Submitted to the 1978 Annual Meeting American Section of the International Solar Energy Society, Denver, Colorado August 28-31

BNL-24579
CONF-780808--13

THE POTENTIAL FOR GROUND COUPLED STORAGE WITHIN THE SERIES SOLAR ASSISTED HEAT PUMP SYSTEM *

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ABSTRACT

The potential for ground coupling in the series solar heat pump system is explored. The ground is a thermal medium of high heat capacity, low conductivity, and a heat source and sink of virtually limitless extent. Throughout the continental United States, the natural ground temperature a few feet below the surface normally averages about 55°F. Thus, the ground is a plausible additional element useful in solar heat pump systems. This new resource permits seasonal energy storage and transfer. That is, during the summer and fall surplus energy is delivered to the ground by the solar collectors which are otherwise unused. This energy is partially retrieved during the winter season. Significantly reduced collector area results. Likewise, heat deposited in the ground acts as a "buffer" to keep the water storage temperature above 40°F so that expensive resistive heating is not used. In this paper, various ground coupling schemes are explored. Previous results and original computational models are discussed. Cost-effectiveness is emphasized heavily and the near term possibility of an economically viable solar heating system via ground coupled storage within the series solar heat pump system is projected.

1. THE ROLE OF GROUND COUPLING

Research is underway at Brookhaven National Laboratory on the series solar assisted heat pump system. The system consists of solar collectors which provide heat to a storage device which heats the load when possible. If the storage temperature is too low to do this, the heat pump removes heat from storage and delivers it to the load. The major advantage of this approach is that the presence of the heat pump "in series" with the collectors means that the collectors do not have to provide energy at a high enough temperature to carry the load when the ambient temperature is very low to be useful. As a result, the collector design requirements can be relaxed considerably. This permits the use of inexpensive solar collectors unsuitable for other solar heating systems. Since solar collector purchase and installation dominate solar system economics, this savings can be large.

*Work performed under the auspices of the United States Department of Energy.

The solar collectors provide the heat pump with a source which is at a higher temperature than the cold ambient. In order to exploit this higher temperature source, a heat pump is needed whose efficiency increases with source temperature above 40°F as permitted by the Second Law of Thermodynamics. Existing air-to-air heat pumps do not have this property due to design concessions made so that they can operate optimally with a low temperature ambient source. Heat pumps suitable for the series system are being developed under an RFP issued by the Solar R&D Branch of the Department of Energy's Solar Division. The series system has been discussed in detail in an earlier work [1].

One part of the solar assisted heat pump research program discussed above is a study of ground energy coupling techniques and their effect on the solar assisted heat pump system. There is evidence to indicate that the introduction of thermal coupling between the storage device and the ground can improve the performance and reduce the initial cost of the series solar heat pump system. The ground acts in two roles in order to achieve these improvements:

1. The ground can be used as a long term or "quasi-annual" storage device. All solar thermal energy systems designed for winter space heating have excess collector capacity during the summer and part of the spring and fall (even if the collectors are used to heat the domestic hot water). Long term storage (~months) would permit a smaller collector area to carry a given load. This is of economic importance as the collectors are the most expensive part of the solar system. Several long term storage schemes for solar energy systems have been proposed, but they are large and more importantly, expensive. The ground is an available resource for this purpose.

2. The earth acts as a "buffer" or transient heat source/sink. When the storage temperature is below the ground temperature, the ground provides heat and thus behaves as a "buffer" to help raise the storage temperature. This "smooths out" the storage temperature fluctuations and raises the annual minimum storage temperature. As a result of the latter, resistive heating is reduced or eliminated. Additionally, in the summer the ground

temperature is below the ambient temperature. Thus, the use of the earth as a space cooling heat sink means that the heat pump operates with a smaller lift and hence at a higher efficiency.

2. THE FEASIBILITY OF GROUND COUPLINGS:

It is not likely that thermal coupling between the ground and the storage element of an ordinary solar heating system will be beneficial. In such a system the storage must be maintained at a temperature (~100 to 180°F) much higher than the ground temperature (~55°F). Thus, thermal contact with the ground results in a perennial loss and is undesirable. Calculations indicate that the magnitude of this loss is unacceptably large for an uninsulated vessel. This conclusion was also reached by other authors recently via computer simulations for a particular water storage pool of volume 103m^3 (27,400 gallons) [2].

