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THE DESIGN AND ECONOMICS OF DIRECT-CONTACT SALT HYDRATE STORAGE SYSTEMS

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JOHN D. WRIGHT

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NOTICE

THE DESIGN AND ECONOMICS OF DIRECT-CONTACT SALT HYDRATE STORAGE SYSTEMS

John D. Wright

INTRODUCTION

Latent heat storage (LHS) devices have long been regarded as superior to, and likely to supplant, the sensible heat storage devices (water tanks and rockbeds) currently used in active solar home heating systems. Advantages envisioned by early workers included reductions in storage volume and improved system efficiency. Recent studies at the University of Wisconsin (Morrison 1976; Jurinak 1977) have shown that reductions in volume can be achieved, but that little difference exists between the performance of LHS and sensible heat storage systems.

LHS devices using salt hydrates require only 10% of the mass of a rockbed and 50% of the mass of a water tank to provide equivalent system performance (Morrison 1976), corresponding to volume reductions of seven-to-one and three-to-one compared to air- and liquid-based sensible heat systems. However, the need for large heat-transfer areas to overcome the heat-transfer resistance of the solidifying storage media has resulted in substantially smaller volume reductions (four-to-one and two-to-one).

LHS systems exhibit about the same overall performance as sensible heat storage for active solar heating systems. This is due in part to the utilization patterns of storage. In an optimal system, almost all of the energy collected during the winter is used immediately, and the storage is seldom charged. In the early fall and late spring, storage is often completely charged, but the load is so small that little energy is withdrawn from storage. Only for a brief time in the fall and spring is storage frequently cycled. Furthermore, during mid-winter the LHS device is often fully frozen, while in early fall and late spring the device is often fully melted. During these periods, the LHS device acts as a sensible heat device. The effect of variations in melting point of the latent heat media were also found to be minor. Indeed, the important choice for system performance is not between latent or sensible heat storage, but between air- or liquid-based systems. Furthermore, system configurations are critical.

Earlier studies (Shelpuk 1976; Jurinak 1977) concluded that research and development efforts should concentrate on developing LHS for air-based systems, since large volume reductions over rockbeds are possible. However, liquid-based collectors account for over 90% of the space heating and domestic hot water markets. Therefore, to achieve widespread use, a storage system must be compatible with liquid-based collectors.

By requiring that a proposed LHS device be capable of working with a liquid collector, and remembering that there is little intrinsic difference in performance between latent and sensible heat systems, some of the characteristics of the LHS device can be immediately defined. The LHS device must utilize bulk storage of a salt-hydrate storage medium in order to offer significant volume reduction. The device must cost the same as or less than a water-storage system with a comparable storage capacity since there is no performance advantage. The device should allow direct transfer from the collectors to the load, as this is a frequent mode of operation. The number and size of the temperature drops during heat exchange should be minimized.

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One possible means of meeting these requirements is to use bulk containment of the salt hydrate and direct-contact heat exchange to add heat to and remove heat from storage. In such a system the salt hydrate storage medium (simply a salt-water solution when melted) is stored in a tank. To add energy, hot oil is bubbled through the salt hydrate, transferring heat directly to the melting salt solution. After rising through the solution, the drops coalesce into a floating layer of oil. The oil is then pumped off to the heat source, reheated, and recycled through storage. To discharge the unit, drops of cold oil are introduced at the bottom of the tank and absorb heat as they rise. After coalescing at the top, the warm oil is pumped to the load to deliver heat. As heat is extracted, flakes of solid salt hydrate form, grow, and settle to the bottom of the tank.

Direct-contact heat exchange allows realization of the full potential for volume reduction, and provides efficient heat transfer into and out of the salt hydrate. A third major benefit is that it agitates the salt solution, preventing phase segregation and the resulting reduction in storage capacity exhibited by salt hydrate storage media.

