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In-tube melting in the presence of circumferentially nonuniform heating

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Abstract—Experiments were performed to investigate the melting of a phase-change medium contained in a circular tube when the heating at the tube wall is nonuniform around the circumference. Melting experiments for uniform heating conditions were also carried out to provide baseline information. For a vertically oriented tube with heating confined to half the circumference, the amount of melting, relative to that for uniform heating, was reduced by 45% in the early stages of melting and by 35% in the later stages. When the containment tube was inclined to the vertical, the decreased melting associated with the nonuniform heating was recouped at inclinations large enough to cause the solid to be pressed by gravity against the heated portion of the tube wall. This direct contact mode of melting was achieved consistently at an inclination of 30° and intermittently at an inclination of 15°. The use of a low-friction base surface for supporting the melting solid was shown to favor the direct contact mode. Timewise measurements of the shape of the melting solid enabled identification of the pattern of melting for the different types of heating and the various inclinations. Results are also presented for the timewise variation of the stored energy.

INTRODUCTION

THE EXPERIMENTAL work to be described here is concerned with melting in vertical and inclined tubes which are nonuniformly heated around the tube circumference. Such a heating pattern may occur, for example, in a thermal energy storage system in which cylindrical containers filled with a phase-change medium are exposed to direct solar radiation. In such an arrangement, the rear portion of each container is in shadow and is, therefore, virtually adiabatic, while the front portion is strongly heated. It is reasonable to expect that nonuniform heating patterns of the aforementioned type will decrease the rate of melting of an encapsulated phase change material, but the extent of the decrease has not heretofore been quantified.

The present investigation has two complementary foci. The first is to quantify the reduction in melting due to nonuniform heating, and the second is to investigate means of recouping these reductions.

In the first part of the work, melting of a phase-change medium encapsulated in a vertical tube was investigated, this configuration being a likely candidate for applications such as the aforementioned direct storage of solar energy. Two types of melting experiments were conducted for the vertical tube. In one, baseline information was obtained for the case in which the heating was circumferentially uniform. In the other, the tube was subjected to nonuniform heating such that half the circumference was adiabatic while the other half was exposed to uniform temperature higher than the phase-change temperature.

The use of the direct-contact mode of melting to recoup the degradation caused by the nonuniform heating was investigated in the second part of the work. In this mode, the melting solid is pressed against the heating surface by the force of gravity. Although there is, necessarily, a film of liquid between the heating surface and the solid, the film is very thin, and relatively high heat fluxes are carried across it by conduction, thereby enhancing melting [1]. The direct contact mode was activated here by inclining the containment tube away from the vertical so that the melting solid was brought into contact with the heated half of the tube circumference. Inclinations of $7\frac{1}{2}°$, 15° and 30° relative to the vertical were employed. In connection with the sliding of the melting solid into the wall, some consideration was given to the friction characteristics of the base of the tube on which the solid rested.

For each operating condition, measurements were made of the variation of the melted mass with time. At selected times during the melting period, the bulk temperature of the liquid melt and the shape of the unmelted solid were determined. Measurements were also made of the circumferential and axial variations of the tube wall temperature. The experiments were performed using 99% pure *n*-eicosane paraffin, with a melting temperature of 36.4°C.

EXPERIMENTS

Apparatus

The containment tube used to encapsulate the phase-change medium was chosen to be nonmetallic in

NOMENCLATURE

c	specific heat of liquid melt	M_{max}	total mass available for melting
E_{max}	energy stored during complete melting with melt at T_∞	R	inner radius of containment tube
E_s	energy stored as sensible heat during $t = 0$ to t	Ste	Stefan number, $c(T_\infty - T^*)/\lambda$
E_{tot}	sum of E_s and E_λ	T_L	bulk temperature of liquid
E_λ	energy stored as latent heat during $t = 0$ to t	T_∞	temperature of melting environment bath
$E_{\lambda,max}$	energy stored as latent heat during complete melting	T^*	melting temperature
Fo	Fourier number, $\alpha t/R^2$	t	melting period.
k	thermal conductivity of liquid melt		
M_L	melted mass		

Greek symbols

α	thermal diffusivity of liquid melt
λ	latent heat of melting
ρ	density of liquid melt.

order to reflect the probable realities of phase change thermal storage systems. The tube was of NEMA grade G-10 phenolic, chosen for its high strength, excellent surface finish, low water absorption and roundness. In the initial set of melting experiments, where the heating was circumferentially uniform, the tube was provided with end caps but was otherwise unmodified. Subsequently, to facilitate the non-uniform heating experiments, the tube was fitted with a thermal environment chamber which suppressed heat transfer over half its circumference.

