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Research Report on

FUNDAMENTAL HEAT TRANSFER PROCESSES RELATED TO PHASE CHANGE THERMAL STORAGE MEDIA

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ABSTRACT

This report describes research on fundamental heat transfer processes which occur in phase-change thermal storage systems. Four research problems were investigated--two involving freezing and two involving melting. The freezing studies led to the discovery of new phenomena which should have a significant impact on the functioning of phase-change storage devices. It was found that under certain operating conditions, freezing can be drastically retarded and even terminated by natural convection. Under other operating conditions, the dominance of natural convection in the freezing process ultimately gives way to a freezing mode controlled by heat conduction in the solidified material. By taking account of geometrical and thermal symmetry, the relationship between freezing about a single vertical tube and about an array of vertical tubes was established.

The melting studies were focused on determining quantitative data for the heat transfer coefficients in two basic phase-change systems. One of these is an array of horizontal tubes and the other is a single vertical tube. These experiments involved parametric variations of the heating rate and of the degree of subcooling of the melting solid.

INTRODUCTION

The design of phase-change thermal storage systems involves a knowledge of the heat transfer characteristics of both melting and freezing. In recognition of this, research on both of these phase-change processes is being performed at the University of Minnesota under DOE sponsorship. The current research program, which encompasses four problems, two in freezing and two in melting, consists of the following studies:

1. Retardation and termination of freezing due to natural convection
2. The transition from natural-convection-controlled freezing to conduction-controlled freezing
3. Melting about an array of horizontal heating tubes
4. Parametric study of melting about a vertical heating tube, including effects of solid-phase subcooling

Broad-brush descriptions of these research problems will be presented in the paragraphs which follow. A fuller description of each problem will then be given in successive individual subsections of the report.

The first of these studies might well be regarded as a landmark research effort in that it has demonstrated, for the first time experimentally, the overpowering effect of natural convection on freezing. It was shown that natural convection can substantially retard the rate of freezing and can actually terminate the freezing process altogether. This discovery indicates that the heat transfer performance for the freezing portion of a thermal storage cycle will not be as good as might have been expected from a model which ignores natural convection. The omission of natural convection from freezing calculations has been standard practice in the past and, therefore, those calculations will necessarily predict higher heat transfer rates than will actually occur in practice.

The presently standard computational model for freezing is based on heat conduction as the sole transport mechanism. The second of the current research studies consists of experiments aimed at determining how freezing that is controlled by natural convection can undergo a transition and tend toward conduction-controlled freezing. In addition, as will be described shortly, these studies, which were actually performed with a single cooled tube immersed in a liquid phase-change medium, are applicable to a large array of vertical cooled tubes.

Experiments were performed for melting about a horizontal array of heating tubes situated in a solid phase-change medium. Prior work in our laboratory on melting about a single horizontal heating tube had established the important and enhancing role of natural convection in the melting process. It was found that due to natural convection, heat transfer coefficients for melting are very much higher than are those which would occur by pure conduction.

The current work on multi-tube horizontal melting was motivated by the need to determine whether the substantive and affirmative natural convection effects for single-tube melting carry over for a tube bank. When there are numerous tubes, the natural convection flows induced by melting around the individual tubes interact. The question of whether the interaction yields enhanced or diminished heat transfer coefficients has been a prime focus of the current research.

The last of the current research problems is concerned with melting about a vertical heating tube embedded in a phase-change medium. Prior qualitative work had demonstrated that natural convection plays a dominant role in vertical melting (as it does in horizontal melting). However, quantitative data for the melting coefficients have not heretofore been available. Experiments were, therefore, carried out to determine these heat transfer coefficients and, with this information, a dimensionless correlation was sought which would convey design data in a useful form. The experiments encompassed both the case in which the melting solid is at its fusion temperature and the case where it is subcooled below the fusion temperature. Another part of this study dealt with the question of whether melting in an open-topped containment vessel differs in a quantitative manner from melting in a closed-top containment vessel.

