DEVELOPMENT OF ENHANCED HEAT TRANSFER/ TRANSPORT/STORAGE SLURRIES FOR THERMAL-SYSTEM IMPROVEMENT

by

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NOMENCLATURE ▶

Nomenclature

A	surface area of heat exchanger
C_p	specific heat
d	particle diameter
e	local flow shear rate
h	fluid/wall heat transfer coefficient
K, K_{mol}	single phase fluid molecular thermal conductivity
K_{eff}	effective thermal conductivity of slurry
$\dot{m}, \dot{M}$	mass flowrate
P	pumping power
ΔP	thermal system pressure drop
Q	storage tank heat loss to ambient
q_{in}, q_{out}	source and sink thermal energy transfer
ΔT_{tot}	source-to-sink total temperature difference
T	temperature
U	flow velocity of slurry

Nondimensional Parameters

C_f	flow frictional loss coefficient
Nu	Nusselt number
Pe	particle Peclet number
Pr	Prandtl number
Re	Reynolds number
ϕ	volume fraction loading of particles in carrier fluid

Greek Symbols

α	thermal diffusivity of the carrier fluid
λ	latent heat of fusion of phase change particles
μ	viscosity of carrier fluid

Subscripts

c	denotes conditions at cold thermal sink
h	denotes conditions at hot thermal source
PC	denotes conditions of phase change slurry
S	denotes conditions of single phase working fluid
W	denotes conditions of heat transfer surface
∞	denotes conditions away from the surface
1,2,..4	denotes conditions on thermal system diagram

Development of Enhanced Heat Transfer/Transport/
Storage Slurries for Thermal System Improvement

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ABSTRACT

This report constitutes a formulation of a new concept for improving thermal-system performance by utilizing the combined mechanisms of enhanced heat transfer, transport, and thermal energy storage associated with a phase-change slurry as the working fluid. In addition, pertinent literature is surveyed and a quantitative scoping assessment of enhancement potential confirms concept merit. It has been determined that additional research and development is required in order to adequately understand the enhancement mechanisms to the degree that enhanced performance thermal systems using slurries can be designed. The concepts presented are identified as being new, rewarding research activities. This report satisifes a commitment A. R. Valentino (ANL/EES) has to the DOE, Conservation, to identify new promising research activities.

1. INTRODUCTION

1.1 Thermal System Improvement Concepts

In industry the transfer of thermal energy from a heat source to a heat sink or a storage medium using a working fluid is a commonly occurring situation, whether related to front end heat utilization or waste-heat recovery. Currently, various efforts related to improving thermal-energy storage are underway. Some of these activities are exploring the use of eutectic salts and other change-of-phase mediums (solid $\updownarrow$ liquid) to increase the ratio of energy stored per mass of substance. Of much broader scope and more basic to achieving an optimum heat-transfer system design, the thermal-hydraulics of the entire system must be studied as a result of the strong coupling between the heat source, transport, and storage operations.

Specifically, it is felt that combined utilization of the phenomenon of increased energy transport due to the phase transition of an immiscible change-of-phase additive to a carrier fluid (slurry) with the recently recognized phenomenon of enhanced heat transfer at a surface due to particle/fluid boundary-layer interaction could be used to enhance overall thermal system performance. The enhancement would also be realized in conjunction with thermal systems employing direct-contact heat exchangers. Some specific benefits accruable from using phase-change slurries in thermal systems rather than single-phase sensible heat fluids are:

a. Increased fluid/solid surface heat-transfer coefficients resulting from several mechanisms. This will reduce the temperature difference required for a given amount of heat-transfer and allow reductions in heat transfer surface areas.

b. Increased heat capacity of the heat-transfer fluid, due to the latent heat of the fusable material in suspension. This will result in reduced flow rate, and, hence, reduced pumping power.

c. Improved quality of usable thermal energy. The working fluid end-use temperature will be closer to the heat-source temperature.

d. Improved adaptibility of an integral storage concept employing a fusable material accumulator to a thermal system. In the storage accumulator the fusable material is stored at a higher concentration (at volume fractions of 0.6-0.8) than that of the circulating suspension (with

volume fractions in the vicinity of 0.3). In this way the temperature drop associated with heat transfer to and from a stationary storage material is eliminated. Furthermore, the size of the storage tank, and accordingly the heat loss from the storage tank, would be substantially smaller than that associated with sensible heat storage.

1.2 Overview of Related Efforts

Thus far, most of the investigations related to improving the performance of a thermal system have focused on improving the storage of thermal energy (i.e., maximizing thermal energy stored per mass of storage medium). None of the efforts to date have used the proposed slurry heat transfer enhancement mechanism for improving system performance. Many interesting concepts have been proposed and examined. One of the most prevailing themes of the various energy-storage concepts involves the use of phase-change materials with large latent heat of fusion. The phase-change materials employed include organic compounds and salt hydrates at moderate temperatures, and inorganic compounds, pure salts, and eutectic mixtures at higher temperatures. Much effort has also been focused on containerizing the phase-change material to improve handling and on techniques for preventing the separation of constituents in the case of hydrates or other mixtures. The majority of these studies employed stationary energy-storage materials. For the most part, the collection and delivery of heat to the storage tank is accomplished by single-phase transfer fluids. However, a few studies do propose the use of transported phase-change materials in order to facilitate the heat-storage processes.

A brief sampling of some of the recent work related to thermal-system improvement through energy-storage improvement and minor variations upon this theme follows. Typical of the many activities related to solely improving energy storage are the works of Refs. 1-4. Reference 1 explored the usage of salt-hydrate storage in conjunction with solar collector/home energy storage. Static tanks of the phase-change medium were used. Many of these type activities experienced difficulties in obtaining full latent heat of fusion during phase transition due to phase separation. Reference 2 typifies various attempts at trying to improve phase transition efficiency and reliability of the salt hydrates. In this effort, mechanical agitation of the

entire storage tank was used to minimize phase separation and improve recrystalization during thermal cycling of the tank. Reference 2 reports success in improving reliability of the salt-hydrate storage medium. Other efforts have similarly used pumps or stirrers in storage tanks to improve phase transition efficiency. Of importance relative to the concept of using phase-change slurries for improving heat transfer, it is learned from the studies of static storage tanks that difficulties in obtaining complete phase transition may not be as great with hydrate slurries because of the agitation associated with pumping the slurry past a heat-transfer surface. References 3-4 report on efforts to develop carbonate magnesium oxide composites and ice solar storage, respectively. Both of these studies involve static thermal energy storage improvement.

Finally, Ref. 5 explored using thermal-energy storage as a means of load leveling for utility applications. One proposed scheme for utility storage used fluoride salts in conjunction with molten lead in droplet form passing through the storage tank to extract heat. This effort differs from the previous static tank phase-change applications by virtue of the direct-contact heat transfer employed for storage-tank heat extraction. However, again the phase-change medium was not used as the working fluid in the entire system as is proposed in this paper, in order to take advantage of enhanced heat transfer.

References 6 and 7 reflect work analogous to that of Ref. 5. Direct-contact heat transfer with a single-phase working fluid was used to remove or supply thermal energy to a phase-change medium stored in a tank. Reference 7 is somewhat unusual in that water evaporating directly from a salt-hydrate solution was used to cool the storage tank.

References 8 and 9, which are preliminary conceptual design-paper studies, represent the very limited efforts which have used a slurry to move energy around a thermal system. However, these studies do not recognize or take advantage of the working fluid/solid surface heat-transfer enhancement obtainable by using a phase-change slurry working fluid to increase surface heat-transfer coefficient. Reference 8 utilized silica-glass in the molten or bead form in conjunction with direct-contact heat transfer with an air stream to move the thermal energy from a 100-MW solar-power-plant solar collector to a molten-glass storage tank. No slurry/solid surface heat exchangers were used in this study, nor is glass classified as a phase-change medium having a

latent heat of fusion. Reference 9 explores using an encapsulated salt-hydrate carried by a slurry to transport and collect thermal energy from a fluidized bed heat source and sink in conjunction with a molten-pellet storage tank. The encapsulation is used to eliminate the corrosion and surface-coating problem associated with the salt-hydrates. However, depending on how closely the envisioned metallically encapsulated phase-change medium's density matches that of the carrier fluid, very high transport velocity may be required to maintain the capsules in suspension, especially during start-up of the system. Furthermore, pump action, capsule/capsule impact, and abrasive wear may shorten capsule life. Finally, as for Ref. 7, no slurry/solid surface heat transfer was employed in this study, only fluidized heat source/sink heat exchangers. Hence, the general concept is not amenable to the vast majority of thermal systems which employ or require heat transfer through a fluid/solid surface interface.

In summary, the concept of thermal system performance enhancement utilizing phase-change slurries to increase surface heat transfer is new and unique.