A schematic diagram of the containment tube with the isolation chamber in place is displayed in Fig. 1. The tube had an overall length of 39.4 cm, an internal diameter of 5.10 cm and a wall thickness of 0.16 cm. It was closed at each end by an insulating cap. The thermal isolation chamber was an open-topped, plexiglass-walled rectangular enclosure, 9.5 × 20.5 cm in cross section and 31.5 cm deep (all internal dimensions). The chamber was filled with silica aerogel powder insulation whose thermal conductivity is 15% less than that of air. To prevent its levitation, the powder was sheathed in plastic. Conduction contact between the chamber walls and the tube was minimized by chamfering the walls adjacent to the zone of contact.

The portion of the tube occupied by the solid phase prior to the onset of melting is indicated in the figure (length–diameter ratio of the solid = 4.3). The phase-change material rested on the top of the lower end cap, which consisted of a 3.81-cm-long, plastic-covered cylinder of Styrofoam insulation backed from below by a 4.45 cm length of Delrin rod. An O-ring embedded in the Delrin sealed against outleakage of the phase change material and inleakage of water when the apparatus was situated in a water bath. The diameter of the exposed portion of the lower cap was somewhat enlarged to serve as a handle and, as seen in the figure, the adjacent portion of the containment tube was fitted with a plexiglass collar to provide stiffness and strength.

The upper end cap, also of plastic-covered Styrofoam, protruded downward into the containment tube by about 3.6 cm. A plexiglass collar was affixed to the tube just below the exposed portion of the cap in order to support a pair of trunnions from which the tube was suspended when it was in place in a water bath (the collar and trunnions were omitted from Fig. 1 to simplify the drawing).

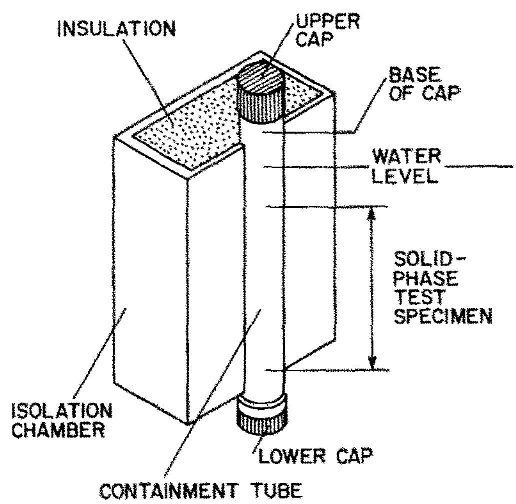

FIG. 1. Schematic diagram of the containment tube with the thermal isolation chamber in place.

The 7.6 cm clearance between the upper surface of the solid phase and the base of the upper end cap served to accommodate the expansion which accompanies both solid-to-liquid phase change and the heating of the liquid melt. By design, the clearance readily accommodated the melt even when the tube was inclined at 30° to the vertical. The remaining air space provided additional insulating capacity.

The temperature of the wall of the containment tube was measured by 20 thermocouples cemented into grooves in the outside surface of the tube wall. Eleven of the thermocouples were located on the exposed side of the tube while the remaining nine were on the thermally isolated side. The thermocouples were made from 30-gage, Teflon-coated chromel–constantan wire that had been calibrated specifically for these experiments.

Two temperature-controlled water baths were used during the course of the experiments. One of the baths served to bring the containment tube and its charge of solid paraffin to a preselected uniform temperature prior to the initiation of a melting run. Temperature control was achieved to better than 0.1°C. The bath was equipped with fixturing to hold the tube erect and at the desired depth in the face of the naturally occurring buoyancy forces.

The other bath served as the thermal environment in which the containment tube was situated during the melting run. The water in the bath was highly agitated to ensure high values of the heat transfer coefficient at the outside surface of the tube. An adjustable support fixture was provided which enabled the tube to be oriented either vertically or at various angles of inclination with respect to the vertical. The water level at which the tube was positioned is illustrated in Fig. 1. Again, temperature control was better than 0.1°C.

In addition to the aforementioned main pieces of apparatus, supplementary equipment was used in connection with the experimental procedure, which will now be described.

Experimental procedure

Each melting experiment consisted of five steps: (1) preparation of the solid-phase test specimen; (2) thermal equilibration of the solid and the containment tube; (3) the melting period; (4) post-melting data collection; and (5) cleaning of apparatus components to remove all residual paraffin. The procedure used to execute certain of these steps differed somewhat depending on the heating mode (i.e. uniform or nonuniform).

As noted earlier, the uniform heating experiments were performed prior to the attachment of the thermal isolation chamber to the containment tube. In that case, the solid test specimen was prepared by utilizing the containment tube itself. However, with the chamber attached to the containment tube for the nonuniform heating runs, it was found more convenient to prepare the specimen in another tube (a phenolic tube identical to the containment tube) and then to introduce it into the containment tube.

