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Publisher's version / Version de l'éditeur:

International Journal of Energy Research, 11, 4, pp. 573-581, 1987

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by O.J. Svec

ANALYZED

Reprinted from
International Journal of Energy Research
Vol. 11, No. 4, 1987
p. 573-581
(IRC Paper No. 1523)

Price \$3.00

NRCC 28788

RÉSUMÉ

Ce document présente un historique de la technologie des pompes à chaleur à captage au sol, suivi d'un examen de ses défauts actuels. En se basant sur ces observations, l'auteur évalue le besoins en R-D et propose des thèmes de recherche pour l'avenir.

POTENTIAL OF GROUND HEAT SOURCE SYSTEMS

O. J. SVEC

Division of Building Research, National Research Council of Canada, Ottawa, Ontario, Canada, K1A 0R6

SUMMARY

This paper presents a historical background of ground source heat pump technology, followed by a review of its current shortcomings. Based on these observations the author assesses the R&D needs and recommendations for future research.

KEY WORDS   Heat pump   Ground source

INTRODUCTION

Storage of thermal energy will play an important role in heating systems if efficient, cost-effective energy exchange can be achieved. One of the most promising methods of storage uses undisturbed ground as the storage medium, but to make ground heat storage feasible, construction costs must be lowered, energy transfer into and out of the storage system must be improved, and heat losses to the surrounding ground and ambient air must be minimized (see Table I).

The first problem, high construction costs, can be dealt with by developing novel drilling and excavation methods and a ground heat exchange system that is an integral part of the installation. Efficient energy exchange between stored heat and a building space can be achieved by improving heat exchanger efficiency, operational strategy and the storage/source configuration. The problem of minimizing heat losses to the surrounding ground can be approached by using either natural or artificial insulation (which might escalate construction cost), or by lowering the storage temperature level (which would lower storage capacity).

The operational ground storage temperature will determine the type of storage-source device; temperature variation above, around or below ground mean temperature classifies such a device as storage, storage/source or source, respectively. By using heat pumps, storage/source and source systems can still be effective at much lower storage temperatures.

One of the most promising possibilities is to use natural ground as a low-grade heat storage/source medium and to employ a heat pump to upgrade the energy level and improve ground coupling energy exchange. This paper will review the development of ground energy source technology, i.e. ground-coupled heat pump systems, focusing on problems related to the design and performance of ground heat exchangers. It is the author's opinion that improvement in heat exchange efficiency together with economical installation techniques, possibly as an integral part of a heat exchanger design, are key factors in the marketing success of this emerging technology.

HISTORICAL BACKGROUND

The first 25 years

The idea of using undisturbed ground as a heat source for heat pump applications was introduced in a Swiss patent by Zoelly in 1912 (Wirth, 1955), but only after the Second World War, particularly following the energy

Received May 1986

Table I. Research and development storage/source

Minimize heat losses		Improve energy exchange		Develop better construction techniques	
Low cost insulation	Lower storage temperature	High efficiency heat exchangers	Operational strategy	System configuration	Novel techniques, e.g. drilling
Natural (dry soil)	Above mean T (storage)	Design	Cycling (short/long term)	Single heat exchange	Jetting
		Material		Group/line	Pushing
Foam	Around mean T (storage/source)	Backfill	Steady-state	Spacing	etc.
	Below mean T (source)		Operating temperature	Depth	
			Fluid flow		

crisis in the early 1970s, was this concept revived for commercial use. Probably the first to re-introduce Zoelly's plan were Kemler (1946) and Crandall (1946). An early survey of post-war research efforts in the United States was published by the Joint AEIC-EEI Heat Pump Committee (*Initial Survey of Heat Pump Research*, 1948). The objectives of ground-coupled heat pump research were set by the committee and published as *Progress Report on Heat Pump Research* (1949). Among the initial, theoretical studies was that by Ingersoll and Plass (1948) who adopted Kelvin's heat source theory of flow of heat from soil to buried pipes; Hadley (1949) correlated operating data of existing test heat pump installations. The first research installation in Canada during this period was reported by Hooper (1952).