The series heat pump system has special needs which may be met by ground thermal coupling. In Ref. 1 performance analyses (using the University of Wisconsin computer program TRNSYS) and economic analyses were performed. An ordinary insulated storage tank was simulated. The economically optimally sized system occurs when the collector area is just large enough to keep the use of resistive heating very low. The average storage temperature curve is roughly sinusoidal (about ½ cycle during the heating season) as is the curve which describes the annual ambient temperature variation. These "sine curves" are in phase, i.e., they reach their minimum temperature on almost the same date (sometime in January). The curves are in phase because it is not economically feasible to provide enough storage to carry the load for more than a few days. Hence, the storage temperature is pulled down as the ambient drops and the heating demand rises, despite infusions of collected energy. The result is that during about two months of the "hardcore" heating season (roughly December 10 to February 10), the storage temperature is often below the ground temperature. It is at this time that the system would benefit most from thermal coupling with the earth. If the ground can be counted upon to provide this "emergency" heat, to facilitate long term storage, and perhaps as a sink for summer space cooling heat, the collector area can be reduced and/or the system heating and cooling efficiency can be increased.

The goal of our ground coupling investigation is to develop cost effective heat transfer and storage devices suitable for the task described above. A literature search indicated that the use of the earth as a heat pump heat source/sink is by no means a new idea. Many papers have been written on this subject (see the ASHVE Transactions from ~1948 to 1957 for many such papers). Some of the experiments described in these papers were successful. For instance, Baker (1953) reported on a heat pump system with a 146m (480 ft.) buried coil through which water circulated [3]. A storage tank (also exposed to the ground) provided thermal inertia - i.e. it acted as a sort of ballast to smooth the load. This system provided up to 8.6×10^6 Btu/month. The average seasonal COP (including compressor, fan and pump) was 3.05. This is considerably higher than the equivalent quantity (SPF) for modern air-to-air heat pumps! The main reason that this idea did not catch on, despite its apparent success, was that the considerable capital investment was not justified due to the extremely low electrical rates of the 1950's. This is no longer a problem.

A few ground coupling experiments other than the one at Brookhaven National Laboratory are presently underway. Bose [4] has an "earth coil" which is 308m (1,000 ft.) of 4 inch polyethylene pipe buried 4 ft. deep in a serpentine array. Heat transfer rates in the range of 15,000 to 20,000 Btu/hr were obtained throughout the winter. The minimum water temperature reached was 38°F. The Phoenix House has a solar heat pump system which has a large (7000 gallon) buried steel storage tank. Detailed results are contained in the most recent annual report [5]. In summary, the system was able to successfully heat the load with only a very small amount of resistive heating (1975-1976 season). Storage losses were low during the winter, and during the worst part of the heating season heat flowed from the ground into the storage tank.

Thus, there is evidence to indicate that ground coupling is desirable in the series solar heat pump system. The next section describes some of the research that has been accomplished and the experiments that are planned.

3. RESEARCH PROGRAM

The ground coupling research program at BNL is organized into a series of iterations, the first of which contains four steps:

1. Creation of heat flow models.
2. Determination of experimental configurations and inputs.
3. Analysis of experimental results.
4. Identification of promising ground coupling configurations, and validation or refinement of heat flow models for next iteration.

Modeling underground heat flow is complicated as the presence of soil inhomogeneities causes variations in the soil thermal conductivity typically on the order of 5 to 10%. Thus, no experiment based on a theory using average soil properties (even if temperature or water content dependent parameters are used) can be expected to be more accurate than this level. The presence of water in unsaturated soil leads to moisture movement in the presence of temperature gradients. This movement carries heat which modifies the temperature distribution. So in general, underground heat flow must be represented by a set of coupled differential equations to describe the coupled heat and moisture flows. However, this is not a good place to begin modeling due to the complexity of the problem, and also because the relevant ground parameters (conductivity, density, heat capacity, ground water potential, etc.) must first be experimentally determined.

Therefore, our first computational models were analytical calculations using simple geometrical shapes and transient temperature boundary conditions. Constant thermal conductivity (k), heat capacity (c), and density (ρ) were assumed, and moisture movement ignored. The values of k, c, and ρ used were those typical of a moist sandy soil [6]. These models were used to study roughly the heat flow around a given plane, length of pipe, tank, etc. Transient temperature boundary conditions that are of interest and lead to analytical solutions include a sinusoidal variation (to simulate annual storage temperature variation) and also various step functions (which help to determine maximum "emergency" heat flow rates).