To begin the preparation of the test specimen utilizing the containment tube, a new film of plastic wrap (Saran Wrap) was applied to the Styrofoam portion of the lower end cap, and the cap was put in place in the tube. With the upper end cap removed to provide access, a very small weight attached to a fine nylon thread was lowered into the tube and positioned at the center of the bottom. The thread, which was constrained to coincide with the axis of the tube, was used to extract the unmelted solid at the end of the melting period.

The tube was then weighed, after which the paraffin was introduced in liquid form and the tube placed in an ice bath. Void formation during the freezing of the paraffin was prevented by irradiating its upper surface with a heat lamp set at low intensity. The upper surface of the solidified specimen was made flat by contact with a heated disk whose controlled depth of penetration into the containment tube fixed the axial length of the specimen. The tube and its contents were then weighed.

The preparation of the test specimen utilizing the auxiliary phenolic tube was basically similar to that just described, but with differences in detail. First, the small weight and the nylon thread were positioned off-center in recognition of the fact that the melting would be unsymmetric in the presence of nonuniform heating. In addition, the freezing of the liquid paraffin in the auxiliary tube was performed at a higher temperature (i.e. in a 25°C water bath) than before. After the freezing, the tube and the solid paraffin were cooled to the ice point in order to contract the paraffin and facilitate its removal from the tube. While still highly chilled, the solid specimen was introduced into the containment tube, and as its temperature rose, it expanded to form an intimate contact with the tube wall.

After the preparation of the solid-phase test specimen, the containment tube was capped and introduced into the equilibration bath. When the tube was without the thermal isolation chamber, a period of 12 h was needed for the tube and its contents to attain a uniform temperature equal to that of the equilibration bath. However, with the isolation chamber attached to the tube, an equilibration period of 16 h was needed. During the equilibration period, the bath temperature was maintained just below the 36.4°C melting temperature of *n*-eicosane.

At the end of the equilibration period, the containment tube was transferred to the melting bath, an operation which was completed in either 10 or 15 s, depending on the absence or the presence of the isolation chamber. The fixture for establishing the inclination of the tube had been set prior to the transfer, and the bath temperature had already been maintained at the desired value for several hours. During the melting period, the tube wall and water bath temperatures were read at regular intervals.

At the conclusion of the melting period, the tube was uncapped and the remaining unmelted solid extracted with the aid of the nylon thread. Immediately upon removal of the solid, the bulk temperature of the liquid melt was measured. This was accomplished by stirring the liquid with a plexiglass rod to which a thermocouple was attached. Subsequently, the liquid was poured out of the tube into a storage reservoir.

The extracted solid was weighed and its shape determined. For the uniform heating case, the solid was axisymmetric, and its shape was specified by measuring the diameter as a function of axial position and the overall length. For nonuniform heating, the solid was unsymmetric. It was cut into a succession of cross-sectional slices in a miter box, and the perimeters of each slice were traced on paper.

RESULTS AND DISCUSSION

The mass of paraffin melted between the beginning of the melting period and any time t will be denoted by M_L (L ~ liquid), while the total mass available for melting is M_{max}. In dimensionless terms, the melting results will be presented as the ratio M_L/M_{max}. The duration time t of the melting period will also be expressed in dimensionless terms by employing the product of the Fourier and Stefan numbers, a group suggested by heat conduction theory, where

$$Fo = \alpha t/R^2, \quad Ste = c(T_\infty - T^*)/\lambda. \tag{1}$$

In equation (1), T_∞ is the temperature of the water bath in which the containment tube was situated during the melting period, and T^* is the melting temperature. The thermophysical properties k, ρ and c are those of the liquid phase. For n-eicosane paraffin, they were taken from ref. [2] and evaluated at the temperature T^*. This temperature was chosen for the evaluation of the properties because it occurs at the solid–liquid interface, which is believed to be the location of largest thermal resistance since its surface area is always smaller than that of the wall of the containment tube. The latent heat λ was also taken from ref. [2].

The experiments were performed for values of $(T_\infty - T^*) = 5$ and 25°C, for which the corresponding Stefan numbers are

$$Ste = 0.0445 \text{ and } 0.222. \tag{2}$$

The energy E_λ stored as the mass M_L is transformed from the solid phase to the liquid phase is

$$E_\lambda = \lambda M_L. \tag{3}$$

If all the mass M_{max} were to be melted, then

$$E_{\lambda,max} = \lambda M_{max} \tag{4}$$

and

$$E_\lambda/E_{\lambda,max} = M_L/M_{max}. \tag{5}$$

Energy is also stored in the liquid melt as its temperature increases during the melting period. The initial temperature of the liquid melt is T^*, while its temperature at the end of the melting period is T_L, where T_L is the bulk temperature measured subsequent to mixing. Then, the stored sensible energy E_s follows as

