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AUG 07 1985
CONF-851030--1

LA-UR -85-2703

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LA-UR--85-2703

DE85 015736

TITLE: PASSIVE VAPOR TRANSPORT SOLAR HEATING SYSTEMS

AUTHOR(S): James C. Hedstrom and Donald A. Neeper

SUBMITTED TO: Solar '85 Conference
Raleigh North Carolina
October 15-20

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PASSIVE VAPOR TRANSPORT SOLAR HEATING SYSTEMS

James C. Hedstrom
Donald A. Neeper
MS J577
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

In the systems under consideration, refrigerant is evaporated in a solar collector and condensed in thermal storage for space or water heating located within the building at a level below that of the collector. Condensed liquid is lifted to an accumulator above the collector by the vapor pressure generated in the collector. Tests of two systems are described, and it is concluded that one of these systems offers distinct advantages.

1. INTRODUCTION

Our investigation of vapor transport was stimulated by a perceived need for systems with particular characteristics. Brief system studies [1,2] indicate that the solar resource on the envelope of a building is in principle adequate to meet the heating needs even in severe climates of the US, but for this resource to be exploited the solar energy systems would need to have higher efficiency, or to utilize more of the envelope (including the roof) for collection, or both. Most present passive heating systems deliver uncontrolled heat to the room or zone directly behind the south wall of the building. The floor plan of the building may not always permit adequate heat distribution to other zones by natural convection, and many existing buildings do not have a suitable southern exposure for direct gain, thermal storage wall, or sunspace systems. We therefore sought an idealized passive system that would a) provide superior efficiency by maintaining a low absorber temperature and by diode action that prevents heat loss at night; b) provide downward transport of heat, thus enabling elevated surfaces of the building to be used for collection; c) provide passive distribution of heat to all zones of the building regardless of the building architecture; and d) enable some control of heat delivery--at least seasonal shutoff. As exemplified by a heat pipe, a vapor system can transport large amounts of power through a small pipe across several tens of feet with low temperature drop, and can prohibit transport in the reverse direction--thus displaying thermal diode action. If multiple condensers are connected in parallel and located in thermal storage units in different zones of the building as shown in Fig. 1, the vapor will preferentially condense in the coldest unit, thus tending to provide uniform temperature throughout the building. Because all transport occurs via small pipes, the building architecture is minimally disrupted by the heating system. Seasonal shutoff (or even more frequent control) can be achieved by a single valve. We noted that vapor systems thereby offer opportunity for achieving the idealized system characteristics mentioned above, if means could be found to provide downward transport--which implies passive return of condensate upward to the collector. We have therefore examined two self-pumping systems as described below. In all of our experiments, we have used Refrigerant-11 as the working fluid, although in principle any fluid with suitable density, vapor pressure, and latent heat could be used.

2. THE SINGLE-ACCUMULATOR SYSTEM

The single-accumulator system is shown in Fig. 2. Earlier published work on this system and on related systems is reviewed in Refs. 3-6, and details of our experiments are given in Ref. 3. In this system, the condenser fills with condensed liquid until the reduction in heat transfer causes a sufficient rise in collector temperature for the vapor pressure to lift liquid from the condenser to the accumulator. When the accumulator is full, valve V opens to equalize the pressure in the accumulator and collector, and the accumulated liquid drains into the collector. When the accumulator is nearly empty, V closes and the operating cycle begins again. For experimental convenience, we used a solenoid valve, but we have also used a passive float valve with success. We configured a space-heating test cell with the collector on the roof, requiring 17 feet of liquid lift, as shown in Fig. 3. The system operated as expected, with a self-regulating liquid level in the condenser. The pressure difference between the collector and the accumulator during the pumping phase of operation was exactly as required for liquid lift.