Even at this developmental stage it was recognized that it is important to know such thermal ground characteristics as soil thermal conductivity and specific heat capacity. These properties are directly dependent on the type of soil (mineral composition and particle distribution), soil density, and moisture content, and indirectly dependent (in a non-linear sense) on heat and mass transfer processes. For example, temperature gradient causes migration of moisture by diffusion towards the heat exchanger during the heating season, with the result that there is an increase in thermal conductivity (Ingersoll *et al.*, 1951). These changes in conductivity and specific heat capacity at various distances from a heat exchanger were measured by Vestal (1949). At about the same time the influence of moisture content was demonstrated by Kemler and Golesby (1950), who showed how significantly it alters the soil thermal conductivity. For example, thermal conductivity can differ tenfold, from 0.25 to 2.5 W/m K, under dry or wet conditions. Kemler also showed that any thermal changes occurring in soils as a result of heat extraction are rather slow. Many other consequences of heat and mass transfer were recognized thirty years ago: the effect of freezing on thermal conductivity, ice lensing in frost-susceptible soils and the resulting influence on heat transfer, soil structural changes around heat exchangers after thawing, the effects of forced and natural convection in porous media, the effects of drying and wetting, etc.

The end of the 1940s and the first half of the 1950s was marked by the installation of a large number of experimental ground source heat pumps. Experiments published by Coogan (1949), Smith (1951), Penrod *et al.* (1950), Kidder and Neher (1952) and Harlow and Klapper (1952) are examples of research efforts in the United States at this period. Besides encompassing practical demonstrations, the research provided information on the heat extraction rates. For example, Penrod (1954) obtained a heat flux of up to 50 W/m for 25 mm diameter copper pipes buried horizontally at a depth of 1.5 m. Similar extraction rates were achieved by Vestal and Fluker (1956) for copper pipes 13 and 25 mm in diameter at a depth of 1.6 m in various soils in Texas; heat extraction rates up to 100 W/m were achieved with larger 50 mm diameter copper pipes during short runs (7 days). Similar results were published by Smith (1956) and Freund and Whitlow (1959), and in the Canadian study by Hooper (1952) that has already been mentioned. The seasonal average extraction rate from 1.8 cm horizontally laid copper coil reported by Hooper was about 21 W/m. Among other Canadian efforts are a private experiment in Burlington, Ontario, that is still operational after some 30 years, and experiments with

ground heat extraction coils by Brown and Wilson (1963) at the National Research Council of Canada.

The first ground-coupled heat pump installation in Great Britain was designed and built by Griffith (1952) to determine the rate of heat extraction using horizontal copper pipes buried at 1.25, 1.8 and 2.5 cm in London clay. He reported rather high heat absorptions of 30–60 W/m and 80–100 W/m (pipe) for steady-state and the initial transient state (2 h), respectively. Another U.K. researcher working on residential heat systems during the early 1950s was Sumner (1955). At about the same time a well-known German researcher, von Cube, installed in his own home a horizontal steel pipe system that is still operational (von Cube and Stiemle, 1981); he recorded an annual average seasonal performance factor close to 3.

A review of earth heat pump installations in the U.S., published by the AEIC–EEI Heat Pump Committee (1953) showed interesting results for heat transfer on two surfaces—horizontal (tubes) and vertical (tanks). For horizontal tubes the ranges of heat transfer were 1.1–8.9 W/m²°C and 1.1–2.3 W/m²°C for heating and cooling cycles, respectively; for vertical surfaces the ranges were 6.1–38.2 W/m²°C and 8.3 W/m²°C (one test only), again for heating and cooling cycles. There is a striking difference between heating and cooling cycles. Other authors, for example Smith (1956), Ambrose (1966) and recently Svec *et al.* (1983), have also observed that the thermal contact resistance between a pipe wall and the surrounding soil is important, particularly during the cooling season.

It was during this time that the concept of a combination of a solar collector and buried pipes to permit storage of solar energy in the ground was suggested by Penrod (1956). More than a decade later, in 1969, he helped to design a pilot plant (Penrod and Prasanna, 1969). After this relatively brief period of enthusiasm, however, interest in ground source pump technology dwindled, owing to the availability of cheap energy.