$$E_s = M_L \int_{T^*}^{T_L} c \, dT. \tag{6}$$

The total stored energy E_{tot} is given by

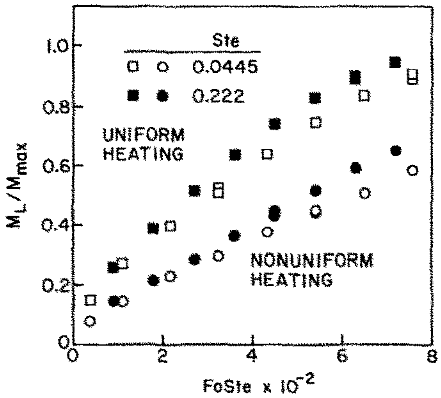

FIG. 2. Comparison of the melted mass for uniform and nonuniform heating of the vertical containment tube.

$$E_{tot} = E_\lambda + E_s = M_L\left(\lambda + \int_{T^*}^{T_L} c \, dT\right). \tag{7}$$

The maximum value of E_{tot}, to be denoted by E_{max}, is attained when all the solid has melted and when the liquid melt has been heated to T_∞

$$E_{max} = M_{max}\left(\lambda + \int_{T^*}^{T_\infty} c \, dT\right). \tag{8}$$

Results for the stored energy will be presented as the ratios E_λ/E_{max} and E_{tot}/E_{max}.

Vertical tube results

The timewise variation of the melted mass for the vertical orientation of the containment tube is presented in Fig. 2, where M_L/M_{max} is plotted as a function of $FoSte$. The data for the uniform and nonuniform heating cases are respectively represented by square and circle symbols, while the respective Stefan numbers are delineated by open symbols ($Ste = 0.0445$) and closed symbols ($Ste = 0.222$).

The data naturally separate themselves into two bands according to the mode of heating, with nonuniform heating giving rise to substantially less melting. At small times, the mass melted in the presence of the nonuniform heating is about 55% of that melted when the heating is uniform. At larger times, the corresponding ratio is about 65%. Furthermore, these percentages are virtually independent of the Stefan number. In view of these findings, it is inappropriate to design a circumferentially nonuniformly heated phase-change thermal storage system using information for uniform heating. An approach to reversing the degradation of performance associated with the nonuniform heating will be considered shortly.

For each mode of heating, the data separate moderately with the Stefan number, with those for the higher Stefan number lying higher. This ordering is just opposite to that which would exist if conduction across the liquid melt were the sole mode of heat transfer. The reversal is due to the presence of natural convection. The higher Stefan number corresponds to

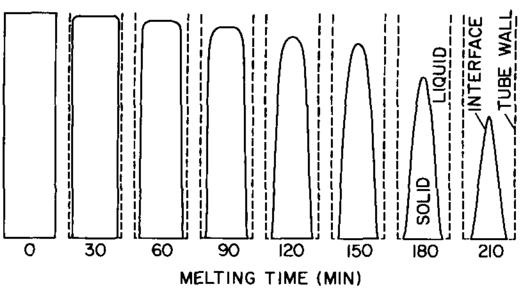

FIG. 3. Pattern of melting in the uniformly heated, vertical containment tube.

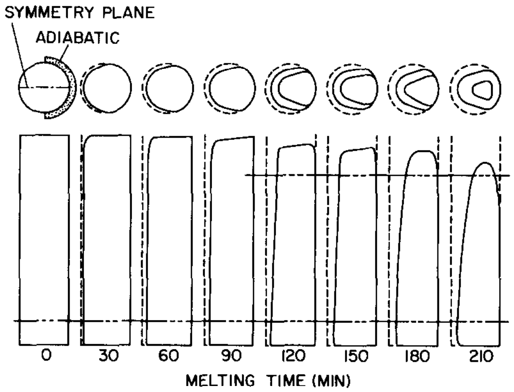

FIG. 4. Pattern of melting in the nonuniformly heated, vertical containment tube.

a larger temperature difference across the liquid and, thereby, to a stronger buoyancy which gives rise to more vigorous natural convection and more rapid melting.

To complement the comparison of melted mass results of Fig. 2, representative melting patterns for uniform heating and nonuniform heating are presented in Figs. 3 and 4, respectively. Both figures correspond to $Ste = 0.0445$. In each figure, longitudinal cross sections of the unmelted solid are shown at eight instants of time. The unmelted solid, the liquid melt, the solid–liquid interface, and the tube wall are designated at the right in Fig. 3, and these designations apply to all the diagrams in Figs. 3 and 4.