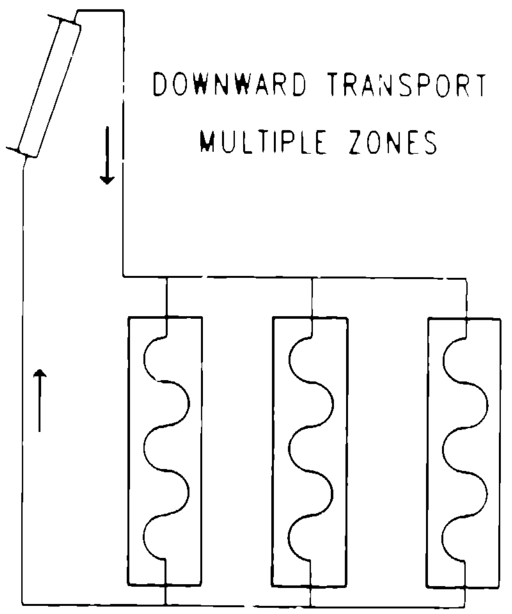


Fig. 1. Schematic diagram of a space heating system with multiple condensers.

During the pumping phase of operation (with heat transport to the condenser), the vapor pressure in the accumulator must be less than that in the collector by at least the static head of liquid lift. Hence, the temperature of the accumulator must be less than that of the collector. During the valve-open phase, some portion of the accumulator and its liquid contents are warmed to the temperature of the collector. This means that the accumulator is alternately warmed and cooled each cycle. The temperature to which the accumulator is cooled and the temperature difference required for liquid lift establish a lower limit for the collector temperature and thus have a strong impact on system efficiency. The energy from the collector required to warm the accumulator each cycle we call the "parasitic energy." Some portion of the parasitic energy is absorbed by the cold liquid returning to the accumulator from the condenser. However, greater system efficiency results if external cooling of the accumulator also occurs. Results of experiments with cooling of the accumulator of the apparatus of Fig. 3 are shown in Fig. 4, which plots the difference between collector and storage temperatures as a function of incident solar radiation for a bare pipe accumulator, a finned pipe with enhanced cooling, and an insulated pipe with little external cooling. External cooling of the accumulator clearly results in lower collector temperatures.

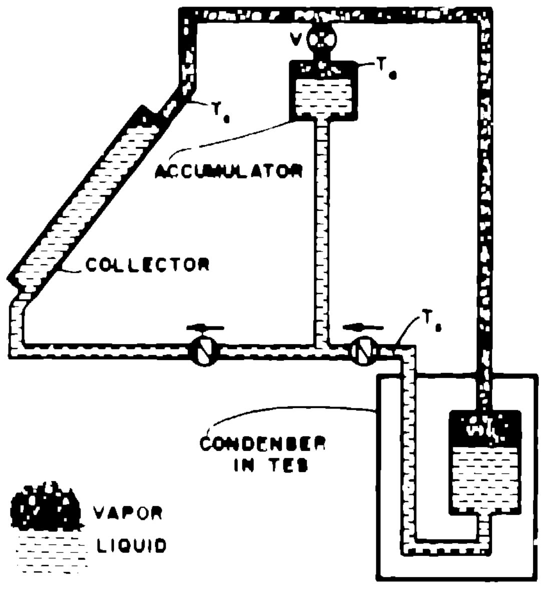


Fig. 2. Diagram of the single-accumulator system with the partly flooded condenser located in thermal energy storage (TES). Temperatures are indicated at key points.

A detailed theoretical analysis [3,4] provides quantitative understanding of the impact of cooling of the accumulator. The effectiveness of the system can be indicated by the ratio of the energy delivered to storage each cycle (Q_d) to the base-case energy (Q_b) that would be delivered by the same collector operating at the temperature of storage. Figure 5 shows this ratio as a function of q_L, which is the ratio of energy externally lost from the accumulator each cycle to the latent energy delivered to storage. The Q_d/Q_b ratio also depends on q_p, which is the ratio of parasitic energy to latent energy delivered to storage. q_L and q_p are not necessarily equal because some cooling is provided by the incoming cold liquid and because the energy for condensing the volume of vapor that displaces liquid must also be removed from the accumulator during each cycle. The important features of Fig. 5 are that system performance is quite sensitive to q_L and q_p, and that maximum performance is achieved for q_L greater than q_p. Optimal design requires that the accumulator have as little heat capacity and free liquid surface as possible, and that adequate external cooling be provided. Ideally, q_p of approximately 5% should be attainable, but near-optimal external cooling might require a temperature-regulated heat sink [3,4]. From our integrated daily measurements of system performance, we estimated that q_p of our pipe accumulators was approximately 30%, and that this caused excessive collector tempertures. While investigating accumulator design, we conceived a configuration of two accumulators that requires no external cooling.