1.3 Report Contents

The following sections of this report present information on the fundamental enhancement mechanisms that are present when phase-change slurries are used as the working fluid in a thermal system and present scoping estimates of the enhancement which may be obtainable in terms of thermal system performance. Section 2 describes the various enhancement mechanisms and defines the state of the knowledge relative to understanding these mechanisms. Section 3 presents results from a quantitative scoping assessment which compares a phase-change slurry thermal system performance with that of a conventional single-phase working fluid. This section clearly demonstrates the merits of the phase-change-slurry enhanced heat-transfer concept. Section 4 surveys the large number of phase-change mediums which are possible candidates for designing slurries for various applications and discusses some of the criteria which are important in the design process. Finally, Sec. 5 summarizes the findings of this report.

2. ENHANCEMENT MECHANISMS

Because of the complexity of the phenomenology involved, thus far the major portion of the research effort in multiphase flows (slurries) has been focused on the fluid mechanics and rheological properties of the slurries, References 10 and 11 summarize some of these efforts. Systematic studies on heat and other transport processes are relatively scarce by comparison. Nevertheless, the literature contains repeated indications that with multiphase fluids the transport processes are significantly enhanced in comparison with single-phase flows. However, since the mechanisms of the enhancement are not well understood and reproducible data are scarce, there has been little or no attempt at taking advantage of these high transport rates in engineering systems. This picture, however, is gradually changing. A number of the mechanisms are now qualitatively, or even partially quantitatively, understood. Therefore, practical exploitation of these mechanisms to obtain thermal system improved heat-transfer performance can now proceed. The enhancement mechanisms and related literature are discussed in this section.

2.1 Microconvective Enhancement of the Bulk Transport Properties

The realization that the bulk transport properties, including mass diffusivity and thermal conductivity, can be significantly enhanced in slurries first arose in the study of transport processes in blood, relevant to the research on cardiovascular diseases and the development of artificial organs. These works consist of studies on platelet diffusion (Refs. 12-14), solute transport (Refs. 12, 15-17), and heat transfer (Ref. 18). Some of these data were obtained with particle suspensions as blood simulants or on blood itself. Particle self-diffusion coefficients were also studied in Ref. 19. Enhancements up to two orders of magnitude were reported. However, because the experiments were often conducted under rather trying conditions, there were considerable data scatter and disagreement. Nevertheless, it is generally agreed that the enhancement was due to the microscopic stirring motion of the particles in the shearing flow field. Theoretically, the problem is quite difficult and rigorous analyses exist for the special case of very dilute suspensions (Refs. 20 and 21). Note also that most theoretical

and experimental studies have focused on laminar flows in conjunction with simple geometries. While the developed theories do show enhanced transport properties, the results apply only to unrealistically dilute suspensions and cannot be extrapolated to the high concentrations most suitable to improving thermal-system performance. Simple model considerations (Refs. 12, 22 and 23) on the other hand, suggest that the enhancement would be insignificant if the Peclet number for particle rotation, $Pe = ed^2/\alpha$, is small. Here e is the local shear rate, d the particle diamter, and α the heat diffusivity of the carrier fluid. For high Peclet numbers, the models suggest correlations of the form

$$k_{eff}/k_{mol} = Ce^n, \tag{1}$$

where the left-hand side is the ratio of the effective slurry thermal conductivity to that of pure molecular conduction associated with the single-phase carrier fluid. The exponent n has been variously assessed values between 1/3 and 1. Although the limited data sets available exhibit power-law behaviors, the scatter and disagreement among the data do not permit the determination of either the coefficient C or the exponent n.

In a more careful study, Ref. 24 recently obtained relatively scatter-free and reproducible data for suspensions of polyethylene and polystyrene particles for the Peclet number range 0.1-2500. The data showed that for Pe below 100, the enhancement was insignificant. For Pe >500, the data approached a power law with n = 0.5. In an effort to explain the results of Ref. 24, Ref. 25 recently developed a model for the microconvective effects associated with particles rotating in laminar shear flow. The results were in agreement with the earlier experimental data. The qualitative agreement between the theory and the observed results is encouraging, in that it supports the physical mechanisms assumed in the model. The quantitative agreement, however, was probably fortuitous, because of the crudeness of the model. A number of potentially important phenomena were not accounted for, including particle-particle collisions, particle behavior in turbulent flow, and the role of the so-called particle depletion layer near a wall. Speculations on the role of the particle depletion layer in influencing the heat transfer coefficient can be found in Ref. [15].

It is clear that both more refined theoretical and experimental studies covering ranges of conditions, slurries, and geometries more typical of those likely to be used in engineering thermal systems are needed. Additionally, the work to date deals with slurries not using phase-change materials.

2.2 Slurry Heat Transfer in Laminar Pipe Flow without Phase Change

The heat-transfer coefficient for laminar flow is intimately related to the molecular thermal conductivity of the flow. Therefore, the enhancement of thermal conductivity by microconvection would lead directly to an increased heat-transfer coefficient. Indeed, at least one early study of enhanced thermal conductivity contained in Refs. 18 and 26 was actually based on measurements of enhanced heat transfer coefficients. The data were then used to compute the effective thermal conductivity employing the theoretical relationship between the thermal conductivity and heat-transfer coefficient for the so-called Graetz problem. Reference 27 pointed out, however, that since the results of Ref. 26 showed that the conductivity was shear-rate dependent, hence, radius-dependent, whereas the theoretical solution employed was for uniform conductivity, the data-reduction procedure for determining thermal conductivity was not self-consistent. The data on enhanced heat-transfer coefficient, however, clearly indicated enhancement was realizable in practice.

In an effort to assess the role of shear-enhanced thermal conductivity on the enhancement of the heat-transfer coefficient, Ref. 27 carried out theoretical analyses for the heat-transfer coefficient for laminar pipe flows of a Newtonian medium with a shear-dependent thermal conductivity. This analysis showed that significant enhancement of the heat-transfer coefficients could be achieved in laminar pipe flows. Unfortunately, reliable experimental data are not available for checking this result.

As an example of the potential increased heat transfer that could be accrued from non-phase-change slurries in laminar pipe flows, Table 1 shows the enhancement ratios for the conductivity and heat transfer coefficient estimated from the above theories.

It is seen that there is a potential for very significant enhancement to be achieved. For example, a 30-fold increase in the effective thermal

Table 1. Theoretical Enhancement Ratios for Thermal Conductivity
and Heat-transfer Coefficients in Slurry Flow in Pipes
without Phase Change

				Heat-transfer Coefficient Enhancement Ratios					
Velocity, m/s	Particle Diameter, mm	Thermal Conductivity Enhancement Ratios[a]		Laminar Thermal Entrance[b]		Laminar Fully Developed[b]		Turbulent Fully Developed[c]	
		3-mm-dia tube	10-mm-dia tube	3-mm-dia tube	10-mm-dia tube	3-mm-dia tube	10-mm-dia tube	3-mm-dia tube	10-mm-dia tube
0.1	0.1	—	—	—	—	—	—	—	—
	0.3	<2	—	<1.6	—	<2	—	<1.6	—
	1	5.5	3.0	3.1	2.1	5.5	3.0	3.1	2.1
1	0.1	<2	—	<1.6	—	<2	—	<1.6	—
	0.3	5.2	2.8	3.0	2.0	5.2	2.8	3.0	2.0
	1	17	9.5	6.7	4.5	17	9.5	6.7	4.5
10	0.1	5.5	3.0	3.1	2.1	5.5	3.0	3.1	2.1
	0.3	16	9	6.5	4.3	16	9	6.5	4.3
	1	55	30	14	10	55	30	14	10

[a] Based on the theory of Ref. 25 and the extrapolation of the data of Ref. 24.

[b] Based on sources cited in footnote a and the theory of Ref. 27.

[c] Based on the assumption that the particle diameters are small relative to the laminar sublayer and that the slurry behaves as asingle-phase fluid of similar bulk properties. See Eq. 3.

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conductivity and a 10-fold increase of the heat-transfer coefficient are predicted for a 30% suspension of 1-mm particles in a 10-mm-diameter pipe at an average velocity of 10 m/s. A 10-fold enhancement of conductivity and a 5-fold enhancement of heat transfer could be obtained even at the modest velocity of 1 m/s. Whether these predicted enhancement ratios could be realized in practice is a tantalizing question which can only be answered with further experimental investigations. The column for turbulent flow represents only a conjecture as to what the enhancement would be. Heat-transfer enhancement in turbulent flow will be discussed in some detail in the next subsection.

2.3 Turbulent Heat Transfer in Slurries without Phase Change

Heat-transfer phenomenology for turbulent slurry flow is considerably more complex than for laminar flow, and even less well understood. It can be expected that migration of particles in the boundary layer or shear zone adjacent to a surface (see Fig. 1) aids in disrupting the laminar sublayer and would significantly increase the heat transfer-rate. However, the precise role of the phenomena involved has not been clarified. For example, the influence of the possible lack of thermal equilibrium between the phases near heat-transfer surfaces is unclear. In general, the important parameters influencing heat transfer are:

   a. the particle type and size distribution,

   b. the thermal properties of the particles and the carrier fluid,

   c. the near-surface flow shear rate, and

   d. the surface-geometry orientation relative to the direction of flow.

