Experiments on Contact Melting Under Vibration Within Rectangular Enclosures

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Nomenclature

A = amplitude of vibration
AR = aspect ratio, H/W
a = maximum acceleration of vibration, $(2\pi f)^2 A$
C_p = specific heat
Fo = Fourier number, $\alpha t/HW$
Fr = Froude number, a/g
f = frequency of vibration
Gr = Grashof number, $g\beta(T_w - T_f)H^3/\nu^2$
g = gravitational acceleration
H = height of test cell
k = thermal conductivity
Ste = Stefan number, $C_p(T_w - T_f)/\Delta h_f$
T = temperature
t = time
W = width of test cell
α = thermal diffusivity
β = thermal expansion coefficient
Δh_f = latent heat of phase change material
ΔT = $T_w - T_f$
ν = kinematic viscosity
ρ = density

Subscripts
f = fusion (melting)
l = liquid
s = solid
w = wall

Introduction

CONTACT melting has received considerable attention during the last two decades. Many studies have been published, for example, melting inside a horizontal cylinder[1,2] and melting in a rectangular cavity,[3,4] were among the related investigations. Viskanta[5] gave a comprehensive review of natural convection melting.

Convective heat transfer can be enhanced by vibration. Lemlich[6] reported an improvement in the coefficient of heat transfer from wires vibrated in transverse modes at frequencies between 39 and 122 Hz. Fixed melting processes under the influence of ultrasonic vibration were experimentally investigated by Choi and Hong.[7] The numerical solution of the effect of vibration of contact melting under a low-gravity environment was reported by Shirvanian et al.[8] The authors recently reported ice ($\rho_l/\rho_s > 1$) contact melting within rectangular enclosures under various vibration conditions.[9] It was shown that melting rates were increased for all configurations while the vibration was applied. The enhancement depended on the frequency, the amplitude of vibration, and the direction of vibration.

The motivation of the present study was to conduct experiments by using n-octadecane ($\rho_l/\rho_s < 1$) under mechanical vibration because n-octadecane is most often used as a phase-change material and there is no density inversion characteristic. The experiments were conducted within rectangular enclosures where isothermal conditions were maintained at the walls. The aspect ratios of the test cells were 0.4, 1.0, and 2.5, respectively. Stationary melting experiments were also conducted as a benchmark study.

Experimental Approach

The experimental apparatus consisted of a constant-temperature bath, a pump, test cells, vibration generators, and a data acquisition system. The cross section of the test cell was 55.2 mm × 130.5 mm, 82.5 mm × 82.5 mm, and 130.5 mm × 52.2 mm, respectively. The total volumes of the test cells were the same, with a depth of 152.5 mm. The four walls (top, bottom, and two sides) of the test cells were made of 10-mm-thick aluminum plates. Multipass, countercurrent channels were machined inside of the aluminum walls. The constant-temperature water was circulated through the channels by a pump. Two overflow pipes were also mounted on the test cell.

The test cell filled with 99% pure n-octadecane was firmly mounted on the vibration device. The temperature distributions along the four walls were measured by thermocouples located at different positions to assure the uniformity of the isothermal boundary condition. Each thermocouple is made out of chromel–alumel (type K) wire and embedded from the outside, to within 0.5 mm of the inside surface of each wall. The temperature reading provided by acquisition system is accurate to within ±0.2°C. The temperature measured at the contact surface is consistently lower than the bath temperature. The discrepancy is about 5% of ΔT. The time-averaged wall temperature at the contact surface was used as the wall temperature.

The instantaneous shape of the solid–liquid interface is videotaped. It is impossible to measure the melting rate change in a vibration period caused by experimental accuracy, so the melted volume fractions in the long time step are recorded for comparison. The instantaneous images of the solid–liquid interface are grabbed and digitized for numerical calculation of an area. The accuracy of the liquid volume (or melted fraction) calculation is evaluated by comparing the calculated value with the actual quantity of liquid accumulated at the end of the run. The differences between the liquid volume calculated from videotape and the volume that is measured directly are less than 6%.

The methodology developed by Kline and McClintock[10] is used to estimate the experiment uncertainties. The difference between the liquid volume fraction measured from the videotape image and that measured from the draining test cell at the end of an experiment is less than 6%. In the same nominal wall-temperature cases, the difference in the actual time-averaged wall temperature varies from 0.2–0.5°C. The contribution of wall temperature fluctuation to the overall uncertainty is small. The initial paraffin temperature is controlled within 1.0–2.5°C below the melting point. With consideration of the specific heat and latent heat of paraffin, the uncertainty associated with the initial paraffin temperature is negligible. The uncertainty of the melted volume fraction is estimated to be 8%.

