LATENT HEAT-OF-FUSION ENERGY STORAGE: EXPERIMENTS ON HEAT TRANSFER FROM CYLINDERS DURING MELTING

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Abstract: Melting from an array of three staggered, electrically heated cylinders imbedded in paraffin (n-octadecane) has been studied. The shape of the melting front has been determined photographically, and the local heat transfer coefficients were measured using a shadowgraph technique. The experiments provide conclusive evidence of the important role played by natural convection on the time variation of the melt shape, the surface temperature and the instantaneous local as well as circumferentially averaged heat transfer coefficients around the imbedded heat sources. After a common solid-liquid interface is formed around the cylinders, natural convection circulation around each cylinder interacts strongly with the other two cylinders.

Keywords: heat transfer.

1. INTRODUCTION

In this paper, experiments are described which are aimed at providing quantitative data on heat transfer processes which occur when a solid is melted from multiple, horizontal heat sources. This study was motivated by the need to gain improved understanding of heat transfer during the charging phase of thermal energy storage (TES) system which takes advantage of the latent heat-of-fusion of a phase change material (PCM) [1]. A relevant consideration in such systems is the effective utilization of the PCM by an optimum arrangement of tubes through which the working fluid is circulated. Good heat transfer characteristics between the transport fluid and the PCM for efficient thermal performance of a storage unit are also required. Data needed for the design of latent heat-of-fusion TES systems are not available.

Natural convection is an important process in problems involving X melting, and it is the purpose of this paper to point out some of its characteristics. To this end, heat transfer processes which occur when I a solid is melted from multiple cylindrical heat sources are studied.

2. EXPERIMENTS

Test Apparatus and Test Procedure. The main part of the test cell, a U-shaped aluminum frame 4.0 cm thick with inside dimensions of 16.2 × 13.2 × 4.0 cm, was attached to a rectangular base-plate which could be adjusted in vertical direction at its four corners for precise leveling. The front and back sides of the cell were made of plate glass, 0.6 cm thick, to allow for visualization, photographing and optical observation of the phenomena taking place during phase transformation. The sealing was accomplished by placing an o-ring between the aluminum frame and the glass plate. In order to press the glass plate uniformly against the U-shaped frame a collar was machined to the main frame on each side to accommodate an aluminum stress-relief strip which was pressed against the edges of the glass plate by screws.

To reduce natural convection from the test cell a second glass plate was installed on each side of the cell. The air gap between the two vertical glass plates was selected to minimize heat loss from the cell to the ambient environment. The top of the test cell was closed with a plexiglass cover. A screen was hinged to this cover which could be turned and placed parallel to the window facing the camera. This arrangement was used when the solid-liquid interface was photographed. For photographing the shadowgraphs the second screen was used. The first screen was removed from the optical path by turning it upwards, see Fig. 1.

Electrical cartridge heaters, 0.64 cm OD, were employed as heating elements. The heaters were inserted in snugly fitted brass tubes, 1.9 cm in outside diameter. The 4.0 cm long tubes with the heater inside were then installed in the test cell. Holes were drilled in one of the glass plates for bringing out the power leads of the heating elements and the thermocouple wires. The holes were then sealed to prevent the leaking of molten paraffin from the cell. A schematic diagram of the staggered, three cylinder arrangement used in the experiments is shown in Fig. 2.