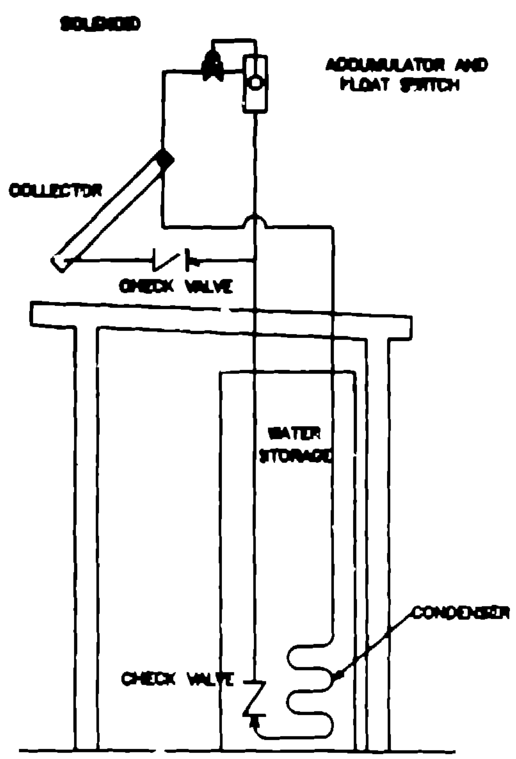


Fig. 3. Diagram of the single-accumulator system arranged for space heating of an outdoor test cell.

3. THE TWO-ACCUMULATOR SYSTEM

In the system of Fig. 6, both accumulators and all piping are insulated to prevent energy exchange with the surroundings. The collector delivers vapor to the top of the lower accumulator, from which the vapor passes upward through the open float valve to the condenser. Condensed liquid drains by gravity through a check valve into the lower accumulator. When the lower accumulator is filled, the float valve closes. The temperature of the collector

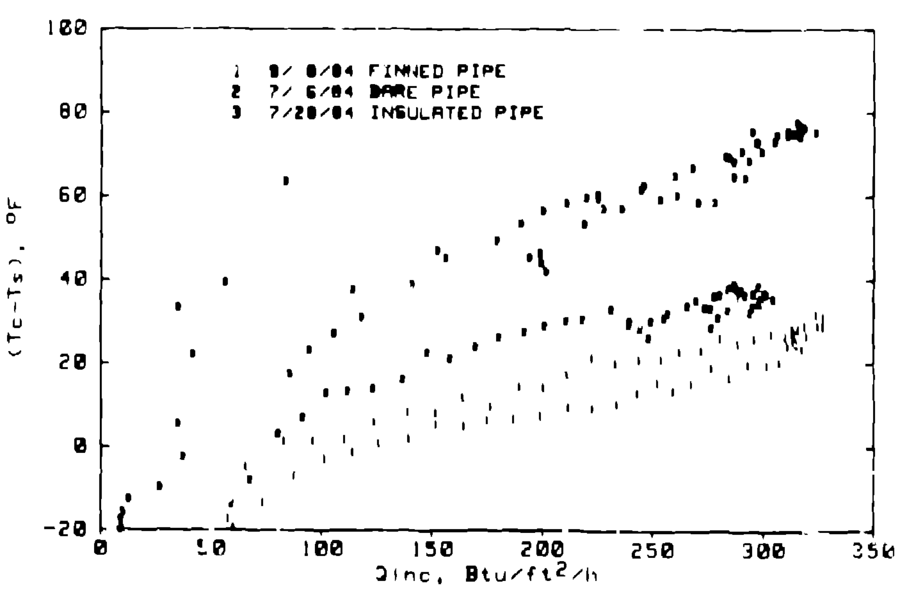


Fig. 4. Difference between the temperatures of collector outlet and the top of thermal storage, as a function of instantaneous insolation, for three accumulators with different heat losses.