In the absence of theoretical understanding, the following simple arguments drawing strongly on single-phase turbulent-flow understanding provide an instructive but possibly incomplete picture of heat-transfer enhancement in turbulent slurry flows.

For single-phase turbulent flows, the dependence of the heat-transfer coefficient on physical properties can be examined semi-quantitatively from the well-known Sieder-Tate equation
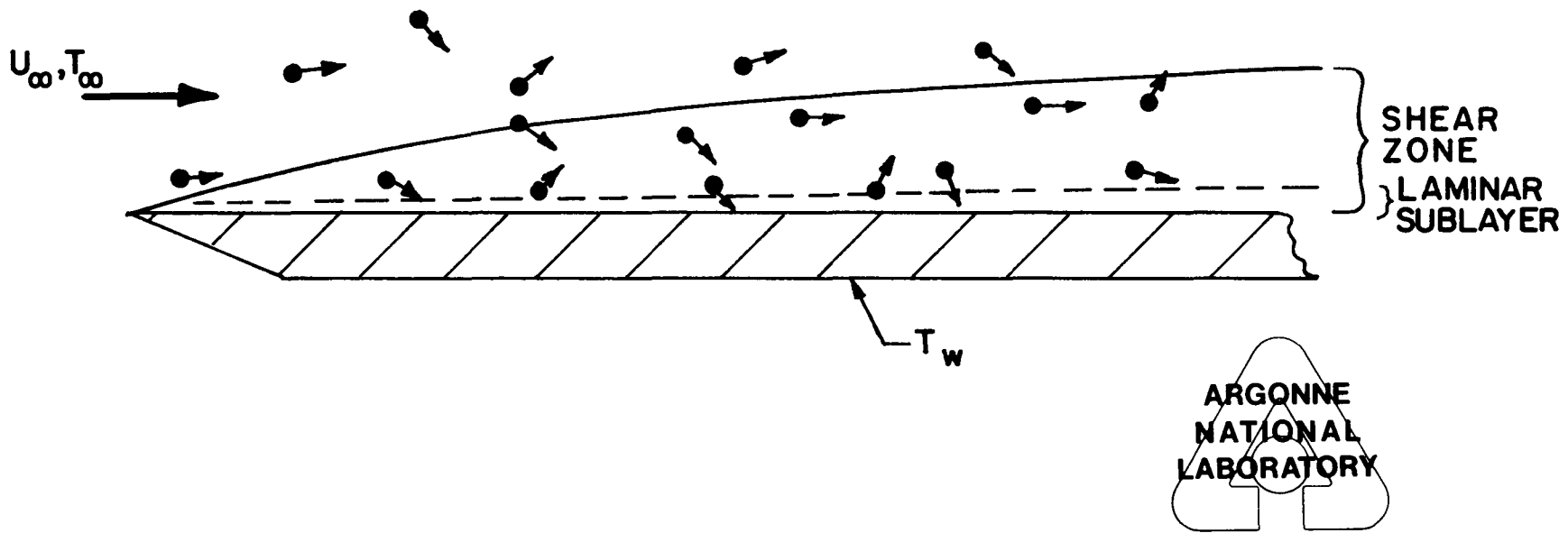
Fig. 1. Simplified Model of Turbulent Slurry Flow over a Surface

$$Nu = 0.023Re^{0.8}Pr^{1/3}, \tag{2}$$

whence

$$h \propto k^{2/3} c_p^{1/3} U^{0.8} \mu^{-0.467}. \tag{3}$$

In other words, the heat-transfer coefficient, h, is proportional to the 2/3 power of the thermal conductivity, k, and for future discussion to the 1/3 power of the specific heat, C_p. Concentrated suspensions whose particle diameters are small relative to the turbulent eddy sizes and the laminar sublayer thickness are expected to behave as single-phase fluids. Therefore, it might be expected that the heat-transfer coefficient would increase with the effective slurry conductivity, k_{eff}, replacing k in Eq. 3, according to the influence of the local shear rates involved, especially the shear rate in the laminar sublayer (see Fig. 1). For suspensions whose particle diameters are large relative to the laminar sublayer, this simple picture is inadequate. In either case, experimental data are needed to guide development and verify theoretical predictions, or to provide empirical or semiempirical correlations where theoretical predictions are not feasible. Such turbulent data, unfortunately, are extremely limited.

A number of studies of dilute slurries, many involving gas-solid suspensions, were reviewed in Ref. 10. A theoretical study of dilute slurries, based on the eddy-conductivity concept, was carried out in Ref. 28. The heat-transfer coefficient was found to increase in some cases, and decrease in others. There are reasons to believe, however, that the results cannot be extrapolated to the concentrated mixtures of interest here.

Two experimental studies that are reasonably close to the concentrated two phase slurry of current interest are those in Refs. 29 and 30. These investigators measured the heat-transfer coefficient for both laminar and turbulent flow in a water-oil slurry. Enhancements of up to 60% were observed, at oil concentrations of 20-30%. Above this concentration the heat-transfer coefficient was found to decrease, probably as a result of the lower specific heat, lower thermal conductivity, and higher viscosity of the oil. Unfortunately, oil droplet-size distribution was apparently not determined. Therefore, it is not possible to compare these results with those to be expected from conductivity enhancement. Finally, a 2 1/2- to 3-fold

enhancement of heat transfer was reported in Ref. 35 for solid slurries, but the exact conditions of the study were not reported.

2.4 Heat-transfer Enhancement Due to Phase Change

Reference 31 reports on a preliminary scoping investigation into the use of phase-change laminar slurries for obtaining heat-transfer enhancement. No other phase-change slurry information was found in the literature. It was argued that since the heat-transfer coefficient increases as the 1/3 power of the specific heat for either laminar flow or turbulent flow (see Eq. 3 above), and since the latent heat of the phase-change medium can be viewed as a form of specific heat with a Delta-function behavior, the use of a fusable suspension with the melting point inside the range of the imposed thermal-system temperature difference would increase the heat-transfer coefficient. It was further shown that for <u>laminar</u> boundary layers with thermal equilibrium between the phases of a slurry the enhancement ratio for the heat-transfer coefficient is

$$h_{pc}/h_s = (\phi \Delta H_{fg}/c_p T + 1)^{1/3}, \tag{4}$$

where ϕ is the volume fraction loading and ΔH_{fg} is the heat of fusion. This expression indicates that slurries using a phase-change medium have the potential for the greatest heat-transfer enhancement. Examination of Eq. 3 would suggest that turbulent heat transfer would behave in the same manner. To test the above result, a limited experimental study found that for paraffin particles suspended in water and a temperature difference in the 10-20°C range, a 3-fold enhancement of the heat-transfer coefficient was obtained.

2.5 Summary of Heat-transfer Enhancement

In summary, the existing literature surveyed clearly demonstrates that enhancement of heat transfer occurs with slurries, whether or not phase change is involved. The enhancement is seen to be potentially greatest when a phase-change slurry is involved. Several mechanisms responsible for this enhancement were examined, including particle rotation in shear flow, particle migration in laminar and turbulent flows, and the role of latent heat in

increasing the heat-transfer coefficient. The existing data, however, were found to be quite incomplete for laminar flows and almost completely lacking for turbulent flows, the most common situation in engineering practice. For none of the above flow cases are proven correlations available for engineering design of a thermal system employing slurries.

In view of the great potential for increasing heat transfer in thermal systems and the lack of understanding found to exist, more systematic studies are necessary to permit implementation of the heat-transfer enhancement mechanisms.

The next section evaluates thermal-system benefits accruable from using a phase-change slurry as the working fluid and compares the performance with that of an identical system using a single-phase sensible heat-working fluid.

3. ESTIMATES OF POTENTIAL THERMAL SYSTEM BENEFITS

The previous section explored the prospects for increased heat-transfer coefficients from the use of phase-change slurries as heat-transfer fluids. In this section, potential system benefits that could result from the higher heat capacity and heat-transfer performance of a phase-change slurry will be illustrated by comparing its performance against a system using a conventional single-phase working fluid. The benefits to be considered will include:

a. Reductions in source-sink temperature difference; hence, the improvement of the quality of the delivered energy.

b. Potential reductions in coolant flow rate and, hence, the pumping power.

c. Potential reductions in storage tank capacity and, hence, storage-tank heat loss.

As the basis for comparison, we consider a conventional single-phase heat-transfer/storage-fluid operating between a source at temperature T_h and a sink at temperature T_c. A schematic of the system and the temperature distributions is shown in Fig. 2. The working fluid is heated from T_1 to T_2 at the source heat exchanger, and delivers the energy to the sink where it is cooled from T_3 to T_4. For simplicity, the temperature change between points 2 and 3 and that between 4 and 1 are neglected. It will also be assumed that both heat exchangers have been designed to have a heat-exchanger effectiveness

of 66.7%. This leads to the result that 50% of the total source-sink temperature difference is vested in the temperature drop ΔT_{fs} of the coolant fluid, and 25% vested in the temperature difference of each of the two heat exchangers, ΔT_{xs}. The subscript s in these and other variables indicates that they are for the sensible-heat single-phase coolant system.