RETARDATION AND TERMINATION OF FREEZING DUE TO NATURAL CONVECTION

As was mentioned earlier, landmark experiments were performed which demonstrated, for the first time, the overpowering effect of natural convection on freezing. For these experiments, the freezing took place on the outer surface of a water-cooled vertical tube situated in a containment vessel filled with a liquid paraffin. A sucession of experiments was performed, in each of which the cooled tube was allowed to remain in the paraffin bath for a different, preselected period of time. The frozen specimen corresponding to each experiment was removed from the tube at the conclusion of the test. The assemblage of such specimens, placed side-by-side and arranged according to the durations of the successive tests, gives the time history of the freezing process.

Representative photographic results which illustrate the role of natural convection in freezing are shown in Figs. 1 and 2. The first of these figures shows three frozen specimens corresponding respectively to run times of 15, 45, and 90 minutes. These specimens are essentially perfect cylinders, the thickness of which increases continuously with time. These characteristics coincide precisely with those for freezing in which the sole transport mechanism is heat conduction across the frozen layer, without any influence of natural convection.

Attention may now be turned to Fig. 2, which shows a sequence of frozen specimens which respectively correspond to run times of 15, 30, 60, 90, 120, and 180 minutes. The freezing pattern in evidence in Fig. 2 is drastically different from that of Fig. 1. First of all, the amount of frozen material does not increase continuously with time; rather, after an initial increase, the thickness of the frozen specimen reaches a terminal value. Furthermore, at any time, the amount of frozen material is much, much less than that of Fig. 1. In addition, the specimens are no longer cylindrical in form. Instead, the specimens display a gently curving contour, with the thickness of the frozen layer increasing from top to bottom.

All of these characteristics are the result of a natural-convection-driven flow which recirculates in the containment vessel. The recirculation pattern involves an upflow along the wall of the containment vessel and a downflow along the surface of the frozen specimen.

A complete physical theory explaining the presence of the natural convection and its impact on the heat transfer coefficients for freezing is set forth in {1}, which is a journal article describing the experiments and their results. That paper includes both quantitative and qualitative information documenting the natural convection effect.

Even without the details contained in {1}, the practical effects of natural convection on the melting portion of a phase-change storage cycle can be readily perceived from Figs. 1 and 2. In making this assessment, it should be noted that the temperature of the water-cooled tube was the same for both figures. It is clear from these figures that freezing is drastically retarded and is ultimately terminated by natural convection. In practical terms, this means that whenever natural convection occurs, the actual rate of heat extraction from a phase-change thermal storage system will be much lower than expected on the basis of conventional calculations.

Natural convection will occur whenever there are temperature nonuniformities in the phase-change liquid. Such nonuniformities were suppressed in the experiments of Fig. 1, but they were maintained for the experiments of Fig. 2 by situating the containment vessel in a constant-temperature water bath.

Further clarifications and elucidations of the natural convection effect will be presented in the subsection that follows, while an approach to mitigating its negative influence will be described in the proposal for the follow-on phase of the research project.

THE TRANSITION FROM NATURAL-CONVECTION-CONTROLLED FREEZING TO CONDUCTION-CONTROLLED FREEZING

This research problem was undertaken in order to investigate freezing about an array of vertical tubes. An important by-product of the research was the discovery of new features in the mechanism of freezing, namely, the transition from natural-convection-controlled freezing to conduction-controlled freezing.

The basic geometry which motivated the work is illustrated in Fig. 3. The figure shows a plan view of a large thermal storage vessel containing a phase-change medium in which is embedded an array of vertical tubes arranged on equilateral triangular centers. If the thermal events which occur adjacent to all tubes are the same, then each tube is surrounded by a hexagonal symmetry envelope that is illustrated by the dashed lines in the figure.