For the uniform heating case, the melting pattern is axisymmetric. When the heating is nonuniform, axisymmetry does not prevail, so that the melting pattern must be more carefully specified. To this end, the longitudinal sections of Fig. 4 are supplemented by top view diagrams. The pair of horizontal dot-dashed lines which cut through the longitudinal sections identify the transverse cross sections which are depicted in the top views. In the leftmost top view (time = 0), note has been made of the adiabatic half of the tube and, by implication, the other half is heated. Also shown in that view is the plane of symmetry which prevails for the imposed heating condition. The longitudinal sections shown in Fig. 4 lie in the plane of symmetry.

Attention may first be turned to Fig. 3 (uniform heating). At short times, the melting front is very close to the tube wall and is virtually parallel to it. This is a period when the rate of melting is governed by heat conduction across the melt layer. The density decrease due to melting requires that the liquid melt occupy a greater volume than did the solid from which it originated. This causes the liquid to overflow atop the solid, giving rise to the rounding of the corners in evidence at time = 30 min.

As time passes, the melting front moves inward, but with more rapid melting in the upper region and with a significant decrease in the height of the solid. This pattern is due to natural convection in the liquid melt, with an upflow adjacent to the tube wall and a downflow adjacent to the melting front. The recirculating flow continuously delivers relatively warm liquid to the upper portion of the tube, thereby accelerating the rate of melting there.

Turning next to Fig. 4, it is seen that the events just described for the uniformly heated tube continue to occur for the nonuniformly heated tube, but the melting is strongly skewed toward the half of the circumference that is heated. As a layer of hot liquid begins to overlay the top of the solid, it causes some melting of the isolated half. Also, as time progresses, hot liquid situated adjacent to the heated wall which borders the insulated wall tends to eat into the solid bounded by the insulated wall. Thus, at larger times, the melting zone has penetrated well into wall-adjacent regions of the insulated portion of the tube. It also appears that despite the low thermal conductivity and small thickness of the tube wall, a small amount of melting may have occurred due to heat conducted through the wall into the insulated region.

Inclined tube results

Consideration will now be given to the use of the direct contact mode of melting as a means for recouping the degradation of performance caused by the nonuniform heating. In this mode, the melting solid is pressed against the heating surface by the force of gravity. Heat is transferred by conduction from the surface to the solid across a thin, intervening film of liquid that is necessarily present due to the continuous melting of the solid.

In the present situation, the direct contact mode was activated by inclining the containment tube so as to create a component of the gravity force which would tend to press the solid against the heated portion of the tube circumference. Tube inclinations of $7\frac{1}{2}^\circ$, 15° and 30° to the vertical were investigated. The inclined tube experiments were performed only for the nonuniformly heated case.

The melted mass results corresponding to the $7\frac{1}{2}^\circ$ inclination are presented in Fig. 5. The figure consists of two graphs, designated (a) and (b), respectively for $Ste = 0.0445$ and 0.222. Each graph contains a pair of reference lines which represent the melting results

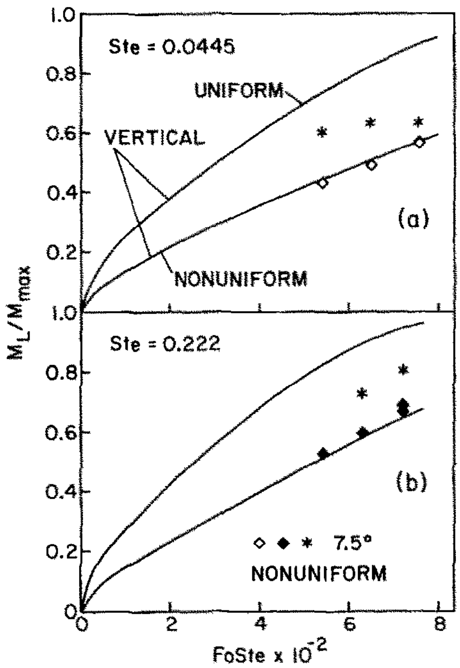

FIG. 5. Melted mass for $7\frac{1}{2}°$ inclination of the nonuniformly heated containment tube.

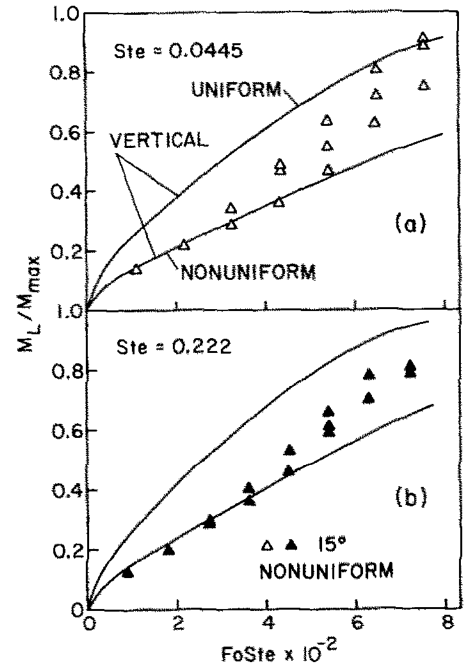

FIG. 6. Melted mass for 15° inclination of the nonuniformly heated containment tube.

for the vertical tube. The upper line of the pair corresponds to the uniform heating condition, while the lower line is for nonuniform heating. These lines are best fits of the data of Fig. 2.

