convection on a Horizontal Surface with Injection or Suction

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Introduction

THERMAL buoyancy forces can strongly influence forced convection flow and heat transfer at relatively small flow velocities and for large temperature differences between the surface and external flow.[1,2] It is also well known that injection or withdrawal of fluid through the surface, as in mass transfer cooling, can significantly modify the flowfield and affect the rate of heat transfer in forced or free convection.[3] This Note is concerned with the combined effect of buoyancy and surface mass transfer on forced convection flows. Specifically, the problem of mixed convection on a horizontal plate with uniform suction or blowing from the surface is considered. The relative effects of buoyancy and surface mass transfer on the wall friction and heat transfer rates are analyzed using a composite measure of these two nonsimilar effects.

Analysis

Consider steady-state laminar flow over a semi-infinite horizontal flat plate maintained at constant temperature T_W. The external flow consists of a uniform freestream with velocity U_∞ and temperature T_∞. The buoyancy force associated with the temperature difference $\Delta T = T_W - T_\infty$ induces a streamwise favorable pressure gradient that interacts with the boundary layer. The fluid properties are constant except for the density variations contributing to the buoyancy force. The governing boundary-layer equations for the problem can be found elsewhere [see Eqs. (1-7) in Ref. 2]. For mass addition or removal through the surface, the y component of the velocity has the value

$$v = \pm V \qquad \text{at} \quad y = 0 \tag{1}$$

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