The symmetry envelope is an adiabatic boundary across which there is no heat flow. Because of this characteristic, there is no thermal communication across the symmetry envelope. As a consequence, each tube and the surrounding phase-change material that is contained within the symmetry envelope can be treated independently of all other tubes.

Another important practical observation is that a hexagonal boundary closely approximates a circular boundary. Therefore, for almost all practical purposes, an infinite array of embedded vertical tubes can be modeled by a single vertical tube surrounded by a phase-change medium contained within an adiabatic circular boundary. This was the model used in experiments conducted during the present contract period.

Each experiment was initiated when a water-cooled vertical tube was immersed into a circular, externally insulated vessel containing liquid paraffin whose initial temperature exceeded the fusion temperature by a preselected value. Freezing then occurred on the outer surface of the cooled tube, and a natural convection recirculating flow was set up in the liquid paraffin as a result of the temperature differences throughout the liquid. This fluid motion enhanced the heat transfer from the liquid to the freezing interface. Since the outer boundary of the liquid region was insulated, the heat transfer from the liquid to the interface brought about a reduction in the temperature of the liquid, with a consequent decrease in the strength of the natural convection. Therefore, the retardation of the freezing process by natural convection diminished during the experiment. For an experiment of sufficiently long duration, natural convection ceased altogether, and the freezing rate was then governed by the heat conduction across the solidified material.

These events are illustrated in Fig. 4, which shows a sequence of frozen samples which correspond to a succession of increasingly longer duration times of the experiment, ranging from ten minutes to four hours. The figure shows that at early times, there is a slow growth and, in addition, the frozen specimens are wider at the bottom than at the top. These characteristics typify natural-convection-controlled freezing. Then, as time increases, the sloping sides tend to straighten and growth accelerates. The final sample in the photograph is straight-sided and, in addition, there is a network of lace-like dendrites on the freezing surface. Both of these features are indicative of conduction-controlled freezing.

By a comparison of Figs. 2 and 4, it can be seen that the degree of natural convection dominance depends on the thermal boundary conditions. In the case of Fig. 2, the outer boundary of the containment vessel was maintained at a uniform temperature, while for Fig. 4 the outer boundary was adiabatic. Whereas the effects of natural convection are substantially smaller in the case of Fig. 4 than for Fig. 2, they still are appreciable. To demonstrate this, experiments are now underway in which freezing occurs without natural convection involvement. These experiments are similar to those of Fig. 1, but are much more extensive both with regard to duration times and to the range of tube temperature levels investigated.

This work is in progress and will be completed before the end of the present contract period. When all of the planned experiments have been carried out, quantitative documentation will have been obtained both for freezing on a large array of cooled vertical tubes and for the transition from freezing controlled by natural convection to freezing controlled by conduction.

MELTING ABOUT AN ARRAY OF HORIZONTAL HEATING TUBES

Prior experiments in our laboratory have established the relationship between the heat transfer coefficients for melting about a horizontal heated tube and those for pure natural convection (without phase change). In applications, an array of horizontal tubes may be employed and, therefore, it is relevant to explore how the single-tube heat transfer coefficients relate to those for a multi-tube array. To this end, melting experiments were performed with an array of parallel, equally spaced heating tubes, all lying in a common horizontal plane. The tubes were embedded in a solid phase-change material which, prior to the initiation of a data run, was at its fusion temperature.

A data run was initiated by supplying electric power for the heating of the individual tubes. The power input was maintained at a constant level throughout the run. Tube surface temperatures were measured to enable evaluation of the melting coefficients. In addition, with a view to determining the shape of the evolving melt region, temperature data were collected from a thermocouple grid deployed throughout the phase-change medium.