Consider first the diamond-shaped data symbols (the asterisk symbols will be described shortly). From these, it is seen that the melting results for the $7\frac{1}{2}°$ inclination are very little different from those for the vertical tube. This suggests that in the face of the restraining forces, the gravity force component associated with this inclination is too small to press the solid against the heated wall.

To examine the effect of frictional restraining forces at the lower surface of the solid, special data runs were performed in which a 0.3-cm-thick Teflon disk was overlaid atop the plastic wrap which enveloped the Styrofoam portion of the lower end cap. Thus, in these runs, the bottom of the solid was in contact with the Teflon disk rather than with the plastic wrap. Teflon was chosen for the disk material because of its low friction characteristics.

The results of the special runs are depicted by the asterisk symbols in Fig. 5. As seen there, the lower restraining forces associated with the Teflon surface enable direct contact to occur, as witnessed by the increased melting compared with that when the Teflon disk is absent. In general, however, the direct contact does not occur at the very beginning of the melting period, but rather is delayed until some later time when the solid slides into the heated wall. The extent of the delay has a marked effect on the M_L value corresponding to a given melting time (i.e. a given *FoSte*). Indeed, owing to the somewhat random nature of the delay, the M_L data may appear to be scattered or irregular.

The foregoing discussion is reinforced by the data for the 15° inclination as presented in Fig. 6. The structure of this figure is identical to that of Fig. 5—including (a) and (b) parts and vertical tube reference lines. The 15° data are for the regular setup at the lower end of the solid specimen (i.e. no Teflon disk).

The figure shows that at this inclination, there is considerable direct-contact-related enhancement of the melting. However, no enhancement occurs at the smaller times, indicating that the solid has not yet slid into the heated wall. At later times, where there is enhancement, the data appear to be arranged in a column-like manner, especially in part (a) of the figure. The spread of the data at a given melting time (i.e. a given *FoSte*) reflects the different history of each solid specimen with regard to when it slid into the heated wall, with the highest data point corresponding to the earliest sliding.

The most enhanced of the data in Fig. 6 fall very close to the reference line for the vertically oriented, uniformly heated tube. Thus, for these cases, the degradation in performance due to the nonuniform heating has been recouped.

Figure 7 presents the melting data for the 30° inclination (regular lower end setup). Here, direct contact is seen to be highly effective in increasing the amount of melting. Not only is the amount of melting greater than for the 15° inclination, but, also, the spread of the data has diminished, indicating a more consistent pattern of sliding. Of particular note are those cases where the 30° data actually fall above the reference

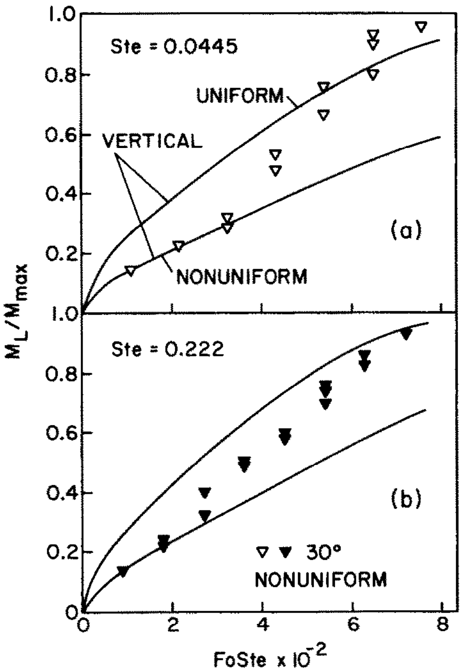

FIG. 7. Melted mass for 30° inclination of the nonuniformly heated containment tube.

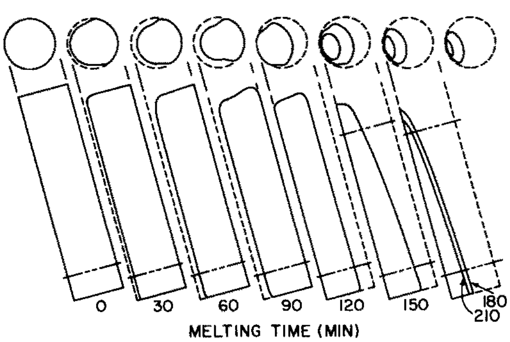

FIG. 8. Pattern of melting in the nonuniformly heated, 15° inclined containment tube.

line for the vertical, uniformly heated tube. Overall, Fig. 7 demonstrates that degraded performance due to the nonuniform heating can be recouped by inclining the tube and activating the direct contact mode of melting.