Latent heat storage in salt hydrates with direct-contact oil/solution heat transfer is not a new idea. It was originally proposed in the 1950s by Etherington for heat pump applications (Etherington 1957). Recently, research has been funded by the U.S. Department of Energy at Clemson, DRI, the Franklin Research Institute, and the Solar Energy Research Institute (Edie 1979; Hallet 1978; Lorsch 1977; Wright 1980). To make direct-contact salt hydrate systems practical, it is necessary to: (1) assure reliable distribution of oil into the salt hydrate, and (2) minimize entrainment of salt hydrate in the oil phase.

Experimental work at SERI is being performed on a pilot-scale storage system. The storage medium is contained in a Pyrex glass column so that the direct-contact process may be observed. Drops of oil are injected into the salt hydrate, rise through the column while absorbing heat from or transferring heat to the salt hydrate, and coalesce into an oil layer which floats on top of the salt hydrate. Oil is withdrawn from this layer, cooled in a heat exchanger, heated to the desired inlet temperature in a resistance heater, and reinjected into the column. Therefore, the initial efforts at SERI are focused on the critical operational issues to establish the potential of this technology.

FLUID DISTRIBUTION

The oil must be distributed in the salt so that:

- Oil flow is established immediately upon startup, regardless of the state of crystallization of the salt;
- Adequate surface area is available for efficient heat transfer; and
- The oil mixes the salt hydrate and prevents salt phase segregation.

The second and third requirements are relatively easily met. If the free path of the rising drops is 60 cm or more, essentially complete heat transfer will occur. If oil is injected at the bottom of the tank, mixing will be great enough to prevent phase segregation (except in the case of sodium sulfate decahydrate, where a much denser anhydrous solid phase exists). The difficult requirement is ensuring reliable oil flow under all conditions. Three main types of distributor have been proposed: single stage, single stage with bypass, and multistage.

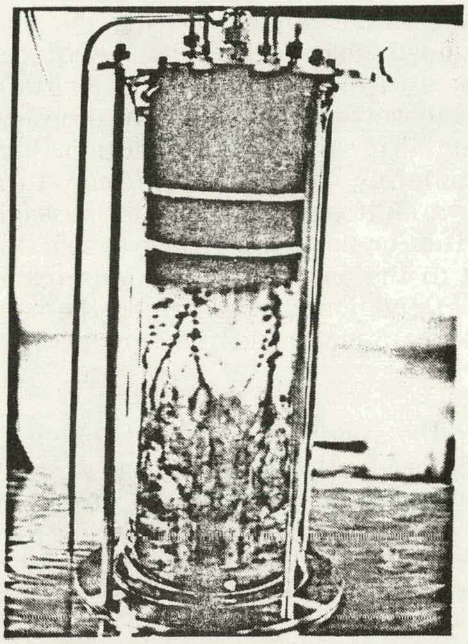


Figure 1. Pilot-Scale Storage Tank in Operation
(Partially Frozen)

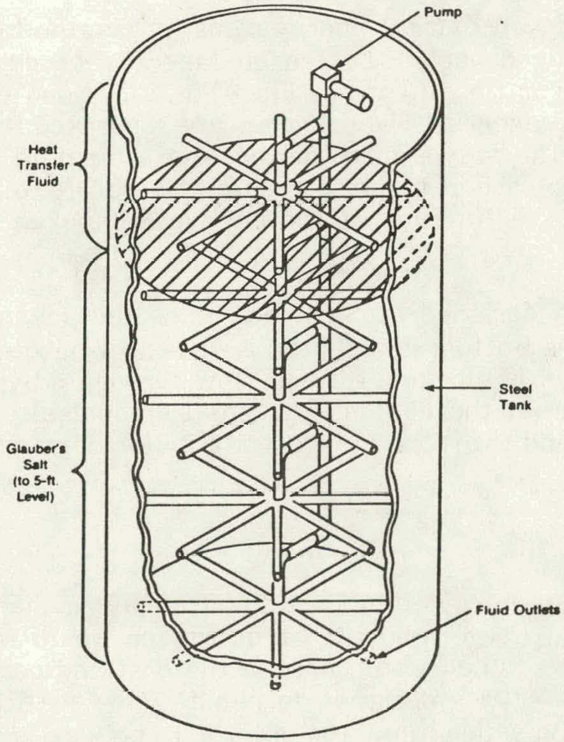


Figure 2. Multi-Stage Fluid Distributor: "Christmas Tree" Design by OEM Solarmatic