A schematic diagram showing the evolution of the melt zone is presented in Fig. 5, where successive solid-liquid interfaces are labeled A, B, C, and D. Case A corresponds to pure conduction, while case B depicts a situation where natural convection is dominant but where the melt layers for the individual cylinders are independent of each other. Case C illustrates the shape of the melt zone shortly after the partitions which separate the individual melt layers have broken through. At larger times, the upper branch of the melt line advances to positions well above the cylinders and becomes nearly horizontal (case D). Throughout the entire process, there is very little melting below the cylinders owing to the buoyancy-driven upward-directed liquid motions.

Quantitative comparisons between the melting coefficients for single and multiple horizontal tubes are presented in {2}. It is shown there that aside from certain relatively minor differences in detail, the two sets of coefficients were generally of the same magnitude. This finding simplifies the task of designing multi-tube systems because the heat transfer coefficients for single tubes can be used as input.

PARAMETRIC STUDY OF MELTING ABOUT A VERTICAL HEATING TUBE

Experiments on melting about a heated vertical tube were undertaken to upgrade the presently available information, which is entirely qualitative, into quantitative information that is suitable for design. To accomplish this objective, the key operating parameters were varied systematically. These included the rate of heat addition to the melting solid and the degree of subcooling of the solid. The measured heating-surface temperature and heating rate enabled heat transfer coefficients for melting to be determined as a function of time during the melting process.

With these results dimensionless correlations were constructed which served to generalize and substantially enlarge their range of applicability. The correlation for melting of a solid at its fusion temperature is in the form of a power law which relates the Nusselt number to the Rayleigh number and to a geometrical parameter.

The experiments involving subcooling of the solid are still in progress. The relevant dimensionless groups have, however, already been identified, and the selection of operating parameters for the experiments is being made with a view to evaluating the relative performance of two candidate correlations.

Another major issue that is being addressed in these experiments is the possible influence of the boundary condition at the top of the containment vessel in which the phase-change material is situated. In one case, there is a space between the upper surface of the material and the top of the vessel, so that the motion of the liquid melt is not inhibited by skin friction that would be exerted by a contacting top. In the other case, the upper surface of the material is in contact with the top of the vessel, and the aforementioned frictional resistance is exerted on the liquid. The results thus-far obtained suggest that the top boundary condition does not have a first-order effect.

It is expected that the experimental work on this problem will be completed by the end of the present contract period (June 1, 1980).

REFERENCES

1. E. M. Sparrow, J. W. Ramsey, and R. G.Kemink, "Freezing Controlled by Natural Convection," ASME Journal of Heat Transfer, Vol. 101, 1979, pp. 578-584.

2. J. W. Ramsey, E. M. Sparrow, and L.M.C. Varejo, "Melting About a Horizontal Row of Heating Cylinders," ASME Journal of Heat Transfer, Vol. 101, 1979, pp. 732-733.