To illustrate the pattern of melting in an inclined, nonuniformly heated tube in which direct contact plays a significant role, Fig. 8 has been prepared. The figure corresponds to a 15° inclination and to Ste = 0.0445. Aside from the inclination, the format of the figure is similar to that of Fig. 4.

For times up to and including 90 min, the restraining forces prevent the solid from sliding, so that the melting pattern does not differ significantly from that of the vertical solid of Fig. 4. At some time between 90 and 120 min, the solid has slid into the heated wall. From then on, very rapid melting occurs, resulting

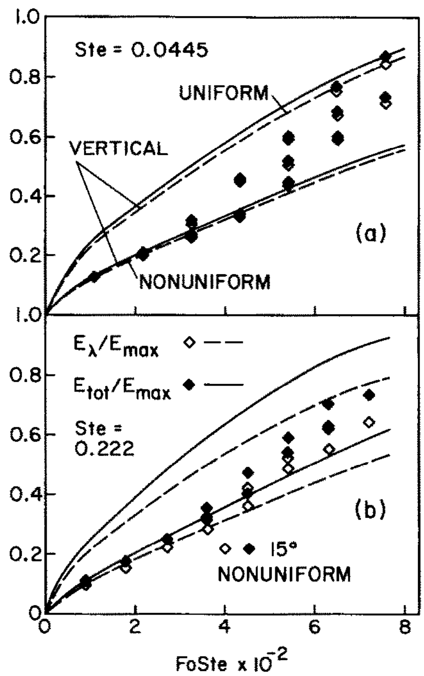

FIG. 9. Stored energy results for the vertical and 15° inclined containment tubes.

in a pattern that is altogether different from that of Fig. 4.

Stored energy

The energy stored both as latent heat and sensible heat between the onset of melting and any time t is represented by E_{tot}, while E_λ represents the latent heat component. Representative results for these quantities are presented in Fig. 9 in terms of the ratios E_λ/E_{max} and E_{tot}/E_{max}. The vertical tube data, both for uniform and nonuniform heating, are depicted by the dashed and solid lines, while the data symbols correspond to the 15° inclination and nonuniform heating. The (a) and (b) parts of the figure respectively convey results for Ste = 0.0445 and 0.222.

The difference between the results for E_{tot}/E_{max} and E_λ/E_{max} is the sensible heat component E_s/E_{max}. As expected, the sensible heat component is very small for a small Stefan number such as 0.0445. For Ste = 0.222, the latent heat component continues to be the major contributor to the stored energy, but the sensible heat component is by no means insignificant.

Owing to the dominance of the latent heat component, the curves and data displayed in Fig. 9 convey trends and relationships that are identical to those for the M_L/M_{max} results of Fig. 6. Therefore, the identification and discussion of those trends and relationships set forth in connection with Fig. 6 also apply to Fig. 9.

CONCLUDING REMARKS

The experiments performed here have documented the substantially reduced melting which occurs when a vertical, solid-filled containment tube is heated only over a part of its circumference. With the heating confined to half the circumference, the amount of melting, relative to that for circumferentially uniform heating, was reduced by 45% in the early stages of the melting period and by about 35% in the later stages of melting. The extent of the reductions was insensitive to the Stefan number. Therefore, it appears to be inappropriate to use information for circumferentially uniform melting to design a circumferentially non-uniformly heated phase-change thermal storage system.

The second part of the work dealt with the re-couping of the degraded performance associated with the nonuniform heating. To this end, the containment tube was inclined relative to the vertical so that gravity would tend to press the melting solid against the heated portion of the tube surface. In this mode of melting, termed the direct contact mode, heat is transferred by conduction from the surface to the solid across a thin, intervening film of liquid that is necessarily present due to the continuous melting of the solid. The inclined tube experiments were performed only for the nonuniformly heated case.

With the tube inclined at $7\frac{1}{2}°$ to the vertical, the wall-directed gravity force component was too small to overcome the forces which restrained the solid from sliding into the wall, and direct contact melting was not attained. However, when the bottom of the solid was supported by a Teflon baseplate (i.e. a low friction surface), direct contact was achieved, but only following a considerable time lapse after the beginning of the melting period.

For 15° and 30° inclinations of the containment tube, direct contact gave rise to substantial enhancement of the melting. The 15° data displayed some scatter because of the somewhat random nature of the aforementioned time lapse. However, at the 30° inclination, the scatter diminished and melting was achieved that exceeded that for the vertical, uniformly heated tube.