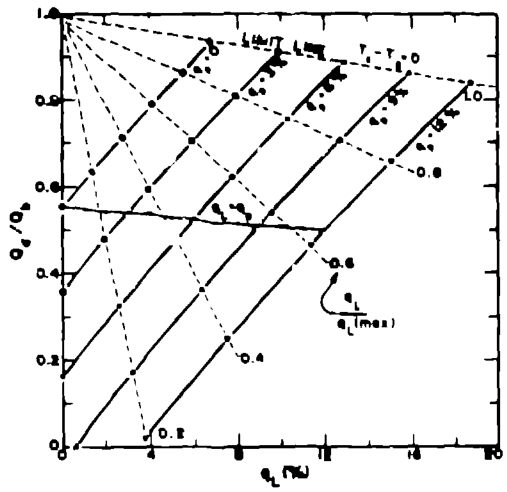
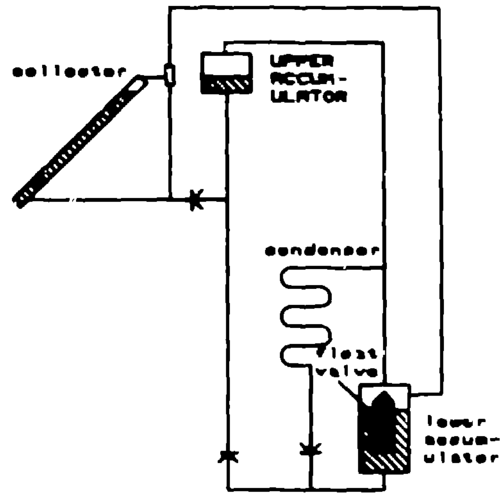


Fig. 5. Delivered fraction of base-case energy yield as a function of loss ratio for a typical collector. Insolation is 100 Btu (ft^{2}h °F)$^{-1}$, storage temperature is 80°F, ambient temperature is 32°F, and the liquid column is lifted by a 20°F difference in saturation temperature.



TWO ACCUMULATOR VAPOR TRANSPORT SYSTEM

Fig. 6. Diagram of the two-accumulator system.

and of the free surface of the liquid in the lower accumulator rises until the vapor pressure is sufficient to lift liquid into the upper accumulator. The temperature and pressure of the upper accumulator remain close to those of the condenser because of the uninterrupted vapor link between these two components. When the lower accumulator is nearly empty, the float valve opens. The temperatures of the collector and lower accumulator rapidly fall to that of the condenser because of the renewed vapor connection. Thus, the thermal energy stored by the collector and acquired by the lower accumulator during the pumping phase of operation is transferred to the condenser as useful heat.

This system has several advantages over the single-accumulator system. 1) During the major portion of the cycle, the temperture of the collector is kept close to that of the thermal storage, whereas in the single-accumulator system the collector temperature is always elevated by at least the amount required to produce liquid lift unless the accumulator is cooled to a temperature below that of storage. 2) No external cooling of the accumulator is required, eliminating the extreme dependence of system efficiency on the effective heat capacity and cooling rate of the accumulator. 3) In principle, no energy is lost from the system--all collected energy is delivered to the condenser. 4) The condenser should always be dry, enabling the condenser area to be as large as desired for heat transfer. The single-accumulator system required the condenser to be partially flooded. 5) Except during the pumping phase of the cycle, liquid continuously drains from the upper accumulator into the collector, thus keeping the collector full of liquid.

We tested the two-accumulator system with an indoor apparatus that has a cylindrical, electrically heated, vertical boiler of approximately the same metal mass and liquid volume as a collector plate of 22.4 ft^2 area. The condenser is a 50-ft coil of copper tubing, 0.625 in. OD, 0.035 in. wall, immersed in an uninsulated barrel of water. Liquid lift is approximately 15 ft. Figure 7 shows temperatures, pressures, and flow rate measured at approximately 20 s intervals during operation with 1 kW [152 Btu(ft^{2}h°F)$^{-1}$] of power supplied to the boiler, which is hereafter referred to as the collector. During the pumping phase, the collector temperature rises more than necessary to provide static liquid lift, and causes the flow rate to rise continuously. Presumably, the tradeoff between the duration of pumping phase and the excursion of collector temperature could be optimized as a function of the diameter and length of the lifted liquid column. After the float valve opens (indicated in Fig. 7 by the sharp peak of collector pressure), the temperatures of the collector and of the condenser inlet