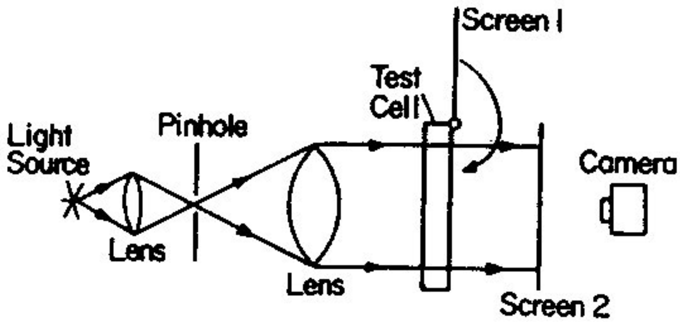

Fig. 1 Schematic diagram of shadowgraph system

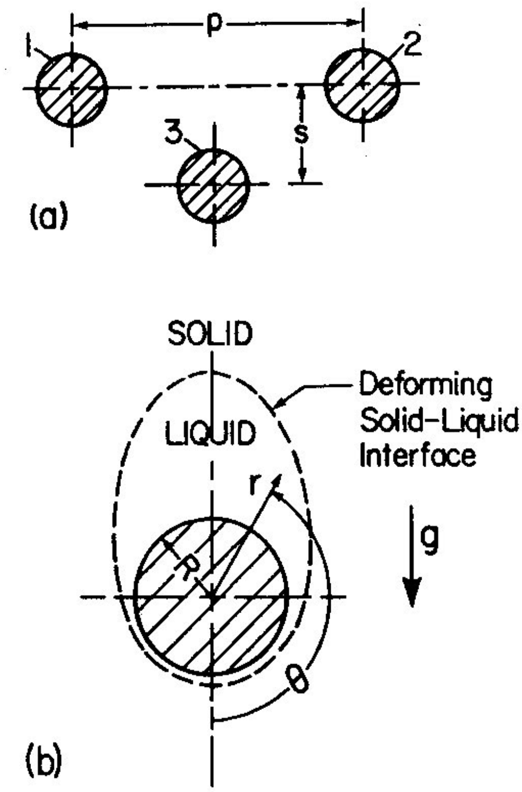

Fig. 2 Schematic diagram of (a) three cylinder arrangement and (fa) coordinate system

The wall temperatures were measured by Chromel-Constantan thermocouples. Small diameter, 1.0 mm OD, holes were drilled axially and radially in the brass tube and then the thermocouple junctions were brought to the surface, soldered and the surface polished. The thermocouples were located at 8 = 0,90,180 and 270 deg. A shadowgraph system, shown schematically in Fig. 1, was employed for observing the melting front and for measuring the local heat transfer coefficient at the surface of the cylinder [1]. The system has been found to be satisfactory in preliminary experiments [3].

The test cell was filled with liquid n-octadecane (99 percent pure, Humphrey Chemical Co., North Haven, CT) and given sufficient time to solidify and reach uniform ambient temperature throughout in a temperature controlled laboratory environment. The initial temperature of the solid was maintained close to the melting temperature and was typically a maximum of only a couple degrees Kelvin lower than the melting temperature. Therefore, the small subcooling (T/- Ti) is not expected to have much effect on the melting front motion. Each experiment was performed at constant electrical power input (constant heat flux) to the heater. Precautions were taken not to entrap any air as the liquid solidified. This was done by vibrating the test cell during freezing of the PCM. No entrapped air was observed to form a cavity. The maximum beam deflection and the motion of the melting front were recorded photographically.

3. DATA REDUCTION

If a parallel light beam enters a uniform test section it remains so toward the screen. During the melting process, however, the material in the test section is nonuniform due to temperature gradients which cause a change of index of refraction of the PCM. Since the light beam remains deflected outside of the test cell, the displacement on the screen can be" minimized by moving the screen as close as possible to the exit of the test section in contrast to studying heat transfer around the heat source where a large displacement is necessary for a quantitative evaluation of the photo graphs. In that case, a sufficient distance between test section and screen has to be maintained.

The path of light in a nonisothermal medium can be calculated from the geometrical optics theory [MJ. For a system where changes in the index of refraction n and of the temperature in the axial direction are negligible in comparison to the radial direction, the geometrical optics theory yields the distance Y of the deflected light beam on the

$$Y = \frac{1}{n}\frac{dn}{dT}\frac{dT_l}{dr} lL \tag{1}$$

For a horizontal cylinder of radius R the local Nusselt number Nu defined by

$$Nu = -\frac{2\left(\frac{\partial T_l}{\partial r}\right)_R R}{T_w - T_f} \tag{2}$$

can be expressed in terms of observed and known quantities as

$$Nu = -n\frac{dT}{dn}\frac{2RY}{lL(T_w - T_f)} \tag{3}$$

where T_w is the cylinder surface temperature. The distance Y is determined from the photographs made during the melting process. The uncernaly in the heat input, which is needed to evaluate the Stefan and Rayleigh numbers, is estimated to be about 5 percent and is due primarily to the lack of precise knowledge of the thermal conductivity of the electric cartridge heater and the thermal contact resistance between the ends of the brass sleeve heater and the test cell wall.