Developments following the energy crisis

Only after the first major increase in OPEC oil prices in 1973 did interest in ground-coupled heat pump research regain momentum. Particularly in Europe, this renewed activity resulted in many experimental installations and research projects: Watterkotte (1972), Sowa (1974), Rouvel (1975), Sumner (1976), Morgensen (1979), *Nordic Symposium on Earth Source Heat Pumps, Proceedings* (1979, see contributions by Berntsson, Rudolph, Rosenblad, Morgensen, Hellstrom, Nivergeld *et al.*, Wiksten and Korsgaard) and Niewergeld *et al.* (1980). In the majority of these installations closed ground coils separate from heat pump refrigerant loops were used. There were efforts, however, to improve efficiency by circulating refrigerant directly in the ground loops. In these cases the ground coil serves as a heat pump evaporator and is an integral part of the heat pump system (Goulburn and Fearon, 1978, 1983). Altogether, many pilot plants were opened during this period.

Many thousands of ground-coupled heat pump systems have been built since the mid-1970s, notably in Sweden. International conferences have been the major forum for the exchange of ideas. Since too many valuable papers were presented at these meetings to mention them individually, the interested reader is referred to the *Nordic Symposium on Earth Source Heat Pumps, Proceedings* (1979), the *Workshop on Solar-Assisted Heat Pumps with Ground Coupled Storage, Proceedings* (1982), the *International Conference on Subsurface Heat Storage in Theory and Practice, Proceedings* (1983), the *Ground Source Heat Pump Workshop, Proceedings* (1985) and the *Second Workshop on Solar Assisted Heat Pumps with Ground Coupled Storage, Proceedings* (1985).

In the U.S. the surge in ground source heat pump research and marketing of these systems began around 1977–1978. In the early stages this activity covered experimental and analytical investigations, its major goal to check past test results and re-examine design methods originally proposed in the 1950s and 1960s. Many factors involved in ground source heat pump systems, such as depth, pipe spacing and loop configurations in horizontal systems, heat exchanger types, backfill and the configuration of holes in vertical systems, as well as the thermal characteristics and behaviour of various soils, were topics of these research efforts. Among well-known researchers who have contributed to the development of earth source heat pumps since the mid-seventies in the U.S. are Bose (1979, 1981, 1982), Parker and Frierson (1981), Metz (1979, 1981a) and Andrews (1979).

A major departure from the design of past installations was the introduction of plastics as heat exchanger

material. The obvious advantages are that plastics are non-corrosive, tough, relatively inexpensive, easy to handle and easy to joint. They do, however, suffer a major drawback: low thermal conductivity. For example, the thermal conductivity of a plastic pipe (even high-density polybutylene) is only one quarter that of clay. Moreover, significant contact resistance may occur. In spite of this, plastic pipe ground heat exchangers have become a common component of ground heat source systems.

In recent years there has been a trend towards improving the basic design of ground source systems, developing mathematical models for predicting their behaviour in various climates and soil conditions, and improving the economic potential of all system components. Examples of recent efforts to develop an advanced, highly efficient ground heat exchange system were reported by Bruck *et al.* and by Svec at the Second Workshop on Solar Assisted Heat Pumps with Ground Coupled Storage (1985) in Vienna. The author is a strong advocate of high-performance ground heat exchangers and in his opinion this is the best area for R&D to concentrate in making ground source heat pumps competitive.

Concerning the development of mathematical models, Ball *et al.* (1982) summarized the current (to 1982) world status of available computer codes. For research purposes the most valuable codes are those that can model complex geometry and complicated ground-to-building heat transfer. Discussion here is therefore limited to two- and three-dimensional, transient, finite-difference and finite-element models. In North America the following have been developed: GROCS (Metz, 1981b), CONVEC (Whiteacre *et al.* 1974) and that by Harlan and Svec (1977). All are finite-difference models (the last two codes include forced convection). Acres Consulting Services Ltd. (Atkinson, 1978) produced a finite-element model, and Mei and Fischer (1983) a finite-difference code. The latter is capable of modelling concentric tubes, including convection inside the tube as well as in the annulus.

Several finite difference models of heat and moisture transfer in soils were developed originally by U.S. universities for mainly agricultural applications between 1974 and 1981 (Schroeder, 1974; Slegel, 1975; Shapiro and Moran, 1978; Sophocleous, 1978; Dempsey, 1978; Ahmed, 1980; Hartley, 1981). An exception is the finite-element model designed by Walker *et al.* (1981) for simulating the trans-seasonal performance of earth storage of solar thermal energy.