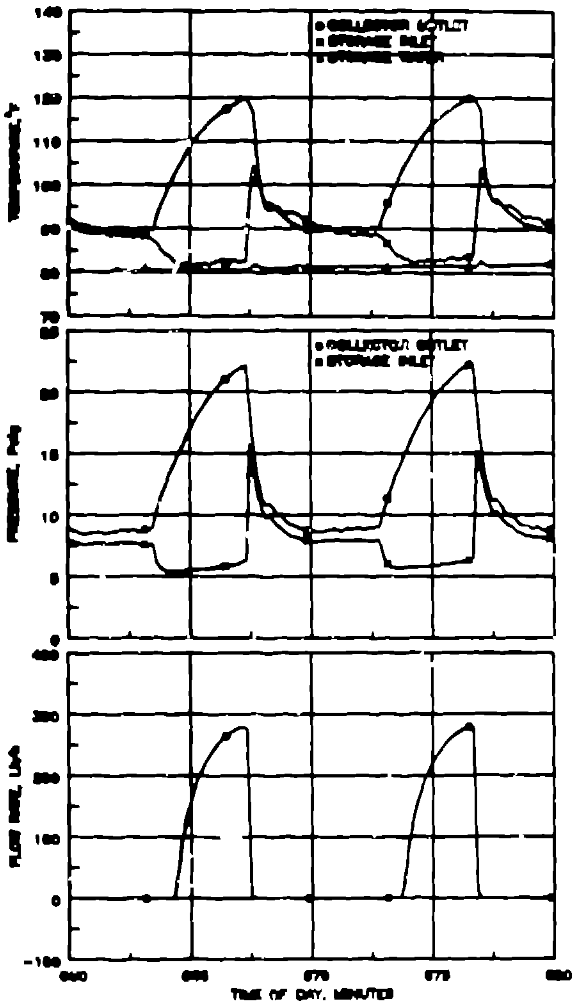


Fig. 7. Temperatures, pressures, and flow rate of the two-accumulator system with 1 kW of electrical power supplied to the boiler.

become nearly equal, and eventually become approximately 8°F greater than the temperature of the water, indicating that this is the temperature drop required for heat transfer across this particular condenser at this power level. The gradual decrease of collector and condenser temperatures that begins approximately one minute after the valve opens may be an artifice due to heat stored in the plumbing (which was unnecessarily massive). The integral of the flow rate indicates that approximately 10.6 lb of liquid is lifted each cycle. Vapor flow of this magnitude would correspond to approximately 1500 W of latent heat transport, in contrast to the 1000 W supplied to the boiler. This indicates that at this power level the flow separator (shown to the right of the collector in Fig. 6) is not completely effective, and some liquid is being carried into the lower accumulator with the vapor flow. Figure 8 shows data when 500 W [76 $Btu(ft^2 h °F)^{-1}$] is supplied to the collector. The excursion of the collector temperature and the temperature drop across the condenser to the water are less than those of Fig. 7, and the cycle time is longer, as expected. The integral of the flow rate corresponds to approximately 450 W of latent heat transport, which leads us to conclude that no liquid is entrained with the vapor flow, and that 50 W is lost through the insulation of the boiler and other components.