Single-stage distributors in which oil is injected into the salt hydrate at the bottom of the tank have been tested by several groups. While they are simple, they have proved vulnerable to freezeup and flow blockage. During the heat extraction cycle, crystals form and grow in the continuous phase. The crystals of $NaHPO_4 \cdot 12H_2O$ grown in the SERI apparatus are flat flakes with a characteristic length of 1 to 2 mm which settle to the tank bottom and form a loosely packed bed. Oil drops channel easily through the bed and bubble through the remaining salt hydrate solution (Fig. 1). If cooling is continued until the salt hydrate is completely frozen, the unit may turned off, left indefinitely, and started at will, as there are a multitude of potential passages for the oil within the bed. However, if the salt is molten or partially frozen when flow is stopped, crystallization will continue as heat is lost to the environment. Consequently, a dense, nonporous layer of solid salt hydrate forms at the boundary between the solution and the settled bed. If the layer grows more than 2 or 3 cm thick, the flow of oil through the column is effectively blocked.

If hot oil is introduced after the stagnant period, channels will usually be melted through the salt, and flow will be restored. However, if heat extraction is resumed after stagnation the passages remain blocked, and the energy stored in the remaining molten salt hydrate will be unavailable until after the next charging cycle. Other investigators have also encountered solidification in the distributor holes during the freezing cycle, and backup of salt hydrate into the oil inlet lines.

Complete flow blockage in single-stage distributors may be avoided by introducing a pressure operated bypass valve. If flow through the distributor is blocked, pressure in the oil inlet line rises, and a bypass valve is opened which allows the oil to flow through a pipe into the floating oil layer. If the bypass line runs next to the distributor line, warm oil circulating through the bypass line melts the frozen salt in the distributor and restore flow. However, this method cannot unfreeze a blocked line during a heat extraction cycle.

To assure that the device can extract energy remaining in the tank after prolonged inaction, oil must be introduced above the frozen layer. One such multi-stage device is patented by O.E.M. Solarmatic of Tampa, Fla. (Fig. 2). Good dispersion is achieved by use of multiple arms or branches. The branches are separated from the oil supply line by pressure relief valves. The valves near the bottom are set to release at low pressure, while the higher valves release at higher pressure. Therefore, oil will preferentially flow from the bottom branches. However, if the bottom is blocked, the oil will be released higher in the tank.

A second, simpler device designed at SERI combines the advantages of the bypass and multistage devices. If the bottom distributor is clear, oil bubbles through the tank from the bottom. If the bottom is blocked, oil will flow through a bypass line and into a large distributor located higher in the column. A small amount also flows through a second bypass line, which heats and frees the clogged distributor during the next heating cycle.

SALT CARRYOVER

The amount of salt hydrate entrained in the oil phase leaving the storage unit has a major effect on the operation. Large amounts of carryover would require the use of large, expensive heat exchangers, which would impose the cost and performance penalties that direct-contact heat transfer was designed to avoid. This section describes methods for promoting phase separation which allow the process to be used to advantage.

An understanding of the drop coalescence mechanism suggests methods for reducing the amount of entrainment. Phase separation is a two-step process. The first step is the coalescence of the oil drops at the oil/salt hydrate interface. The rising drops pack together in a layer, separated from each other and the oil layer by aqueous skins that thin as the water drains away. When the skin has thinned sufficiently, it ruptures and coalescence occurs. When the skin around a drop ruptures, the remaining aqueous phase contracts into many small secondary droplets with a diameter of a few microns. These droplets are entrained within the oil. Since their settling velocity is on the order of 10^{-5} cm/s, they do not settle out, but are carried off with the oil. It is important both to promote coalescence and to remove the secondary drops, but the latter is the more difficult task (Jeffreys 1971).