In many of the comparisons to be made below, the specific heat, C_p, plays an important role. C_p = 1 Btu/lb$_m$°F is characteristic of water. However, for the temperature range of 300-800°F, which is encountered with many energy recovery and solar-energy applications, water is frequently not suitable due to the high vapor pressures, and synthetic coolants are often used. These coolants, including Monsanto Therminol 66, Dow Chemical Dowtherm A, Dupont Hitec, and Humble Oil Humbletherm 500 (Ref. 32), have specific heats in the range 0.4-0.7 Btu/lbm°F. Hence specific-heat values of 1.0 and 0.6 Btu/lbm°F are used in the comparisons to illustrate the C_p influence.

The thermal system illustrated in Fig. 2 is very general. The heat source, for example, could be any one of the many options listed below, all of which could be designed to use a phase-change slurry as the working fluid. The heat-source options include:

    (i)   Solid-surface heat exchangers, using a tube bundle or plate geometry.

    (ii)   Direct-contact heat exchangers, using no rigid fixed surfaces across which heat transfer takes place.

    (iii)   Electrical, induction, or acoustical heating of the working fluid.

    (iv)   Direct radiation absorption into the working fluid; for example, solar heating through a transparent barrier of a highly absorbent working fluid.

Various heat-sink options also exist. Some of these options are:

    (i)   Same as heat-source options (i) and (ii).

    (ii)   Pressure-controlled direct-slurry flash boiling for steam generation (a new concept proposed by us).

    (iii)   A heat sink interfaced with a thermal-storage module for intermittent or continuous use.

The slurry itself can use either a liquid or a gas as the carrier of the phase-change medium.
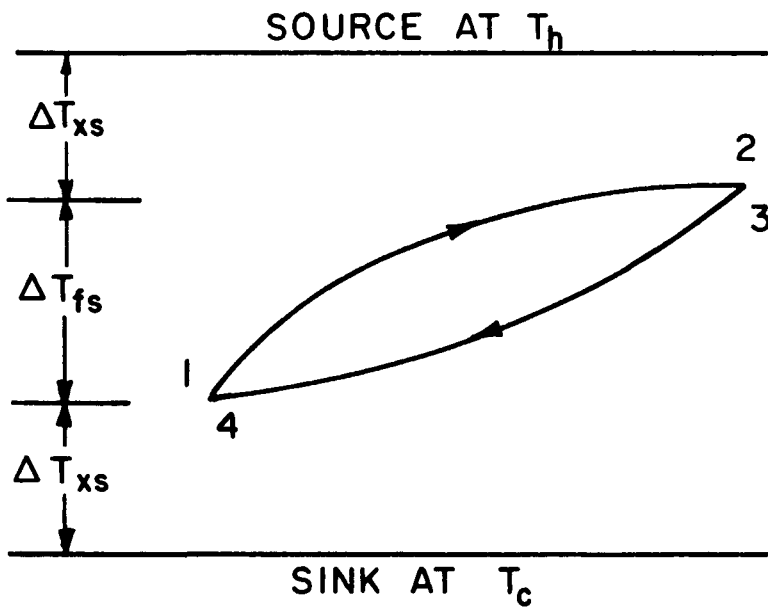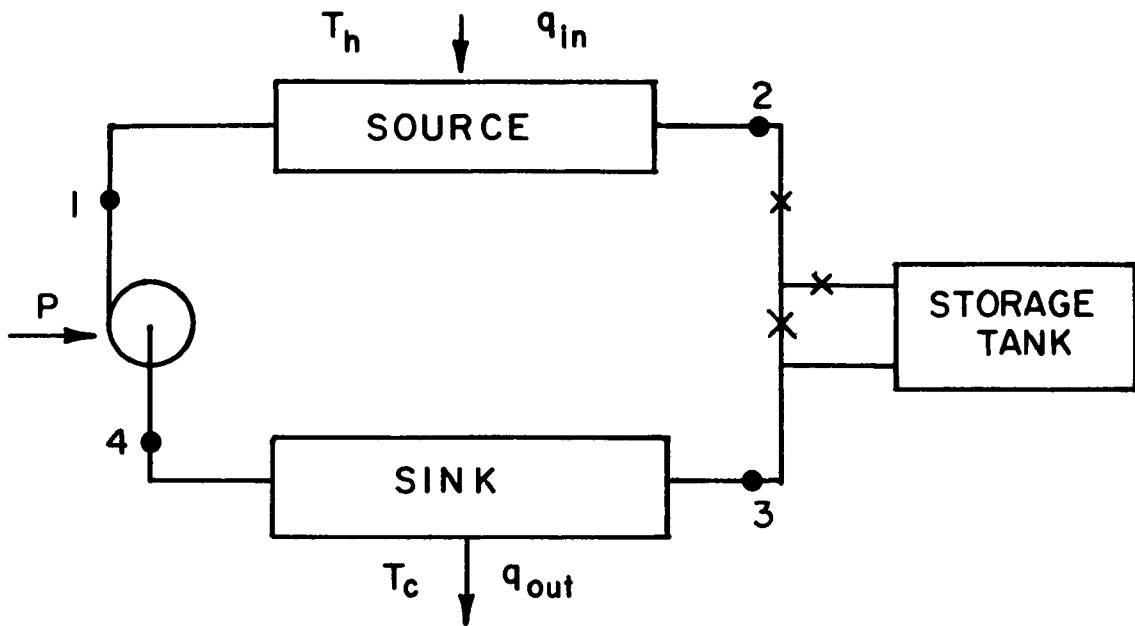
Fig. 2. Single-phase Thermal System Used for Comparison
with the Phase-change Slurry System

In general, which combination of options is used in a thermal system depends on the application. Furthermore, the options selected for a thermal system cannot be designed independently as a result of the strong coupling that exists between the heat source, the sink, and storage operations. This coupling exists in a conventional thermal system using a sensible-heat single-phase working fluid; however, it will be considerably stronger when using a phase-change slurry.

3.1 Source-sink Temperature-difference Reduction

The usefulness of thermal energy depends strongly on the temperature at which it can be delivered to the user. For this reason the reduction of the total source-sink temperature difference in an energy-storage or energy-recovery scheme is of great importance.

For this comparison, it is assumed that:

a. The phase-change slurry system has the same heat exchangers and the same mass flow rate as the benchmark sensible-heat single-phase system.

b. The heat-exchanger effectiveness for the phase-change system is the same as that of a single-phase heat exchanger with the same fluid heat capacity (latent heat plus sensible heat) and the same value of UA, the product of the overall heat-transfer coefficient and the heat- exchanger area.

c. There is a threefold enhancement of the heat-transfer coefficient, due to either the microconvection effect, the latent heat effect, or both. This is conservative in view of enhancement ratios discussed in Chapter 2 and shown in Table 1.

