CR-102782

RESEARCH IN PHASE CHANGE THERMAL CONTROL TECHNOLOGY

(TOTAL PROGRAM SUMMARY REPORT)

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ANNUAL SUMMARY REPORT NO. 1

CONTRACT NAS 8-30511

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21 NOVEMBER, 1968 - 31 DECEMBER, 1969

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FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER

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PREFACE

This report was prepared by the Colorado School of Mines, Golden, Colorado, under Contract NAS 8-30511 "Research in Phase Change Thermal Control Technology" and under Colorado School of Mines Foundation Contracts E6911 and F6915. The work was administered under the direction of the Space Sciences Laboratory, George C. Marshall Space Flight Center, with Mr. T. C. Bannister acting as the contracting officer's technical representative. This report covers work from 21 November 1968 to 31 December 1969. The work at the Colorado School of Mines was under the direction of Drs. J. O. Golden and F. J. Stermole.

ABSTRACT

This report presents a summary of a program of research in phase change thermal control technology conducted at the Colorado School of Mines under NASA sponsorship. Phase change thermal control involves the idea of using the heat associated with the melting process (solid-liquid phase transition) to absorb excess thermal energy of a thermally sensitive component. Conversely, with a properly designed device, the component can be held below a prescribed temperature bound by using the heat of fusion of a given material to release energy to the component. Three separate but related phase change studies are summarized. They are:

(1) A study of the unsteady state temperature response of a phase change test cell with emphasis on the gravity induced free convection effects

(2) A microscopic and thermal study of the solidification of hexadecane

(3) A study of the thermal modeling of the solidification process for a phase change test cell.

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1.0 INTRODUCTION

In recent years the concept of using the heat associated with the solid-liquid phase transition of a number of materials has received increasing attention as an attractive thermal control concept. This concept involves the idea of using the heat associated with the melting process of a given material to absorb the excess thermal energy of a thermally sensitive component. With a properly designed device, the component can be held below a prescribed temperature bound. Conversely, the component temperature could be held above a prescribed temperature bound by using the heat of fusion of a given material to release energy to the component.

This concept, phase change thermal control, is particularly attractive for use in spacecraft thermal control problems from the standpoint that it is a passive system (requires no moving parts) and, therefore, should have a high reliability. However, a number of points require further investigation before phase change thermal control can be applied to spacecraft problems. One point in question is: What effect does the space environment have on the melting or solidification of the phase change material?

In attempting to answer the previous question and to understand the behavior and performance of candidate phase change materials, the following problems immediately arise:

understanding the solidification process,

understanding the melting process,

understanding the crystallization process, and what is the role of various forms of convection in the phase change devices.

Therefore, if phase change thermal control is to be applied as an engineering solution to spacecraft thermal control problems, the above problems must be attacked and some degree of solution obtained. Only when we have a clear understanding of the science involved in the above processes can we reliably predict performance in a space environment for a variety of situations. With this understanding, phase change thermal control can then be used with confidence for spacecraft problem solution.

Therefore, the goal of this research program is a continued attack on the problems mentioned in the previous paragraph. Specifically, three related but separate investigations were undertaken. They were:

(1) A study of the unsteady state temperature response of a phase change test cell with emphasis on the gravity induced free convection effects

(2) A microscopic and thermal study of the solidification of hexadecane

(3) A study of the thermal modeling of the solidification process for a phase change test cell.*

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* Upon agreement of the NASA technical representative, this study was undertaken in place of the original study specified in the scope of work (the original study dealt with a search for new phase change materials).

The results of all three studies are presented in separate reports which are companion documents to this summary report (see References 1, 2, and 3). A brief summary of the purpose, results, and conclusions of each study is presented in the next three sections of this report.

2.0 UNSTEADY STATE TEMPERATURE DISTRIBUTION STUDY

2.1 Purpose

The goal of this investigation is both a theoretical and experimental investigation of the role of natural convection in phase change thermal control devices. Although many studies of natural convection have been conducted in the past using fixed geometry systems, the problem of convection with a receeding solid-liquid interface is not well understood. Only when natural convection effects can be predicted on earth, can we then evaluate the behavior of phase change devices in the space environment with natural convection reduced or absent. Further, the nature of the crystal growth is tied to convection effects from a physical and thermal viewpoint. Therefore, the purpose of this investigation was to verify experimentally a theoretical model for the natural convection process in a phase change test cell undergoing melting.

2.2 Results

Six experimental runs were conducted using a small phase change test cell with thermocouples mounted both inside and in the top and bottom of the cell. By following individual thermocouple response while the bottom of the cell was heated, the movement of the solid-liquid interface and temperatures at given positions in both the solid and liquid could be tracked. This information was then used to test the validity of the theoretical model for the melting process and the natural convection phenomena. The phase change material used in this investigation was n-octadecane, a candidate material for phase change thermal control.

The mathematical model developed for the melting and natural convection process was rather complex (see Reference 1 for details) and consisted of a solution for both the pure conduction process period (before the initiation of melting) and a solution for the combined conduction and convection process (after melting is started). The pure conduction problem was attached by a straight forward finite difference numerical solution technique for the solution of the energy equation. However, the combined conduction and convection problem involved the simultaneous solution of the conservation equations of fluid mechanics in two spatial dimensions and necessitated a sophisticated mathematical formulation followed by a finite difference solution of the resulting equations. The mathematical analysis used in this investigation was patterned after that used by Wilkes and Churchill (Reference 4) who achieved a convection solution for a fixed geometry system. However, in this study, the geometry is not fixed (the interface is moving) and therefore, the problem is more complex.