The first step in a phase-separation device is to ensure that the large oil drops coalesce. Although large drops coalesce readily under normal conditions, high flow rates, small drop sizes, high salt hydrate viscosity, and the presence of solids or surface-active impurities at the interface tend to stabilize the drops. Such situations may be avoided by use of a coalescence screen or mat. Such screens work best when made of a material preferentially wet by the oil phase, such as most metals, metals coated with epoxy, or plastics which are not attacked by the oil. While designed to coalesce oil drops, this device can also aid in separation of dispersions of water in oil, since water drops may be captured, coalesce, and grow at the interstices of the screen. Similar coalescing devices have been used by other investigators (Lorsch 1977).

While screens promote coalescence and eliminate gross carryover caused by foams and dispersions, they do little to remove the secondary aqueous drops formed when the film around the drop ruptures. Because such drops will not settle out in a reasonable length of time, interdrop coalescence must be promoted so that the drops reach a reasonable size. A layer of fibrous packing can be placed on top of the screen to catch the small drops (Mara 1979). Because of the very small size of the drops, the roughness of the fibers is more important than whether they are wet by the oil or aqueous phase. As more drops are caught, they coalesce, grow, and eventually settle back to the aqueous layer. Also to be tested are commercially available water separators which work on the same principle but are placed in the oil line leaving the tank.

SYSTEM DESIGN

In order to determine whether direct-contact latent heat systems are economically competitive, the configuration and performance of the direct-contact system and its alternatives must be defined. In this section three systems are described: a standard liquid-based sensible heat storage system, a latent heat storage design where oil is the heat-transfer fluid throughout the system, and a latent heat storage system where ethylene glycol/water is used in the collectors and oil in the storage tank.

The conventional liquid system with which latent heat must compete is shown in Fig. 3a. An antifreeze solution (50-50 mixture by weight of ethylene glycol and water to provide protection against freezing) is circulated through the collectors. The collected heat is transferred through a shell-and-tube heat exchanger to the water storage and load loops. The heat exchanger is necessary because the cost of storage with an antifreeze mixture would be prohibitive. However, all energy collected is passed through the exchanger whether or not storage is being charged. The collector inlet temperature is raised by the temperature drop across the exchanger, between the antifreeze solution and the water being heated. Use of such an exchanger reduces the annual collected energy by 5%.

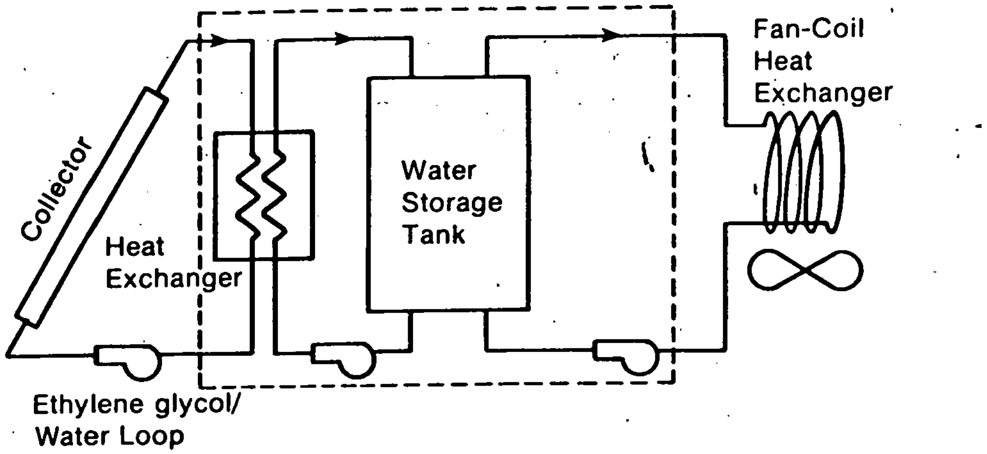
A direct-contact latent heat system in which oil is the only heat-transfer fluid is shown in Fig. 3b. While this system eliminates the expense and performance penalty of the heat exchanger between the collector and storage loops, three major problems are apparent. Because the product of density and heat capacity for oils is approximately half that of antifreeze mixtures, the oil flow rate through the collector must be twice that of an antifreeze solution to achieve the same performance. Therefore, pumping power requirements are also twice as large. Since flat-plate collector temperatures can exceed 400°F during stagnation, safety considerations require the use of oils with high flash points. However, pumping power is further increased because viscosity increases with flash point. High oil viscosity also increases the possibility of carryover, by increasing the difficulty of phase separation and aiding the formation of emulsions or suspensions. The oil temperature leaving the fan coil will rarely, if ever, be above the melting point of the salt hydrate. Consequently, the major problem is the design's susceptibility to flow blockage. Since entrained salt will continually be deposited and will not normally be removed even extremely low levels of carry over will eventually result in flow blockage.