A number of experiments for different wall heat fluxes have been performed with three cylinders (in two rows) imbedded in a PCM. Three rows of cylinders were not considered because after a common solid-liquid interface is formed, the solid would lose support, descend down onto a lower row of cylinders and result in a totally different physical arrangement. Two different staggered arrangements have been considered to examine the effects of natural convection and plume interference on heat transfer and the melting front shape. The pitch and the spacing used are given in Table 1.

Cylindrical heat source arrangements used in tests: D = 1.905 cm. Table 1

Arrangement	Pitch, p	Spacing, s
A	3D	1.5D
B	3D	D

4. RESULTS AND DISCUSSION

Melt Shape. A comparison of typical photographs illustrating the solid-liquid interface positions at selected times for arrangements A and B is given in Fig. 3. The shadows of the cylinders in the figure appear to be slightly out of round. This is not due to faulty imaging of the cylinders but due to the fact that the melting front was photographed off a screen attached to the test cell instead of photographing the cylinders directly. The actual contours of the cylinders in the photographs are indicated with dashed curves on the photographs. At early times (t = 1.2 not shown in figure) the shape of the phase change boundary around an individual heat source is not influenced by the presence of other sources [2,3]. However, the plumes are already developed at the top of the cylinders. The melt regions are no longer annular in shape because of natural convection. The effect of heat source arrangement on the melt shape is clearly seen at j = 2.4. For arrangement B a continuous solid-liquid interface has already been formed while for A the cylinders still have separate melt zones. 1 This is due to closer spacing of the heat sources for arrangement B, I see Table 1. The oscillation of the plumes above the cylinders is evident from the photographs. Observations revealed no definite period of plume oscillations. The dark lines visible in the photographs of arrangement A at 8 = 270 deg and 8 = 90 deg for cylinders 1 and 2, \ respectively, are the thermocouple and power leads.

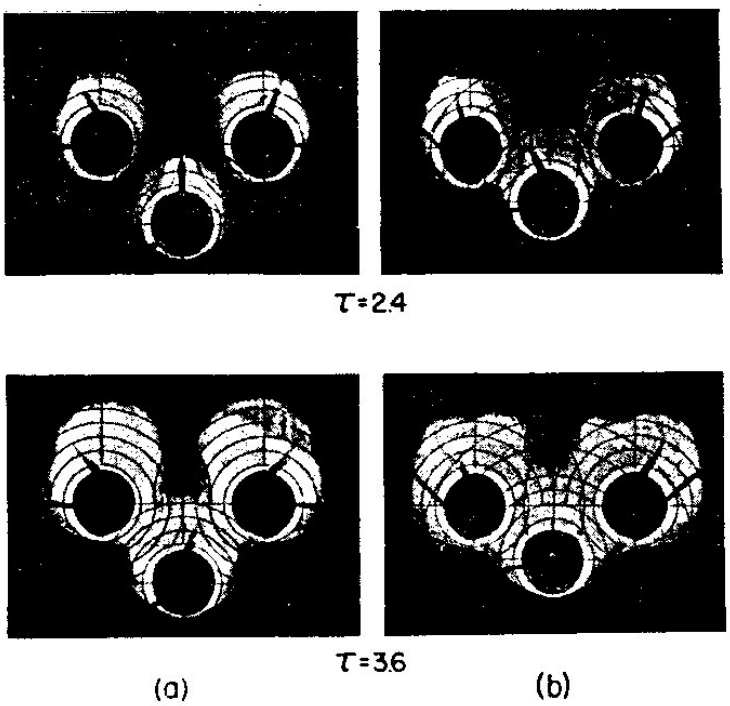

Fig. 3 Comparison of melt shapes for Ste = 1.25: (a) arrangement A and (b) arrangement B

The overall shapes of the melt zones are different for the two heat source arrangements at r = 3.6. For arrangement A the melt zones extend into the vertical and for B into the horizontal directions. A prolonged plume activity in a given direction produces non-uniform local melting above the upper two cylinders. The very important role played by natural convection in forming the melt zone is evident from the photographs. Most of the melting occurs above and to the sides of the heat sources with very little below. The upward motion of the interface is driven at early times by the plume which rises from the top of the heated cylinder, and at later times by circulation which conveys the hot liquid to the upper part of the melt region. It appears that the presence of natural convection reduces the melting below the cylinders compared to that which would occur if heat transfer were by pure conduction.