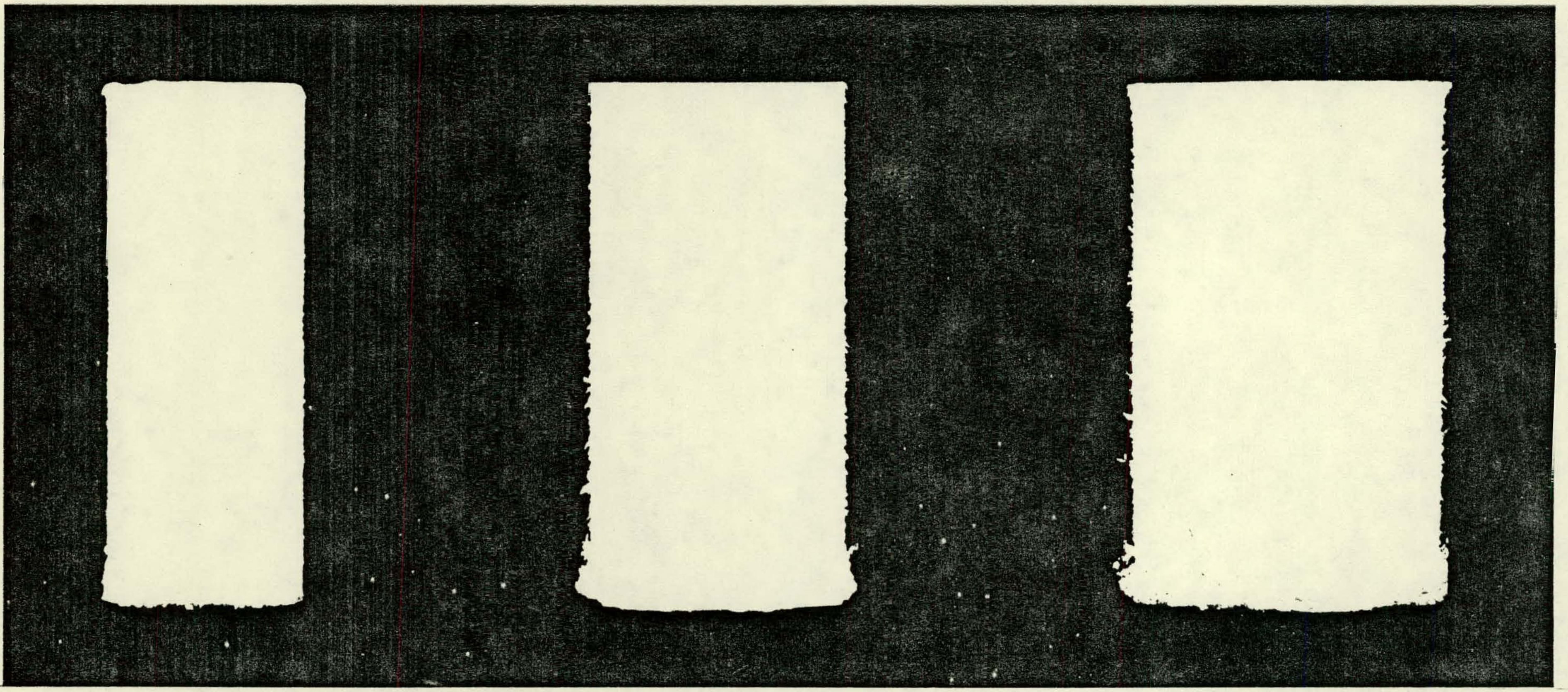

Fig. 1 Conduction-controlled freezing

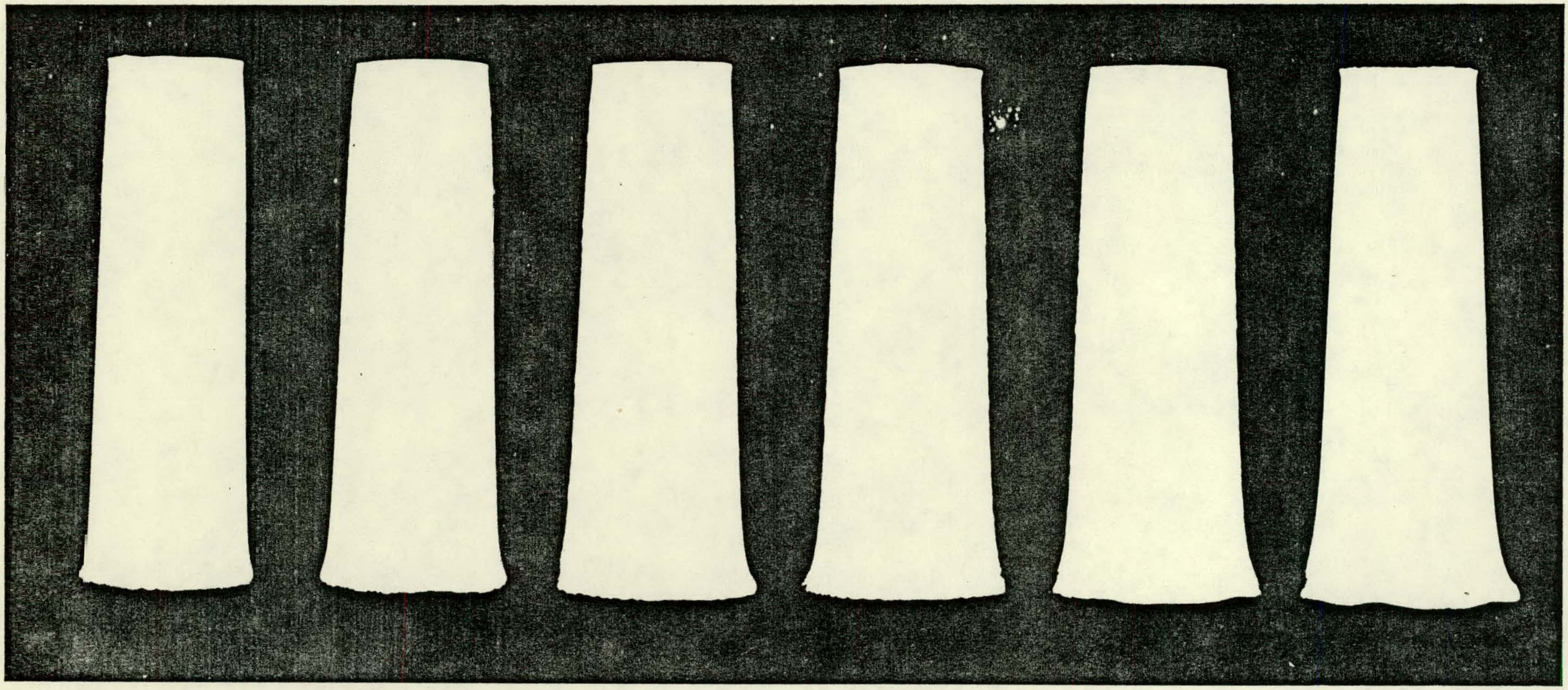

Fig. 2 Natural-convection-controlled freezing