The problems of the previous system are avoided in the system of Fig. 3c. In this system, oil provides direct-contact heat transfer within the storage medium, but interfaces with the rest of the system through a shell-and-tube heat exchanger. Energy which is collected, stored, and later supplied to the load must pass through the heat exchanger twice and is used somewhat inefficiently. However, when energy is to be collected and used immediately, the oil pump is not turned on, and the energy is passed directly and efficiently to the load. While these two effects tend to offset one another, there are indications that such a configuration may slightly outperform one in which all the energy passes through a heat exchanger once. In a study of air-based heating systems, Jurinak (1977) points out that in a system designed to supply half of the annual load, approximately 40% of the energy delivered to the load passes through storage. During January when a low inlet temperature is most important for efficiency, the system operates directly from the collector to the load 88% of the time. However, any advantages would be expected to be small, as the penalty for passing all energy through an exchanger is only 5%.

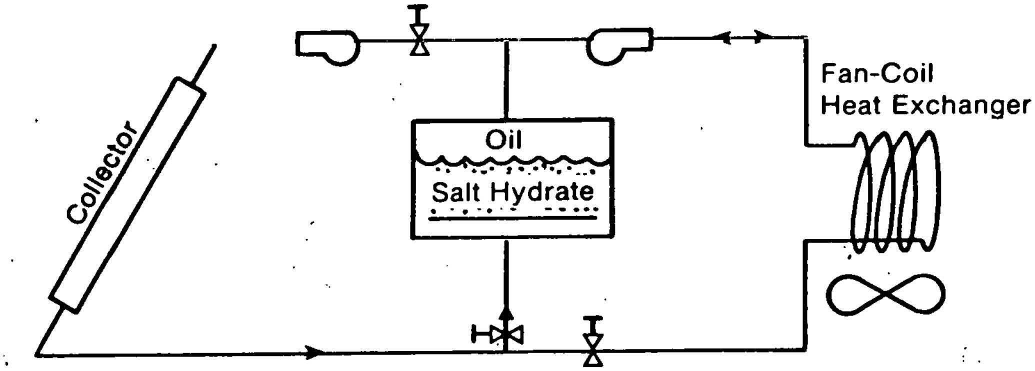
Use of antifreeze in the collectors results in lower parasitic power requirements than for the all-oil case. Because the oil is not subject to stagnation temperatures, a lower flash point is acceptable and the oil used can be less viscous, resulting in decreased pumping power and easier phase separation. Finally, this design is much less sensitive to carry over. Because the same heat exchanger is used to charge and discharge storage, salt deposited in the heat exchanger will be periodically melted and swept away. Although carryover should still be minimized to prevent degradation of the performance of the heat exchanger, low levels of carryover will not inevitably lead to flow blockage.