The positions of the solid-liquid interface at a succession of times are plotted in Fig. 4 (a). These melting front positions were taken directly from the photographs. Inspection of the figure reveals that at early times the melt regions are still separated. There is no detectable interaction, and the melting around the heat source occurs as if the solid were infinitely large and there were no other sources. At early times when heat transfer from the cylinder to the paraffin is dominated by conduction the melt region is symmetrical about the axis of the cylinder. As the heating continues and natural convection develops, the annular melt zone becomes increasingly distorted. The shapes of the molten regions shown in Fig. 4 (a) for the cylinders at early times before interaction begins to take place are different for the same heat flux than those for [4]. The shapes for *n*-octadecane are similar to those obtained by Sparrow, et al. [3] for a eutectic of sodium nitrate and sodium hydroxide which has a melting temperature of ~517 K. The larger initial subcooling of the solid is considered to be the main reason for the somewhat more slender and sharper molten region near die top of the melt zone. The parameter $c_s(T_f - T_i)/\Delta h_f$ can be used as a measure of the importance of subcooling on the shape of the melt. For n-octadecane this parameter was a maximum of 0.03 it was 0.4. This clearly indicates that very little heat was required to bring n-octadecane to the fusion temperature while a substantial fraction of heat input was needed.

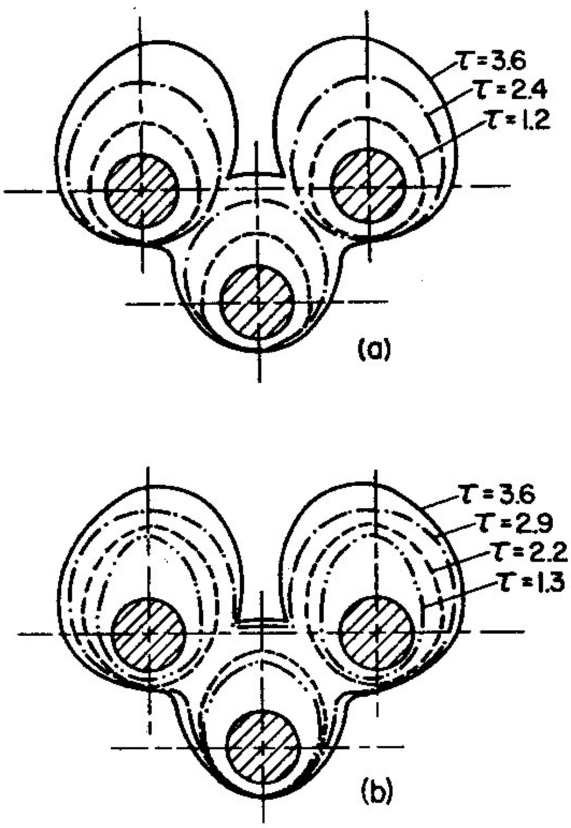

Fig. 4 Position of the solid-liquid interface for arrangement A: (a) effect of time (Ste = 1.25) and (6) effect of Stefan number (Fo = 2.68)

As the Stefan number increases (see Fig. 4 (b)) the solid above the cylinder melts faster which changes the overall shape of the melt After the liquid regions around the cylinders form a common boundary, the natural convection about the lower cylinder 3 supports melting in the region between and above cylinders 1 and 2. With increasing Stefan number the natural convection circulation in the liquid becomes more intense and influences the shape of the melt particularly in the region between and above the upper two cylinders. The interaction between the cylinders causes a shift of the symmetry from the axis of each cylinder to the vertical plane passing through the center of cylinder 3. Observations have shown that the melting was very uniform along the length of the heated cylinders. Only at very late times, after the melt thickness above the heated cylinder had reached about 5 cm, was there an observable (about 2 mm) difference in the melt layer thickness at the center of the test cell in comparison to the test cell wall. This suggests that even though natural convection circulation in the melt region is three-dimensional, the melting process is nearly two-dimensional.

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