The comparison is shown in Fig. 3. It is seen that there is a significant reduction in the slurry-system overall temperature difference, ΔT_{pc}. Note that even for the case of latent heat λ equal to zero, there is a nearly 2-fold reduction of the temperature difference. For higher values of latent heat, the reduction is even more significant. Note that latent heats of value 80 Btu/lbm, or more, are feasible for low temperature applications, with much higher values being feasible for higher temperature applications. A selected list of phase-change materials with their thermal properties is discussed later in Sec. 4.
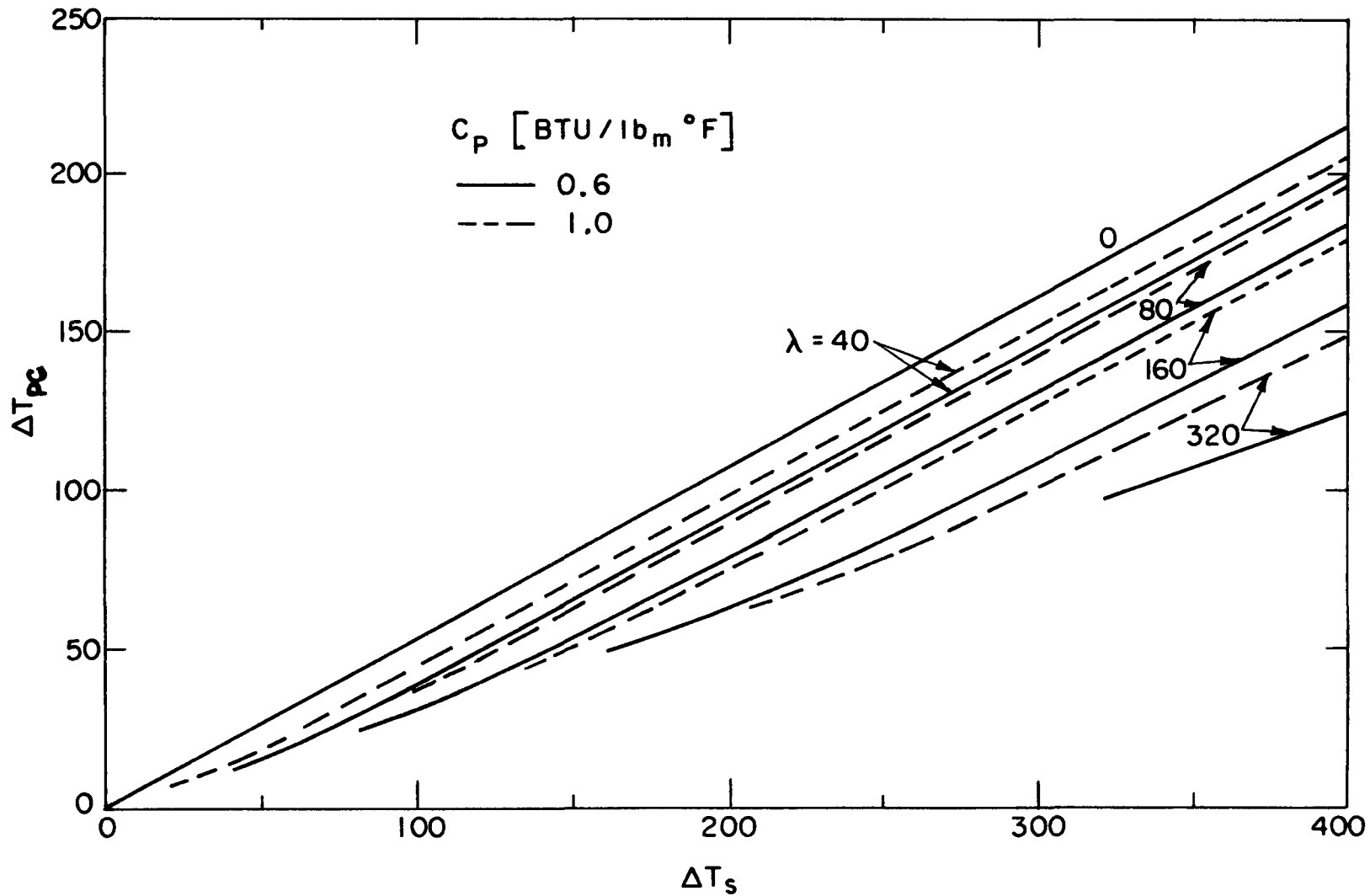
Fig. 3. Comparison of the Total Temperature Drop for a Phase-change
Slurry System, ΔT_{pc}, and a System Using a Sensible-heat Single-
phase Working Fluid, ΔT_s, for Various Latent Heats, λ

3.2 Mass Flow Rate and Pumping Power Reduction

This comparison is carried out under the following assumptions:

a. Both the phase-change slurry and the single-phase system have the same coolant temperature rise (i.e., ΔT_f). Thus the potential additional benefit of reduced heat-exchanger temperature difference, which would permit greater coolant-temperature rise for the slurry system, was not taken into consideration.

b. The densities of the different phases in the slurry are approximately equal, and the volume fraction (or loading) ϕ is 0.3.

c. The same heat-exchanger and piping system is used. Under this condition, the pressure drop and, hence, the pumping power become strong functions of the flow rate. The following approximate relationships were used

$$c_f \propto Re^{-0.2} \dot{m}^{-0.2} \mu^{0.2}, \tag{5}$$

$$\Delta p \propto \mu^{0.2} \dot{m}^{1.8}, \tag{6}$$

and

$$P \propto \mu^{0.2} \dot{m}^{2.8} \tag{7}$$

for frictional losses, pressure drop, and pumping power, respectively. The results of the comparison are shown in Figs. 4 and 5.

As shown, both the mass flow and pumping power for a phase-change slurry are reduced appreciably from that for a sensible-heat single-phase working fluid assuming that both heat-transfer mediums undergo the same temperature rise.

3.3 Enhanced Energy Storage

Two of the attractive features of using phase-change slurries as coolants for energy collection and recovery is that the phase-change material can be stored directly in concentrated form and the storage scheme can be more readily incorporated into the system. One prospective scheme is shown in Fig. 6. In this figure it is assumed that the phase-change particles are heavier than the carrier fluid; note that the inverse situation would also work. As the hot slurry with dilute suspension of droplets (about 0.3 volume fraction) enters the storage tank, the heavier particles/droplets would settle out of