Moisture movement under temperature gradient is an important factor to be considered in developing ground-coupled heat pumps, since the air-conditioning mode is vital, particularly for penetrating the North American market. Rather limited experience and research results indicate that drying of soil around ground heat exchangers (during the air-conditioning season) makes it difficult for them to reject large amounts of heat in a short period of time. The problem of heat and mass transfer in soils has been studied extensively during the last ten years. For a review of the existing mathematical models of this phenomenon with respect to ground heat exchanger systems the interested reader is referred to a paper by Fischer (1983) in which he concluded that Slegel's and Schroeder's models are probably the best for ground source heat pump studies.

There are several two-dimensional finite-difference and finite-element ground-coupled heat pump and ground storage models in use in Europe. Well-known are codes by Blaude of the University of Liege, Belgium (*Nordic Symposium on Earth Source Heat Pumps, Proceedings*, 1979), by Claesson and Johansson (1980) of the University of Lund, Sweden, by AGA-thermia, Sweden, by Neiss and Winter (1977) of the Technical University of Munich, Germany, by von Cube (1980) also of Germany, by Hultmark (1983) of Sweden, by Nievergeld of the TNO organization of the Netherlands (*Nordic Symposium on Earth Source Heat Pumps, Proceedings*, 1979), by Schlosser (1978) at the Technical University of Denmark, by Geeraert and Steffens (1979) of Laborerec, Belgium, by Hellström (1982) of the University of Lund, Sweden, and very recently by Lund and Östman (1985) of the University of Technology, Helsinki, Finland. The author does not suggest that this list of computer models is complete. There are probably any number of other programs concerned with design requirements and installation specifications.

To ensure that computer modelling is successful, the thermal characteristics of soils have to be known. The most important of these is thermal conductivity, a function of many variables. For a particular soil, however, thermal conductivity is mainly dependent on moisture content. Considerable work has already been done in this area. A review of techniques for measuring soil moisture *in situ* (McKim *et al.*, 1980) will provide up-to-date information, and the following publications dealing with thermal conductivity are examples of numerous

other sources: Moench and Evans (1970), Boggs *et al.* (1980), Baker and Goodrich (1984) and Farouki (1981).

In general, there appears to be a lack of computer models suitable for designing a system under given site conditions. Most design procedures are based on past experience and rule-of-thumb rather than on the characteristics to be taken into consideration for a particular installation. The obvious difficulty with ground source heat exchanger design is the dependence of thermal properties of soils on moisture content and density. Further, there is often great variability in soil type at a single location. Without detailed site investigations, gross assumptions have to be made concerning average soil type, water content, thermal conductivity, thermal capacity, frost susceptibility, etc. As a natural extension of measuring techniques, calculation methods have to be developed for estimating thermal conductivity, for example the well-known equations of Kersten (1949). A good source of information on methods and their value in calculating soil thermal conductivity is a CRREL publication by Farouki (1982).

Recently there have been efforts to develop a method for selecting appropriate values of thermal characteristics of soils, particularly thermal conductivity. Salomone (1982) and Salomone and Wechsler (1984) have shown that the critical moisture content of clay soils (the moisture content below which thermal conductivity sharply decreases with further drying) can be correlated with engineering soil characteristics such as shrinkage and plastic and liquid limits. In other words, the thermal behaviour of soils can be estimated by already well-known and rather simple soil tests. Such an approach together with a soil type classification should contribute significantly to better design methods for ground source heat pumps.

PROBLEM DEFINITION

A review of the current status of ground source heat pump technology reveals the following outstanding problems and areas for potential improvement:

- (a) low efficiency of ground heat exchange systems (a problem of basic design)
- (b) lack of optimization of ground heat exchanger design (a question of type of configuration: length, depth, spacing, etc.)
- (c) poor knowledge of soil-heat-exchanger thermal and structural interaction (effect of drying, contact resistance, freezing/thawing soil integrity)
- (d) difficult (for an installer) soil thermal characterization techniques (moisture content, thermal conductivity)
- (e) lack of knowledge of long-term effects on soils (drying/rewetting)
- (f) lack of knowledge about natural recharging (configuration of vertical systems)
- (g) lack of knowledge about operational strategy (cycling versus steady state)
- (h) insufficient degree of integration of system design, i.e. heat pump and ground heat exchange are still separate technologies (only modified for coupling)
- (i) lack of comprehensive yet detailed mathematical models, particularly ones that include heat and moisture migration
- (j) insufficient monitoring of existing systems
- (k) improvement of overall system performance (matching of load, ground heat exchange system and heat pump)
- (l) insufficient design information such as sizing for a particular heating versus cooling load ratio and site specification.
- (m) lack of data and experience in industrial scale system design.