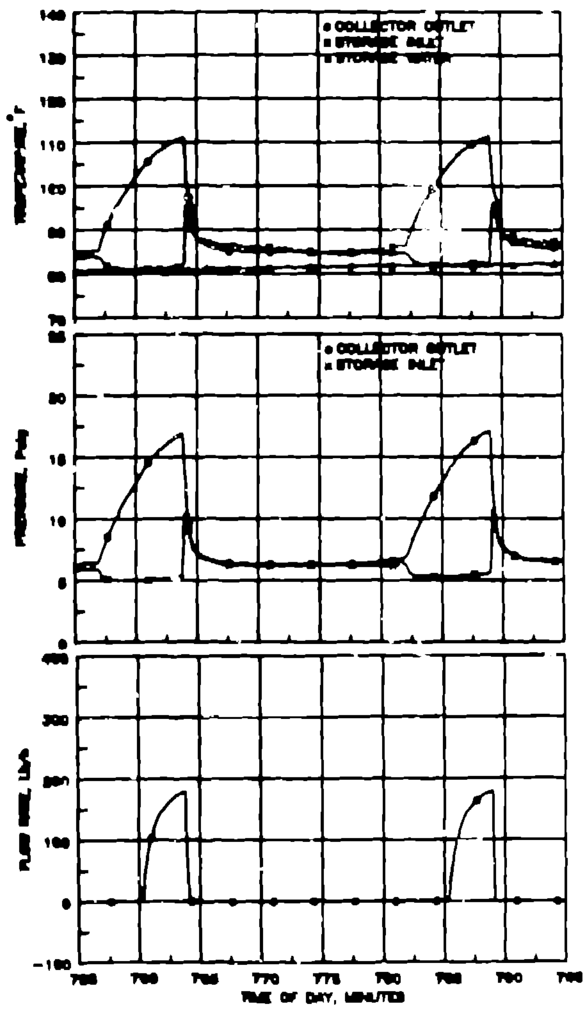


Fig. 8. Temperatures, pressures, and flow rate of the two-accumulator system with 500 W of electrical power supplied to the boiler.

Figure 9 shows the measured minimum and the average temperature differences between collector and storage as a function of power. The minimum temperature difference is due to the properties of the particular condenser and is proportional to power, as expected. The average temperature difference is appropriate for estimation of collector temperature in system studies. Using the data of Fig. 9, we predicted that the two-accumulator vapor system would give the same annual energy yield as an idealized pumped-water drainback system in a hybrid space heating application [6].

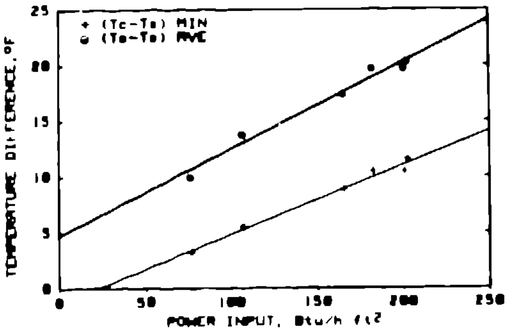
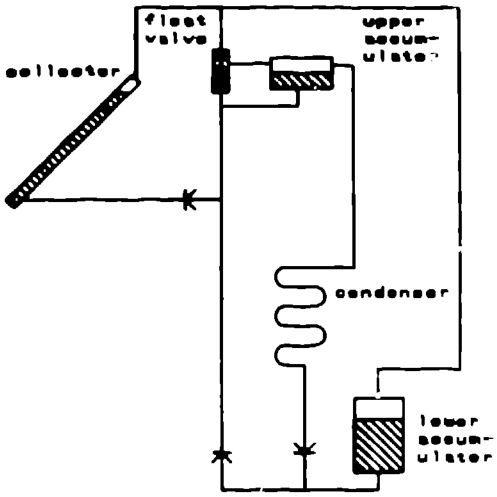


Fig. 9. Measured elevation of collector temperature above storage temperature as a function of simulated collected energy for the two-accumulator system.

Figure 10 shows a modified version of the system in which the liquid level of the upper accumulator is controlled. This version would assure that the upper accumulator always receives liquid when needed, making operation insensitive to the system volume and to the total amount of working fluid in the system. This modified version has been constructed, but not yet tested.

4. CONCLUSIONS

We conclude that passive downward thermal transport is possible for both space and water heating. The two-accumulator system provides its own cooling internally for the self-pumping mechanism, and we conclude that it is superior to the single-accumulator system.



TWO ACCUMULATOR VAPOR TRANSPORT SYSTEM
TOP CONTROL

Fig. 10. Diagram of a modification of the two-accumulator system with level control at the upper accumulator.

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