The realm of interesting problems that could be solved analytically was soon exhausted. A computer program (GROCS) was written to solve more complex problems. The usual way to solve heat flow problems on a digital computer is to convert the involved differential equations to finite difference equations, and then to solve these equations on a "mesh" of discrete points at finite time steps. This is feasible in one dimension, but very time consuming in three dimensions due to the large number of mesh points needed. Since we do not require better than 5 or 10% accuracy, instead of a mesh GROCS uses up to 30 "blocks" (this number could be expanded greatly) of which there are 20 "free" blocks and 10 "rigged" blocks. The free blocks simulate the ground coupling device and its environs, while the rigged blocks surround the free blocks to provide boundary conditions. A sub-program (TINTERP) uses a linear interpolation routine and published underground temperature data for BNL [7] to give each rigged block the temperature appropriate for its depth at each time step. The free blocks can have any initial temperature (a default value causes TINTERP to set this value), and also can have heat added or subtracted from them to simulate a heating load, solar collection, etc. To test a proposed ground coupling device, a model is drawn by hand, with various parameters (volumes, heat capacities, heat transfer areas, heat inputs, etc.) specified and used as data for GROCS.

The interesting cases involve various heat input scenarios such as winter emergency heat withdrawal or summer space cooling heat rejection. However, each model can be tested for accuracy by using a "dummy" heat package with no input. Then the free block temperatures determined by heat flow equations in the program can be compared to the experimentally determined values cited above. This also provided a determination of the best value of the diffusivity (k/cρ). Various values of this parameter were tested, and the one which produced the lowest "χ^2" relative to the experimental data was used for all subsequent work. Note that this is a further theoretical simplification as an early experiment showed that the diffusivity varies with depth [8]. Nevertheless, models using a constant diffusivity were able to produce free block temperatures usually within 1°F of the experimental values. It appears that at moderate temperatures at least, a simple computer model with constant soil thermal parameters can produce accurate results. Because of its simplicity, this is a useful tool.

Based on the computational models and literature described above, the first generation experimental ground coupling devices and heat input scenarios were determined. The devices in this generation are relatively simple so that ground heat flow information can be more easily extracted. Four tank experiments are initially planned. These tanks will be made from precast (solid) concrete cesspool rings, with a precast flat lid and a poured concrete floor. The interior surfaces will be waterproofed. A table of the tank experiments planned is shown below.

Tank	Volume	Heat Input Simulation	Notes
1	$10.6 m^3$ (3000 gal)	winter heating storage only	2" of styrofoam on top & 1/2 way down sides of tank.
2	$17.7 m^3$ (5000 gal)	winter heating & also summer space cooling heat daily storage w/ nocturnal dumping	
3	$10.6 m^3$ (3000 gal)	winter heating, & storage of summer solar collected heat.	
4	$10.6 m^3$ (3000 gal)	winter heating, summer space cooling heat sink, late summer & fall solar collection storage	advanced configuration

The top of each tank is 1.2 m (4 ft) underground. All tanks have heat loads which simulate a moderate size (1500 ft^2) well insulated residential building. In all cases the solar collector input simulates 27.9 m^2 (300 ft^2) of low temperature collector. This size was found inadequate in Ref.1 (with conventional storage) and is used to make more evident any gains from ground coupling.

Four "coil" experiments are also planned initially. Each of these contains a serpentine array of various lengths of 1 1/2 in. o.d. flexible polyethylene pipe. These experiments are described in the following table.

Coil	Length	Gross Configuration	Heat Input Simulation
1	152m (500ft)	15m long x 1.2m wide x 2.4m high, top at 1.2m depth.	winter tank shortfall, summer space cooling
2	229m (750ft)	7.6m x 7.6m x 2.4m high, top at 1.2m depth	winter total storage, summer space cooling, late summer & fall solar collection
3	91m (300ft)	Plane 7.6m x 4.9m at 0.6m depth, insulation over pipe	winter tank shortfall, summer space cooling, fall excess solar collection
4	152m (500ft)	Plane 9.1m x 12.2m at 1.2m depth	winter tank shortfall, summer space cooling

A set of secondary experiments designed to measure the perturbed (under the influence of heat inputs and withdrawals) and unperturbed ground parameters k, c, ρ) has also been planned. Soil core samples will be taken during excavation. These will be weighed to determine their density (ρ). A calorimetric method will be used to determine their heat capacity. If possible, a chemical analysis will be made. This will yield an accurate determination of the heat capacity and a fair estimation of the thermal conductivity (see Ref. 6 for elaboration). Another experiment will use a cylindrical heat source/sink consisting of a long thin copper pipe through which antifreeze, heated or cooled by a heat pump, will be circulated. Temperature sensors will provide a direct measurement of the thermal conductivity. This set-up provides the freedom to test the value of k under extremes of temperature. The diffusivity k,cρ) will also be measured at the experimental site using the method described in Ref. 8.

It is hoped that the experiments described above provide sufficient variety of technique and redundancy to obtain reliable values for the important thermal parameters. These parameters together with the information gained from the tank and coil experiments will be used to generate our second generation computational models. These will be used to determine optimized group coupling devices for further experimentation.

Acknowledgement

I would like to thank J. G. Cottingham for innumerable valuable discussions, suggestions and ideas during the course of this project.

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