Fig. 4. Mass Flow Reduction Comparison for Phase-change Slurry, $\dot{m}_{pc}$, Versus Sensible-heat Single-phase, $\dot{m}_s$, for Various Source-to-Sink Total Temperature Differences, ΔT_{tot}
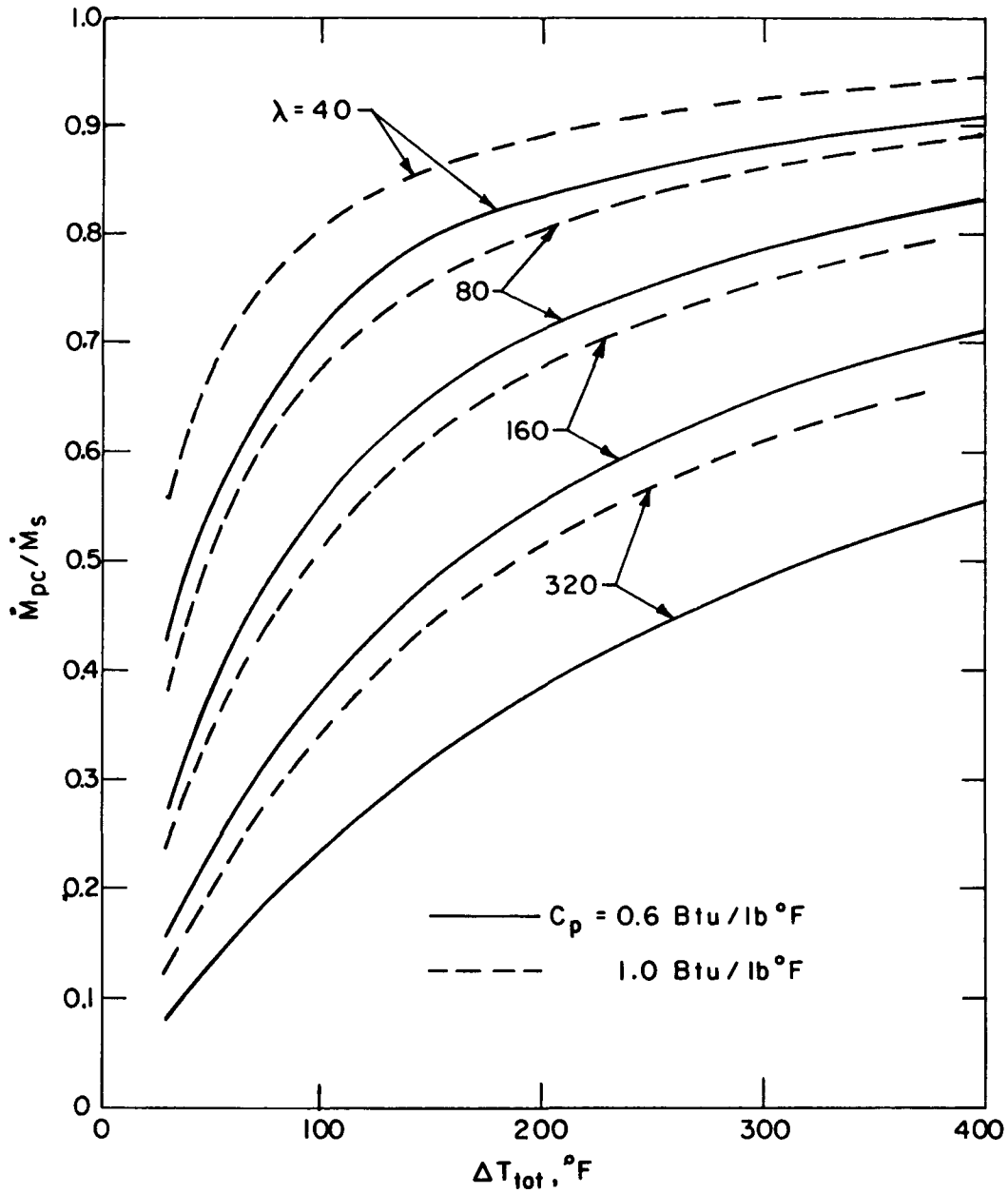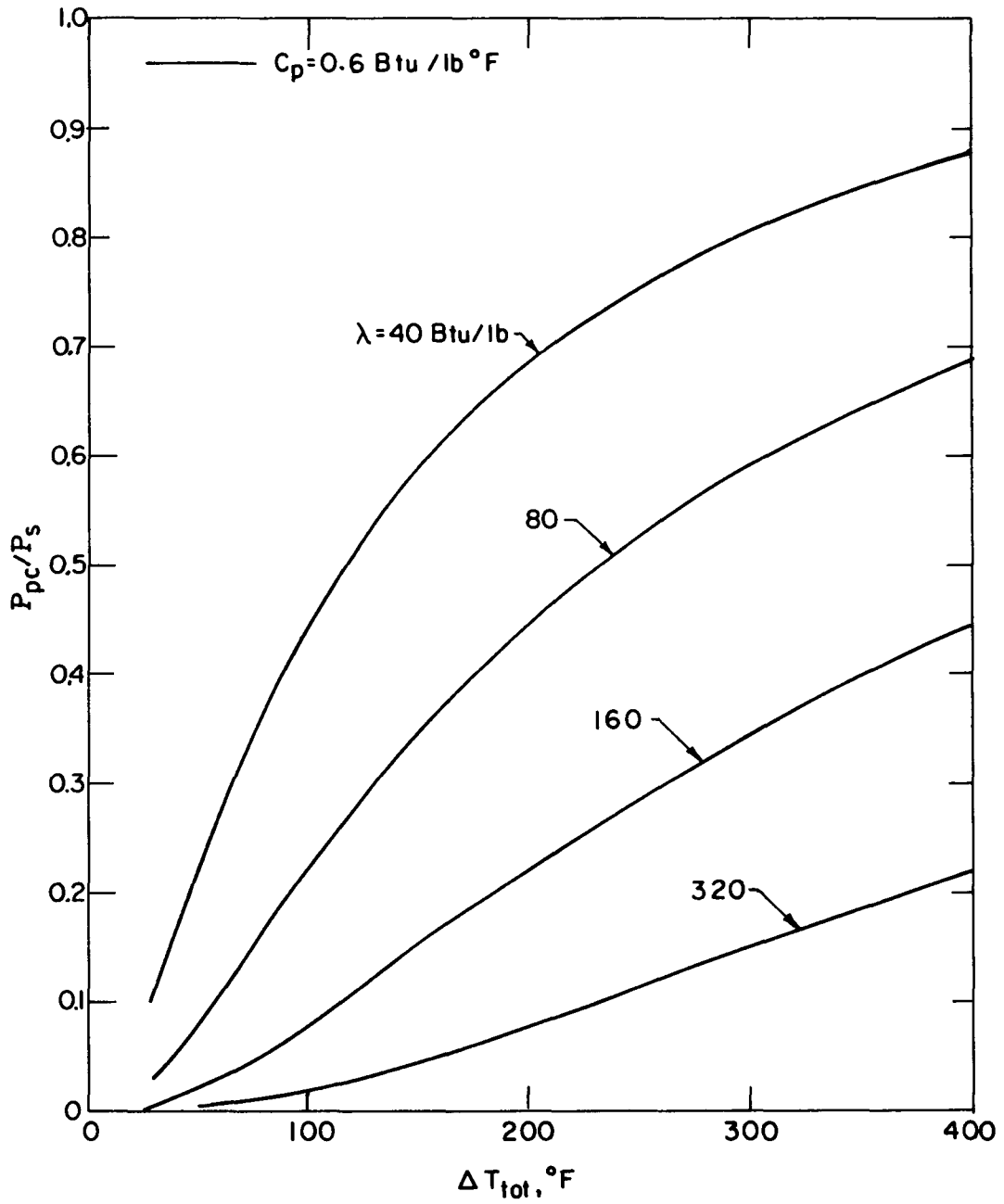
Fig. 5. Pumping Power Reduction Comparison for Phase-change Slurry, P_{pc}, Versus Sensible-heat Single-phase System, P_s, for Various Source-to-Sink Total Temperature Differences, ΔT_{tot}
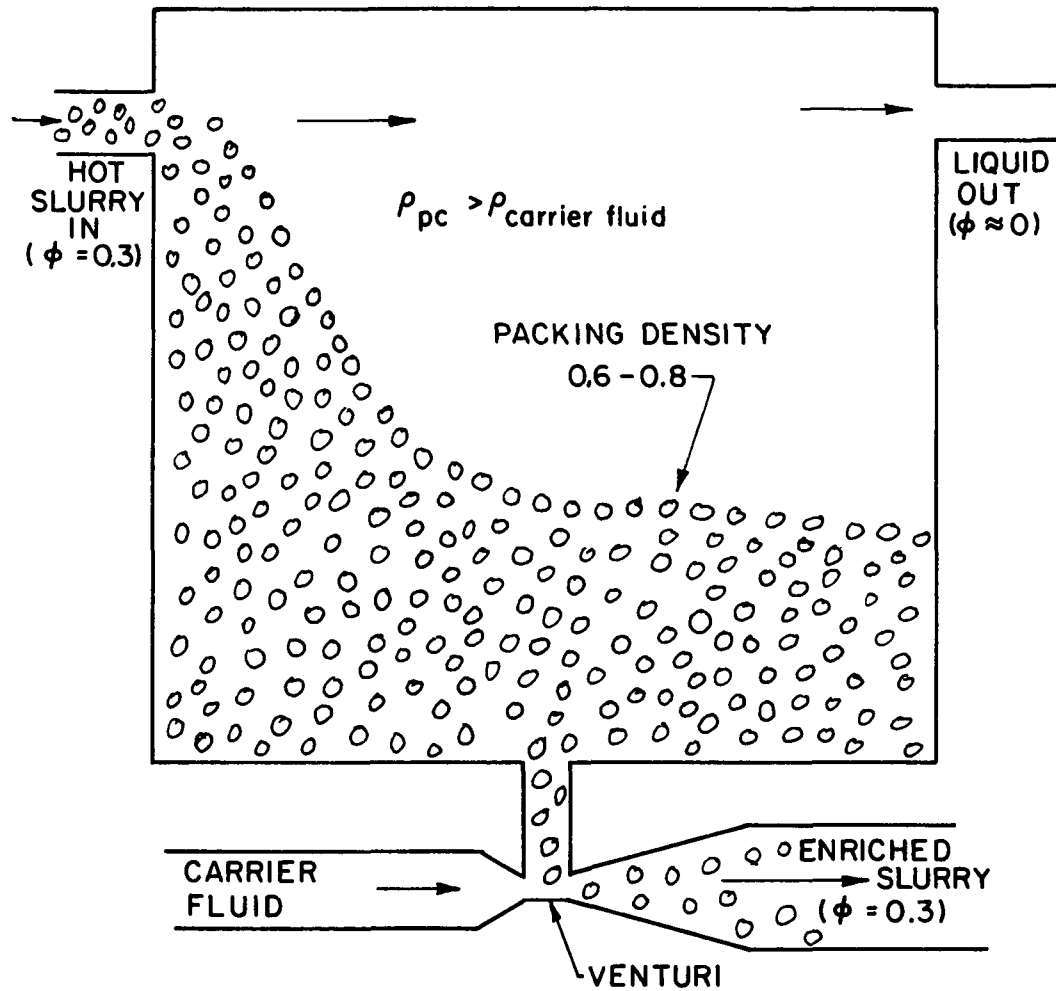
Fig. 6. Slurry-enhanced Thermal-energy Storage Featuring Variable
Storage and Withdrawal Rates with Continuous or Intermittent Use

suspension and accumulate in the bottom section of the tank, attaining a much
higher concentration of 0.6–0.85 by volume. When needed, these particles can
be withdrawn from the bottom for heat utilization and then mixed with
additional carrier fluid and introduced back into the thermal system to
maintain a circulating concentration of about 0.3. This storage scheme can
also be used to collect all particles before the system is shut down to
prevent particles from settling out in regions where they would be difficult
to reentrain back into the slurry upon startup.

Compared to conventional single-phase or static phase-change storage
tanks, the proposed scheme has the following advantages:

a. Conventional stationary phase-change storage systems require
a heat-transfer fluid to deposit and extract the stored energy. Accordingly,
a temperature drop must be invested to effect heat transfer between the
storage material during both the energy deposition and energy extraction part
of the cycle. With the proposed system, this temperature drop is completely
eliminated.

b. The direct storage of the hot coolant in a conventional
sensible heat system does not involve the temperature drop discussed above.
However, such a system has a relatively low capacity for its volume because of
the inefficiency of the sensible heat-storage system.

Figure 7 compares the storage-tank volume for the proposed system,
based on a packed volume fraction of 0.7 for the phase-change material, with
that of a sensible heat system. The savings in storage-tank volume is
considerable, especially for low temperature differences.

A by-product of smaller storage-tank volume is the reduced heat
loss. Assuming that the surface area is proportional to the 2/3 power of the
tank volume, a comparison of the relative rates of heat loss between the
proposed system and a conventional sensible heat system is shown in Fig. 8.
The slurry storage heat loss is considerably reduced over that of the sensible
heat system.