The principal investigators recognized in the beginning of this study that the numerical solution to this problem was difficult. However, numerical difficulties for the digital computer solution to this problem have been far greater than anticipated and, as yet the digital computer program for the convection problem is not working. Therefore, no comparison between theory and experiment has been performed for the convection problem. We anticipate at the present that the model will work as soon as the numerical problems are solved. Once the model is completed and evaluated, useful predictions for other phase change problems can then be made. A revised technical report (Reference 1) will be issued upon completion of the theoretical work in this study (approximately April 1970).

2.3 Conclusions

Based upon the experimental and theoretical results of this study the following conclusions are presented:

(1) The theoretical model for the conduction problem (before the initiation of melting) agrees reasonably well with the experimental data

(2) Examination of the experimental data indicates that natural convection sharply influences temperature profiles in the phase change cell.

3.0 MICROSCOPIC INVESTIGATION OF THE SOLIDIFICATION OF HEXADECANE

3.1 Purpose

The interest in the n-paraffins as potential candidate phase change thermal control materials necessitates a detailed understanding of their solidification processes both on earth and in space. Previous work in the phase change crystallization area had pointed to microphotography as one good method for evaluating the crystallization processes. Therefore, the goal of this investigation was two fold:

(1) Develop an improved microphotography apparatus for observing the phase change process

(2) Perform meaningful studies on the crystallization dynamics of the solidification of the n-paraffins.

In regard to the first goal, one author had the opportunity to spend two summers at NASA/MSFC on a NASA/ASEE Summer Faculty Fellowship Program working with Mr. Tommy Bannister and Miss Barbara Richard (Reference 5) in the microphotography area. Based upon his research using the equipment developed at MSFC, a number of equipment improvements were apparent if a new microphotography apparatus was developed. In particular, variable magnification and more flexible sample holders potentially improve any further microphotography experiments.

In regard to the second goal, a decision was made to study in detail the crystallization of hexadecane. The purpose was to gain quantitative information and understanding of the behavior of one material rather than a brief study of many.

The microphotography study was carried out by photographing the formation and growth of the solid interface in a small test cell. By varying the cooling rate to the bottom of the test cell, one could then vary the growth rate of the solid-liquid interface and thus the type of crystals produced.

3.2 Results

A total of seven runs were analyzed using the improved microphotography equipment to view the solidification process. On each run the following data were obtained:

(1) Temperature versus time behavior for each thermocouple in the test cell

(2) Average solid interface velocity versus time

(3) Average peak height (a measure of the distance that certain crystals led the solid interface) versus time

(4) Individual crystal growth rates versus time

(5) Qualitative observations on crystal morphology throughout the run.

The reader is referred to Reference 2 for precise definition and explanation of the above terms and a report of the total investigation.

3.3 Conclusions

The following conclusions are presented based upon the results of this investigation:

(1) The development of an improved microphotography apparatus was successful.

(2) The slope of the temperature versus time curve flattens as the interface approaches the thermocouple.

(3) The average interface velocity decreases with increasing run time or as the interface moves away from the heat sink.

(4) The variation of peak height with run time is linear up to the region near the first thermocouple. Near the region of the thermocouple, peak height is reduced and then increases as the interface moves away from the thermocouple.

(5) The maximum peak height between various runs increases as the crystal growth rate increases.

(6) Individual crystal growth rates may be as much as 2.5 to 3.0 times the average interface velocity at a given time during a run.

(7) The solid interface takes on a variety of geometrical shapes depending upon a number of conditions. In particular, heat transfer considerations (interface near a high thermal conductivity thermocouple) perturbs the interface geometry. Thorn-like crystals are only observed after the initial growth period.

4.0 SOLIDIFICATION PHENOMENA STUDY

4.1 Purpose

The goal of this investigation was to contribute to the understanding of solidification phenomena as it affects the performance and suitability of phase change materials in thermal control devices. Specifically, the goal was to develop and evaluate a one-dimensional theoretical model for the solidification of a n-paraffin. The essential features of the model involved a finite difference solution of the two-phase heat-conduction equations with moving interface and variable boundary conditions. Constant physical properties were assumed for each phase although the properties varied from one phase to another. The present model neglected the effects of convection, supercooling and nucleation phenomena.

4.2 Results

An experimental system was designed and fabricated to test the validity of the proposed theoretical model. The system consisted of a rectangular cell which was filled with hexadecane ($n - C_{16}H_{34}$). The cell was cooled from the bottom (minimizing convection effects) by a refrigeration system and the solidification process was followed by the response of thermocouples positioned in the cell. This data (temperature versus time and position in the cell) were then compared to theoretical model predictions. A total of six experimental runs were performed to test the model validity. (See Reference

3 for both theoretical and experimental details of this study.)

4.3 Conclusions

Based upon the results of this investigation, the following conclusions are presented:

(1) Good agreement between the theoretical model and experimental results was observed, although a slightly faster rate of solidification was predicted theoretically.

(2) The numerical technique developed in this study has certain advantages for the solution of freezing problems over other published methods in terms of computer time required and minimization of computer memory required.

(3) The numerical technique used in this study has the disadvantage of being approximate in that heat losses were neglected in two dimensions and convection, supercooling and nucleation effects were ignored.

5.0 FUTURE EFFORT

Based upon the results of this program of research, the principal investigators recommend the following research areas for investigation during the coming year:

(1) An experimental and theoretical investigation of the effects of natural convection upon solidification phenomena

(2) An evaluation of the effects of vibration upon both melting and solidification phenomena

(3) A detailed experimental investigation of individual crystal growth in a phase change cell using microphotography techniques

(4) A theoretical and experimental investigation of both natural convection and convection driven by interfacial tension during the melting process in an improved phase change test cell.

The above investigations are logical extensions of this research program and would serve to enhance our scientific and engineering understanding of phase change thermal control technology.

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