Results and Discussion

In the references in the Introduction section of this Note, the theoretical model of contact melting without the vibration is based on the thin-film lubrication theory. The natural convection and melting on the top for paraffin are neglected to get the analytical expression. The Grashof number, the dimensionless parameter of natural convection, was not included in

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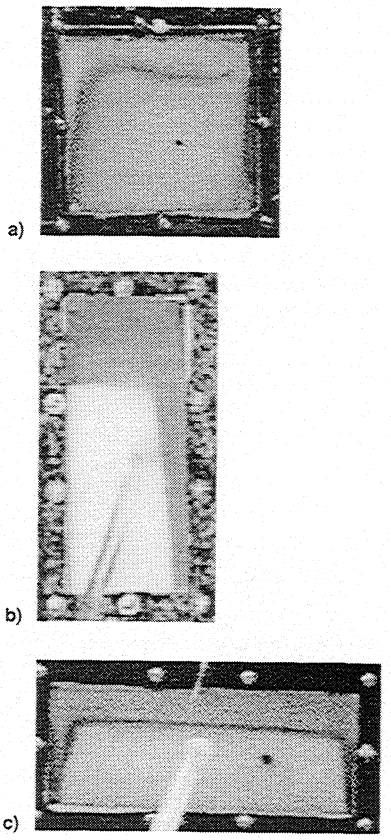

Fig. 1 Typical experimental image: a) AR = 1.0, t = 960 s, ΔT = 9.3°C, f = 1.1 Hz, A = 37.5 mm (vertical); b) AR = 2.5, t = 1080 s, ΔT = 9.1°C, f = 1.1 Hz, A = 37.5 mm (horizontal); and c) AR = 0.4, t = 1440 s, ΔT = 9.2°C (stationary).

the analytic expressions. The contact melting under vibration is more complicated than that without vibration. A preliminary analysis,[9] which is based on the thin-film lubrication, can partially explain the heat transfer enhancement caused by vibration. The interaction of solid and liquid subjected to vibration was beyond the preceding preliminary analysis.

The present experiments are focused on the limited cases to obtain the basic understanding of vibration effects. Some typical experimental images during phase change are shown in Fig. 1. It is observed from the images that the melting at the sides of the solid paraffin is not even. There is more melting at high position of solid bulks than at the low position because of the convection. The solid bulk inclines to the side of test cell in the high aspect ratio AR = 2.5. This inclination is a result of asymmetric melting.

The experimental conditions including aspect ratios, vibration parameters, and average wall temperatures on the contact surface are presented in Table 1.

Effects of vibration on n-octadecane melting with AR = 1.0 and ΔT = 8.9–9.4°C are shown in Fig. 2. Dimensionless time *Fo*Ste* instead of *Fo* alone is used for the abscissa. The vertical axis is the melted volume fraction that is defined as the volume ratio of liquid paraffin to the test cell. Three sets of vibration experiment data are included in Fig. 2. These results are plotted against the experimental data without vibration. Figure 2 shows that the melting rate is related to the Froude number. For the case of vertical vibration f = 60 Hz (±1.5 Hz), A = 0.23 mm (±0.01 mm), Fr = 3.3, Ar = 2.0E+7, an enhancement of the overall melting rate (as much as 95%) is recorded while compared with the stationary melting. Two sets of ice contact melting[9] (same test cell) are also included in Fig. 2. The wall temperatures for ice contact melting varies from 9.5–9.6°C. The data curve is close to that of n-octadecane in the stationary case. The vibration of f = 60 Hz and A = 0.23 mm enhances about 115% compared with 95%. It is observed that the solid bulk slightly oscillates in the test cell. This relative motion (or sedimentation) between solid paraffin bulk and liquid paraffin is induced by vibration because of their density differences. The solid bulk motion stirs the melted paraffin in the test cell and thus enhances convective heat transfer rate.

Table 1 Summary of experimental conditions

No.	AR	ΔT, °C	f, Hz	A, mm	Direction
1	1.0	9.4	0	0	——
2	1.0	9.0	1.1	37.5	Vertical
3	1.0	9.1	1.1	37.5	Horizontal
4	1.0	8.9	60	0.23	Vertical
5	2.5	9.3	0	0	——
6	2.5	9.1	1.1	37.5	Horizontal
7	0.4	9.0	0	0	——
8	0.4	9.2	1.1	37.5	Horizontal

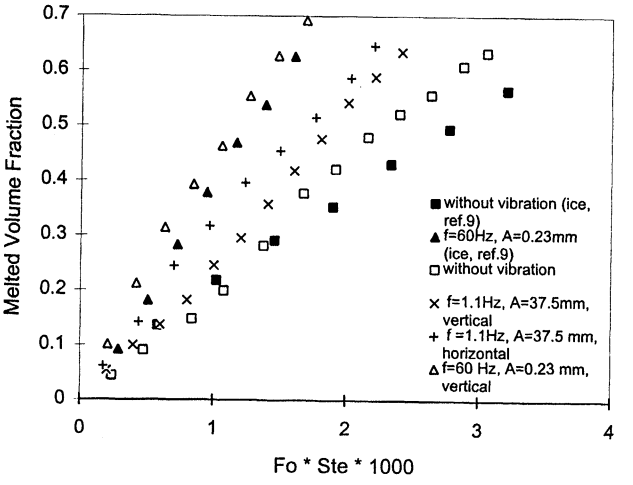

Fig. 2 Melted volume fraction for AR = 1.0.