4. PHASE CHANGE SLURRY MATERIALS

4.1 Categories

Several considerations enter into the choice of materials for the
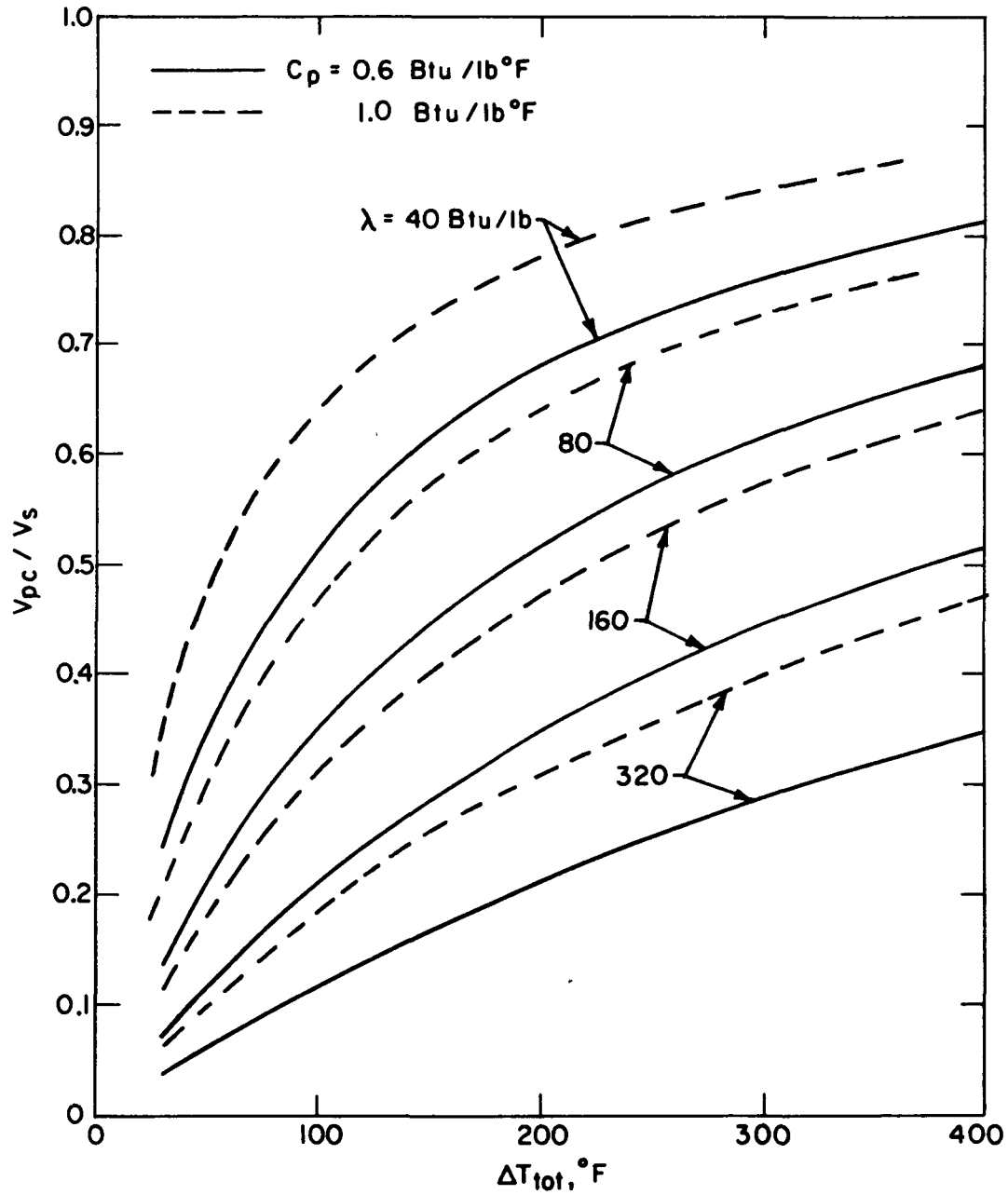
Fig. 7. Comparison of Slurry-storage Volume, V_{pc}, and Sensible-heat
Single-phase Storage Volume, V_s, for Various Source-to-Sink
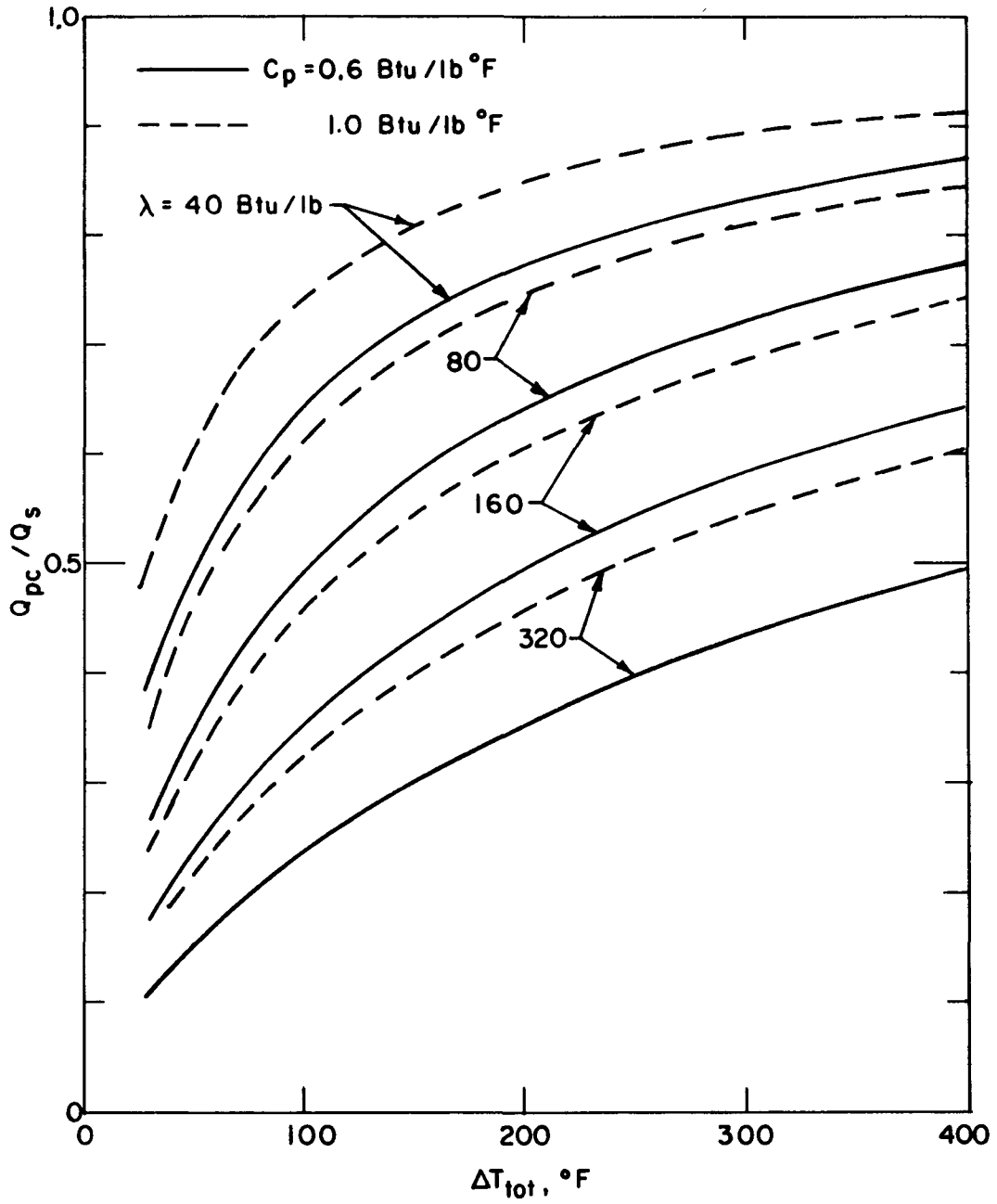Total Temperature Differences, ΔT_{tot}

Fig. 8.   Comparison of Slurry Storage Tank Heat Loss, Q_{pc}, and Sensible-
heat Single-phase Tank Loss, Q_s, for Various Source-to-Sink
Total Temperature Differences, ΔT_{tot}

phase-change slurry. Both the phase-change material for the dispersed phase and the carrier fluid itself must be selected very carefully. For the phase-change material, the most obvious choices involve substances that melt and solidify, although the solid-solid phase transition materials of Ref. 33 may have certain advantages, to be discussed below. The latter, however, have not been investigated thoroughly, and the choice is limited at present. A sample list of some phase-change materials is shown in Table 2. This is not the result of an exhaustive search and serves only to show the great variety of materials available, covering a very wide range of melting points and providing very high latent heats, in one case up to 1150 Btu/lb. In general, the following categories of materials are of particular interest:

a. **Pure Salts.** These tend to have very high latent heats and usually high melting points (378°F or above). They are, therefore, potentially useful for thermal systems where heat of the medium temperature range may be available, such as stack gas from fossil-burning equipment.