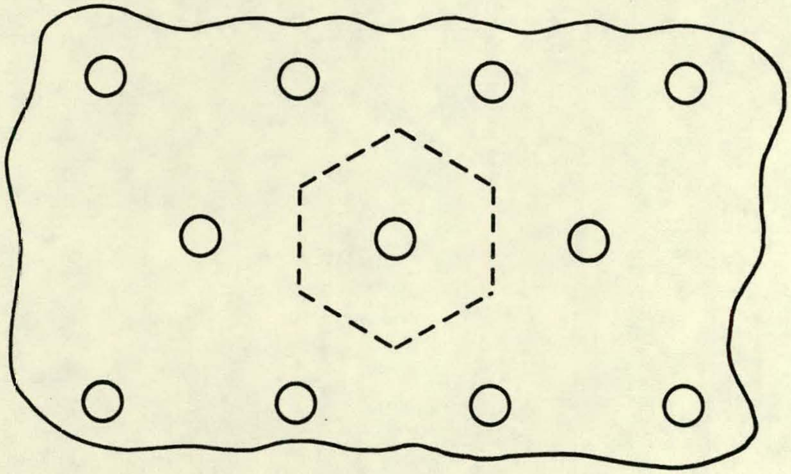

Fig. 3 Typical module in an array of vertical heating tubes embedded in a phase-change medium