Direct measurements of the shape of the melting solid at various times during the melting period were made to track the timewise movement of the solid–liquid interface. The assemblage of this information illustrated the pattern of melting for the vertical, uniformly heated tube, for the vertical, nonuniformly heated tube, and for the inclined, nonuniformly heated tube. Results were also presented for the timewise variation of the energy stored both as latent heat and as sensible heat.

REFERENCES

1. E. M. Sparrow and T. A. Myrum, Inclination-induced direct-contact melting in a circular tube, *J. Heat Transfer* **107**, 533–540 (1985).
2. E. I. Griggs and W. R. Humphries, A design handbook for phase change thermal control and energy storage devices, NASA Technical Paper 1074 (1977).

FUSION DANS UN TUBE EN PRESENCE D'UN CHAUFFAGE CIRCONFERENCIEL NON UNIFORME

Résumé—On étudie expérimentalement la fusion d'un milieu à changement de phase dans un tube circulaire quand le chauffage de la paroi du tube n'est pas uniforme sur la périphérie. Des expériences avec chauffage uniforme sont faites pour fournir une information de référence. Pour un tube vertical avec chauffage sur la moitié de la circonférence, la quantité fondue, relativement au cas du chauffage uniforme, est réduite de 45% dans les premiers stades. Lorsque le tube est incliné sur la verticale, la décroissance de la fusion associée au chauffage non uniforme et recoupée pour les inclinaisons suffisamment larges pour que le solide soit appliqué par gravité contre la portion chaude de la paroi. Ce mode de contact direct de fusion est complet pour une inclinaison de 30° et intermittent pour 15°. L'usage d'une surface à faible frottement pour supporter le solide en fusion favorise le mode de contact direct. Des mesures dans le temps, de la forme du solide permet l'identification de la configuration pour différents types de chauffage et plusieurs inclinaisons. On présente aussi des résultats sur la variation dans le temps de l'énergie stockée.

SCHMELZEN IM ROHR BEI UNGLEICHMÄSSIGER BEHEIZUNG ÜBER DEN UMFANG

Zusammenfassung—Experimente wurden durchgeführt, um das Schmelzen eines Stoffes in einem über den Umfang ungleichmäßig beheizten Kreisrohr zu untersuchen. Es wurden auch Versuche bei gleichmäßiger Beheizung durchgeführt, um Basisinformation zu erhalten. Beim vertikalen Rohr reduzierte sich der Schmelzgrad bei Beheizung des halben Rohrumfangs im Vergleich zur gleichmäßigen Beheizung um 45% im Anfangsstadium des Schmelzens und um 35% in späteren Stadien. Beim geneigten Rohr wurde der Rückgang des Schmelzgrades aufgrund der ungleichförmigen Beheizung bei genügend starken Neigungen dadurch aufgehoben, daß der Feststoff durch die Schwerkraft an die beheizte Wand gedrückt wurde. Dieses Schmelzverhalten bei direktem Kontakt wurde regelmäßig bei einer Neigung von 30° und verschiedentlich bei 15° erreicht. Die Verwendung einer Oberfläche mit geringer Reibung begünstigt das Direkt-Kontakt-Schmelzen. Messungen der Form des schmelzenden Feststoffes zu verschiedenen Zeiten ermöglichten die Beschreibung des Schmelzverlaufs für verschiedene Beheizungsarten mit verschiedenen Neigungen. Es werden auch Ergebnisse für den zeitlichen Verlauf der gespeicherten Energie vorgelegt.

ПЛАВЛЕНИЕ ВНУТРИ ТРУБЫ ПРИ НЕОДНОРОДНОМ ПО ОКРУЖНОСТИ НАГРЕВЕ

Аннотация—Проведены эксперименты по исследованию плавления среды, помещенной в круглую трубу, в случае неоднородного нагрева стенки по окружности. С целью получения базовой информации проведены также эксперименты по плавлению в условиях однородного нагрева. Для случая нагрева по полуокружности вертикально расположенной трубы, по сравнению со случаем однородного нагрева, количество расплава на ранних стадиях плавления уменьшалось на 45%, а на более поздних стадиях—на 35%. При отклонении трубы от вертикали уменьшение расплава, связанное с неоднородным нагревом, компенсируется за счет того, что твердая фаза прижимается силой тяжести к нагретой части трубы. Этот режим плавления при прямом контакте достигался постепенно при угле наклона 30° и скачкообразно при 15°. Показано, что применение поверхности с малым трением для поддержания плавящегося твердого вещества содействует режиму прямого контакта. Измерения во времени формы плавящегося твердого тела позволили определить режимы плавления для различных типов нагрева и углов наклона. Представлены результаты изменения во времени накопленной энергии.