ECONOMICS

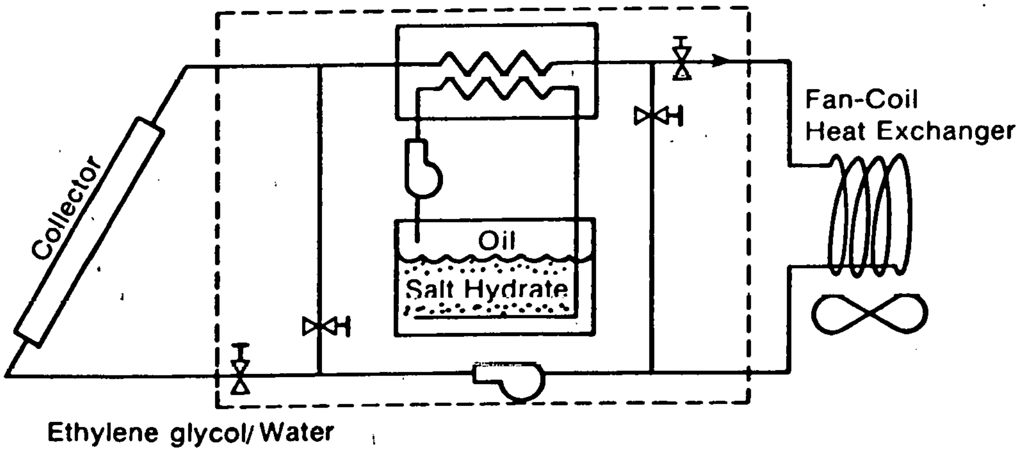
Given a system design, the cost of the preferred latent heat and baseline systems can be estimated. Table 1 presents the storage related costs of the two systems, each sized to provide a 50% annual solar fraction and coupled to 42 m^2 (450 ft^2) of single-glazed flat-plate collectors. The collectors and fan coils are the same in each system, so only the portions within the dashed lines are costed.



a) Standard Liquid-Based Home Heating System with Water Storage



b) Oil-Based Direct-Contact Latent Heat System



c) Hybrid Oil/Antifreeze Direct-Contact Latent Heat System

Figure 3. Liquid-Based Solar Heating Systems

Table 1. COMPARISON OF EQUIPMENT COSTS FOR DIRECT-CONTACT LATENT HEAT AND WATER STORAGE (NOMINALLY SIZED TO STORE 400,000 BTU)

Component	Direct-Contact Latent Heat	Water
Containment		
Tank	316	832
Lining	180	439
Insulation	27	65
Jacket	14	37
Storage medium	332	—
Heat-transfer fluid	200	—
Heat exchanger	768	396
Pump(s)	180	360
Internals	150	—
	$2,167	$2,129

Source of component costs: Lawrence (1980).

The final costs of the two systems are essentially equal, as the cost differences are considerably less than the uncertainty of the estimates. The dominant cost in the water system is the storage tank itself. The smaller volume of the latent heat tank results in substantial savings, which offsets the added cost of the storage medium, heat transfer fluid, and column internals. However, the relatively poor heat transfer properties of the oil cause the heat exchanger required by the oil system to be considerably more expensive than that used in the conventional system.

CONCLUSIONS

Direct-contact latent heat systems have overall costs roughly equal to those of water thermal storage tanks. The increased costs due to the heat-transfer fluid, medium, and heat exchanger are offset by the reduction in containment costs. The total system performance of latent heat and water based designs are also quite similar, with an overall difference not exceeding 5%. The primary advantage of latent heat storage is its substantially smaller volume requirement, which will facilitate its use in retrofit applications. In order to build practical and reliable direct contact storage systems, two problems must be solved: the oil must be injected reliably into the salt phase, and carryover of salt hydrate in the oil phase must be minimized to avoid clogging the system or reducing the heat transfer rate. Experiments are now underway to solve the fluid distribution problem and to minimize the carryover of salt hydrate by use of two-stage coalescer-filters.

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