b. **Mixtures of Salts or Other Pure Substances, Including Eutectics.** Mixing is usually done to alter the melting point, to suit a specific application. It should be pointed out, however, that a noneutectic mixture may undergo inhomogeneous melting and phase separation, so that upon resolidification, a heterogeneous mixture with different melting points and reduced effective latent heats may result. The problem can be minimized by encapsulation or using mixing present from pumping a slurry, but some developmental effort would be necessary. Eutectic mixtures should not pose this difficulty.

c. **Salt Hydrates.** These materials have attracted considerable attention for solar-energy applications, primarily because of their relatively high latent heat of fusion. Unfortunately, many materials suffer an incongruent phase change which manifests itself as a lower realizable latent heat.

d. **Waxes.** There are two classes of waxes, the oil-soluble waxes, such as those in the paraffin family, and the water soluble waxes, such as the polyethylene glycols. Both types are usually available as mixtures of different molecular weights, so that melting occurs in a narrow range of temperatures rather than at a single melting point. This can be an advantage, because the latent heat effect can be spread over a wider range of temperatures. However, purer compounds of a single molecular weight or a

Table 2. Sample List of Phase-change Materials

Pure Elements, Inorganic Compounds, Salts, and Mixtures

	Tm (°F)	λ (Btu/lbm)
Si	2580°F	710
MgF_2	2320	402
Be	2310	520
NaF	1820	322
LiF	1595	400
LiH	1290	1150
$46LiF/44NaF/10MgF_2$	1174	364
$KClO_4$	980	538
Na_2O_2	660	135
$LiNO_3$	486	159
$AlCl_3$	378	120

Waxes and Organic Compounds

Pentaerythritol	369	131
Propionamide	183	72
Pentaglycerine	178	83
Stearic Acid	157	85.5
Tristearin	133	82.1
Parafin (Sunoco 116)	116	90
N-Octodecane	82	105
Polyethylene Glycol 600	68-77	63

Salt Hydrates

$Ba(OH)_2.8H_2O$	179.6	114.3
$Na_2S_2O_2.5H_2O$	120	86
$Na_2SO_4.10H_2O$	90	109

Crystalline Polymers

Polytetrafluoroethylene (Teflon)	620°F	
Cellulose acetate	445	
Nylon: Type 6/6	509	45-80
Type 6	420	45-80
Type 12	354	
Polyethylene	150-200	
Cross-linked HDPE	130	68-77

narrow range of molecular weights are also available, yielding a more defined melting point. One other advantage of this group is that, depending on the molecular weight, a large range of melting points is available.

e. <u>Thermoplastic Polymers</u>. Except for polyethylene, this group has not been investigated extensively for energy storage. Nylon and other higher melting-point polymers might be useful in the temperature range of 200-600°F. One exciting prospect for this group is the partial cross-linking of the molecules, which could render the molten particles form-stable and, hence, incapable of coagulating with neighboring particles or adhering to heat-exchange surfaces. This has already been demonstrated for high-density polyethylene in Ref. 34.

4.2 Selection Criteria

Several criteria enter into the choice of the phase-change slurry material. The material selections, based on these criteria affect the relative benefit to be gained in comparison with a conventional single-phase coolant system. The applicable criteria are discussed below.

a. <u>Source-sink Temperatures</u>. Clearly the fusable material in the slurry should be chosen so that the melting point (or corresponding phase-change temperature) lies between the intended source and the sink temperatures. The list in Table 2 clearly shows that candidate phase-change materials exist for almost all ranges of temperatures that could potentially be of interest.

b. <u>Latent Heat</u>. Table 2 indicates that for the low-melting-point materials, the latent heats generally are about 80 Btu/lbm (190 kJ/kg). As a general trend, the latent heats tend to increase with temperature, reaching several times the above value for materials with higher melting points. Note that because of the possibility of incongruent phase change, mixtures and hydrates may not undergo complete phase change in practical systems. Thus for these materials the realized latent heat may be less than the values listed. This problem, however, does not exist for pure substances or for true eutectics and as discussed earlier, methods are known for minimizing this problem.

c. <u>Other Thermal Properties of the Slurry Constituents</u>. Aside from the melting point and the latent heat for the phase-change material,

other important thermal properties include the specific heats and the thermal conductivities of both constituents of the slurry. Of these, the properties of the carrier fluid would be more important, since it constitutes the greater fraction of the circulating material and serves as the intermediary for heat transfer between the dispersed phases and the heat-exchanger surfaces. In contrast, high specific heats for both states of the phase-change material would be desirable, but not essential. The thermal conductivity of the phase-change material is probably not important if a relatively fine dispersion can be maintained, recognizing that this represents a design trade-off relative to maintaining a large particle Peclet number (see Sec. 2). Clearly, the relative importance of all these properties also depends on the operating conditions. For example, in a system with small overall temperature differences, the contribution of the specific heat to the total heat capacity might be relatively unimportant compared to that of the latent heat; therefore, high specific heat would be unimportant even for the carrier fluid.

It is clear from the above discussion that at moderate temperatures, water would serve as an excellent carrier fluid because of its high specific heat and conductivity. However, at temperatures above 250°F, the use of water would require a pressurized system. For these higher temperatures other liquids, including some of the commercial synthetic coolants, might be more suitable. A gaseous carrier fluid may also be advantageous.

Of the flow properties, only the viscosity of the carrier fluid is important at the loading ratios contemplated for the slurries, <30% by volume. The density difference between the two constituents should be consistent with the fluid velocities required to maintain a suspension and effective storage.

d. <u>Maintenance of the Dispersion</u>. For the phase-change slurry system to operate successfully, the phase-change material must be maintained as a dispersion at all times. The role of the fluid velocity in maintaining the suspension has already been discussed above. Additionally, the two constituents must be substantially insoluble in each other. The phase-change material should not adhere to the heat-exchange surfaces upon solidification, and should not coagulate to form a continuous liquid phase while molten. To prevent adhesion, appropriate surface coating might be adequate. Mechanical scraping, including the possible use of circulating non-phase-change solids,

might be considered. The use of a suitable surfactant should also be considered in maintaining a fine dispersion of the molten liquids. Microencapsulation of the phase-change material would eliminate both the adhesion and coagulation problems. However, limited attempts at encapsulation have not been too successful. The search for and development of effective and economical solutions for these problems would constitute an important part of a future research program.

A rather exciting development in this connection is that of the partially cross-linked high density polyethylene (Ref. 34), which is form stable during melting and does not adhere to other surfaces. Possibly similar partial cross-linking could also be effected for other polymers with different melting points.

e. Chemical Considerations. The slurry used should be chemically inert relative to both interaction with the thermal-system components and interaction between the disperse phase-change medium and the carrier fluid. Very importantly, note that the salt-hydrates do produce corrosion problems.

5. SUMMARY

In summary, the preceding sections describe a new concept for improving thermal-system performance by using the combined mechanisms of enhanced heat transfer, transport, and thermal-energy storage associated with a phase-change slurry as the working fluid. The various fluid mechanics and heat-transfer mechanisms responsible for improving thermal-system performance are described and the supporting literature is surveyed. The literature clearly demonstrates that a threefold, or greater, heat-transfer enhancement is possible with slurries for certain heat-transfer surface geometries. The enhancement is present whether or not the slurry contains a phase-change dispersion. However, the enhancement potential is postulated to be greatest for phase-change slurries. The existing data, however, were found to be quite incomplete for laminar flows and almost completely lacking for turbulent flows over common engineering heat-transfer surfaces. For no case are proven correlations available for engineering design of a thermal system using slurries of the loading required.

A thermal-system enhancement comparison was conducted which compared the performance of a phase-change slurry system with that of a system using a conventional sensible-heat single-phase working fluid. This comparison clearly demonstrate the improved thermal system performance with a phase-change slurry. Source-to-sink temperature difference, mass flow, pumping power and storage volume requirements were significantly reduced. The comparison used realistic heats of fusion and other fluid properties.

In view of the great potential for increasing a thermal system's performance from the use of phase-change slurries and the lack of both sufficient understanding concerning the enhancement mechanisms and useful engineering data, a systematic research and development program aimed at eliminating these deficiencies is recommended. The R & D program should focus on:

     a.   Generation of slurry heat transfer and flow information for the basic heat-exchanger heat-transfer geometries.

     b.   Slurry system development for various temperature-range applications and performance studies with emphasis on "designing" slurries and system components simultaneously, due to the strong coupling between system components. The activity includes development of optimal energy-storage modules.

     c.   Applications research directed at identification and analysis of thermal systems offering the greatest returns from use of phase-change slurries. This activity would also involve preparation of a users' data handbook for designing enhanced heat-transfer thermal systems.

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