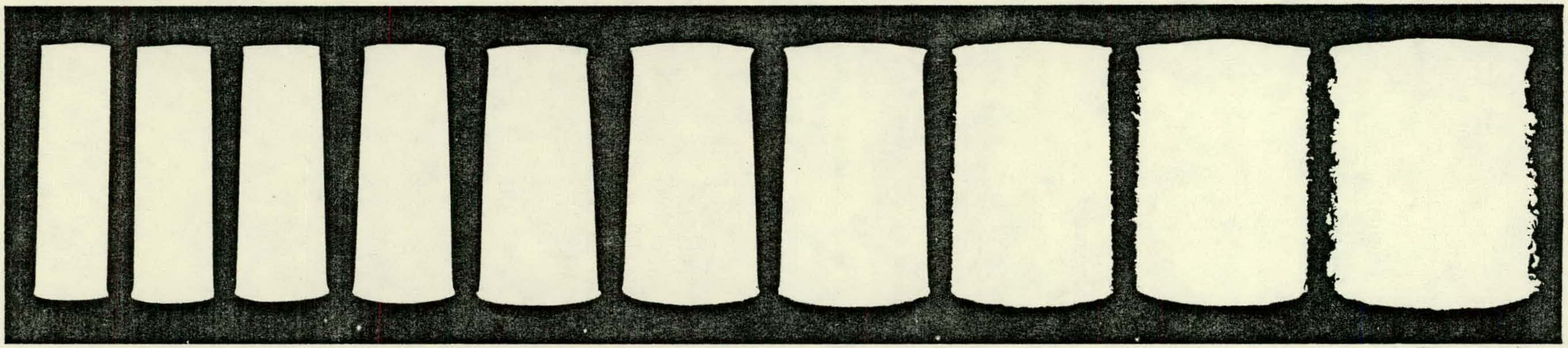

Fig. 4 The transition from natural-convection-controlled freezing to conduction-controlled freezing

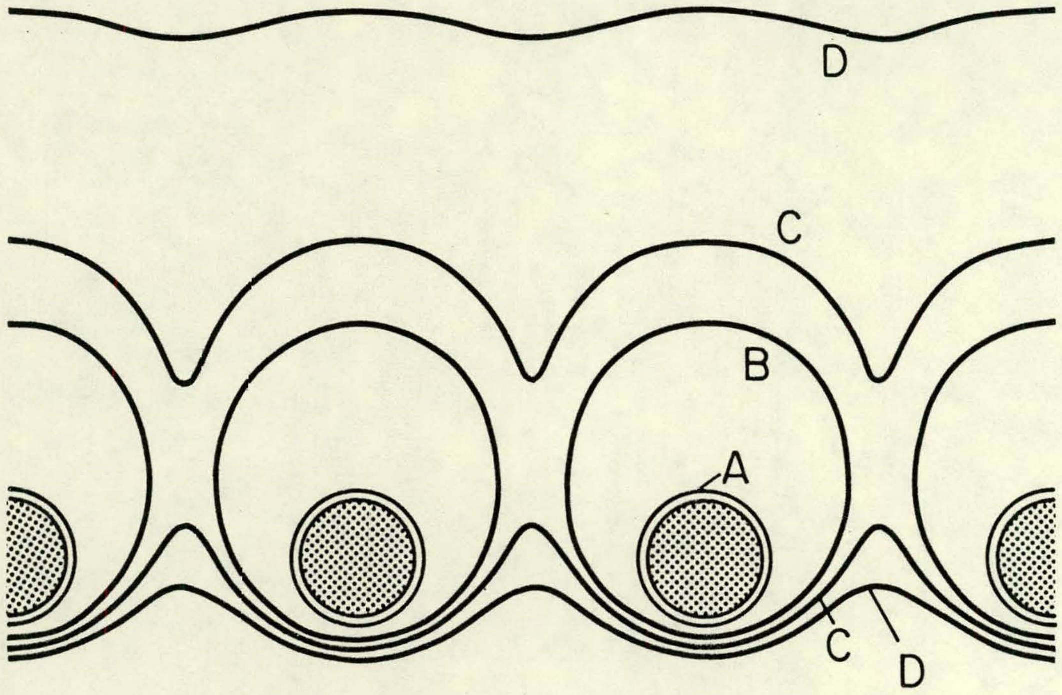

Fig. 5 Timewise evolution of melt zone