The experiment with horizontal vibration at f = 1.1 Hz (±0.03 Hz), A = 37.5 mm (±0.1 mm), and Fr = 0.18, has about a 30% increase of melting rate as well. The relative slide motion of solid paraffin along the surface of test cell is observed. For experiment with vertical vibration f = 1.1 Hz and A = 37.5 mm, the melting rate increases moderately, ~18%. In contact melting with vertical vibration, acceleration force induced by vibration and buoyancy force is in the same direction. Therefore, the enhancement of convection heat transfer by horizontal vibration is larger than that by vertical vibration at the same frequency and amplitude.

The averaged solid–liquid interface displacements vs dimensionless time (*Fo*Ste*) at the sides and at the bottom are shown in Fig. 3. A horizontal vibration (f = 1.1 Hz, A = 37.5 mm) with AR = 1.0 is applied. The displacement at the bottom is measured from the position change of the marker embedded in solid bulk. There are two kinds of melting processes, i.e., contact melting (which occurs at the bottom contact surface), and convective melting (includes natural convection and sedimentation-induced convection). Contact melting is the main mechanism in the present experiment (with and without vibration), as evidenced by the displacements of interface shown in Fig. 3. The effect of vibration on melting is twofold. It promotes the convective melting along the sides (vertical and top) of solid bulk. Vibration also increases contact melting on the bottom. However, the melting enhancement at the bottom is less significant than that along the sides, as shown in Fig. 3.

The effect of aspect ratio on paraffin melting is depicted in Fig. 4. Three different aspect ratios, i.e., 0.4, 1.0, and 2.5 with approximately the same wall temperature difference are evaluated. It is shown that the melting rate for AR = 0.4 and 2.5

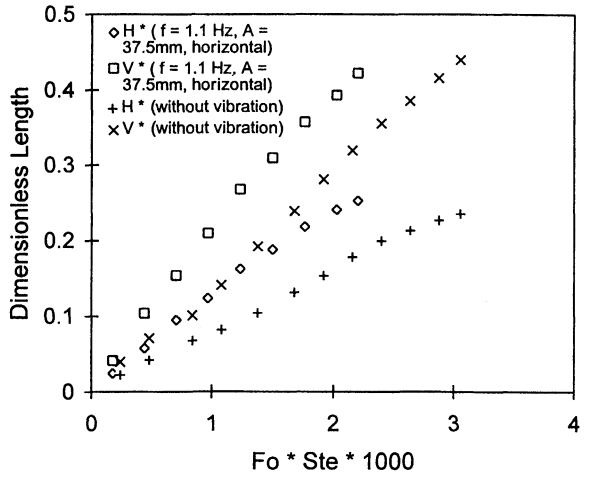

Fig. 3 Comparison of melting at bottom and two sides.

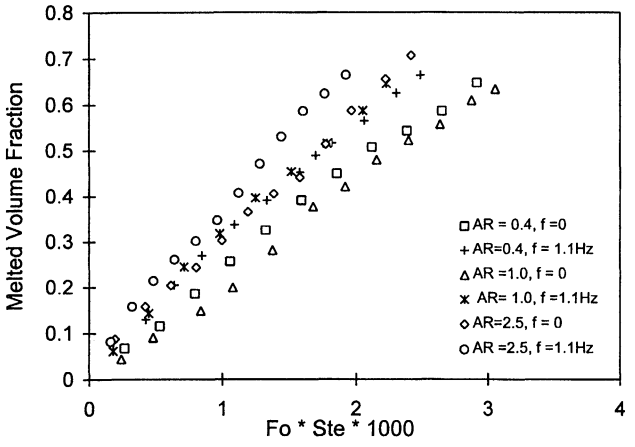

Fig. 4 Effect of horizontal vibration on melting at AR = 0.4, 1.0, and 2.5.

are higher than that of AR = 1.0 for stationary experiments. The higher melting rates for both cases are attributed to the larger contact surface areas. Although the bottom contact surface area for aspect ratio 2.5 is smaller, the total contact melting surface area is actually increased by the solid bulk inclination to the side wall(s), as shown in Fig. 1b. It is noteworthy that test cell AR = 1.0 has the smallest total heating area.

Horizontal vibration (f = 1.1 Hz, A = 37.5 mm) increases melting rates significantly for all aspect ratios. The relative enhancement in melting for AR = 1.0 is about 30%, whereas those for aspect ratios 0.4 and 2.5 are about 18 and 21%, respectively. It is difficult to explain theoretically the differences among three aspect ratios when horizontal vibration is applied because of the complexity of the melting process.

Conclusions

Experimental studies of n-octadecane contact melting within rectangular enclosures under vertical and horizontal vibrations are conducted in isothermal wall conditions. It has been demonstrated that vibration increases the melting rates in all experiments. The convection heat transfer enhancement at two sides is more significant than the contact melting at the bottom when the vibration is applied. Melting enhancement is mainly dependent on the maximum acceleration of vibration (or Froude number). Aspect ratio is an important parameter in contact melting with and without vibration. Melting enhancement with horizontal vibration is greater than that with vertical vibration.

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