It is clear that much research work remains to be done before ground source heat pumps can become truly competitive with other heating systems. There are indications, however, that a strong potential exists for improvement (*International Conference on Subsurface Heat Storage in Theory and Practice, Proceedings, 1983*).

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

The history of ground source heat pumps and the problems still outstanding lead to the following conclusions.

1. Ground source heat pumps perform well provided that the design (sizing) is adequate for a particular site.
2. In most countries the technology cannot yet compete with conventional heating/cooling systems.

Although it is expected that progress will be made in the development of more efficient heat pumps, energy exchange in the ground is a much more promising area for improvement. For example, it has already been demonstrated that heat extraction rates per unit length can be considerably increased by using larger diameter copper pipes. Griffith (1952) showed that by doubling the size (diameter) of a copper pipe from 0.125 cm to 2.5 cm the heat extraction rate in steady state is also doubled from 30 to 60 W/m. Similarly, Vestal and Fluker (1956) achieved extraction rates of up to 100 W/m by using large, 2.5 and 5.0 cm diameter, copper pipes and brine temperatures as low as -5°C .

It can hardly be expected, however, that such large diameter copper pipes will be economically feasible. On the other hand, extraction rates in most current systems, in which plastics and or above-freezing brine temperature are used, are between 15 and 25 W/m. The author's proposal concerning these contradictions (high rates in the past versus low rates in the present, copper versus plastic, small diameter versus large diameter) is that a very high (over 100 W/m) extraction rate can be achieved by designing a heat exchanger that appears (thermally) to be like a large pipe as opposed to one that is actually large. The author's experiments support this argument (*International Conference on Subsurface Heat Storage in Theory and Practice, Proceedings*, 1983). A heat exchanger was built of four small-diameter (1.25 cm) copper pipes placed symmetrically in a 30 cm diameter hole augered in clay and backfilled with saturated sand. For a brine temperature of -3°C the heat extraction in 'steady state' (after 24 h) was 70 W/m; during the initial transient state, an extraction rate over 150 W/m was achieved. This is about triple the rates obtained with a standard 3.75 cm plastic U-tube.

Recently a new vertical heat exchanger was designed and installed. Made of 1.90 cm copper tubing, it was wound into a coil with an outside diameter of 25 cm and stretched into a spiral while being placed in a 30 cm diameter hole drilled in clay. The hole was backfilled with sand. Better heat extraction rates and improved structural integrity with respect to deformation (settlement) of the clay after thawing are anticipated.

The importance of achieving high extraction rates can be illustrated. If the heat extraction of a vertical ground heat exchanger were to be increased by a factor of three, its length could be reduced, in theory at least, by the same ratio for the same performance. Drilling costs would be reduced by a factor of three and a 20–25 per cent saving on the overall cost of the system could be realized. It is the author's belief that such a reduction in cost is possible and, further, that ground source heat pumps will become a competitive alternative for heating/cooling systems.

Based on these arguments, the author suggests that a comprehensive list of research topics should include

- (1) development of advanced designs of ground heat exchange systems, including a basic geometrical configuration for a heat exchanger, material, backfill, depth, grid spacing, operational temperatures and strategy, direct expansion of refrigerant versus secondary brine circulation and soil-heat-exchanger interaction
- (2) optimization of earth-coupled heat exchangers, for example, with respect to cost (including novel designs) using computer models, laboratory scaled-down models or full-scale demonstration projects
- (3) characterization of soil thermal properties, for example, development of a method of determining thermal conductivity of soil from its engineering properties, such as plastic, liquid and shrinkage limits
- (4) investigation of soil thermal behaviour, such as drying (due to heat rejection or seasonal), moisture regeneration (by natural or artificial means), consequences of freezing/thawing, natural thermal recharging and means of artificial recharging
- (5) development of advanced mathematical models of the entire ground source system, i.e. various types of complex heat exchangers and their specific operational modes
- (6) monitoring of existing ground source heat pump plants, particularly performance in the cooling mode
- (7) development of design and installation manuals
- (8) development of industrial-scale ground-coupled heat pump systems.

CONCLUSION

It has been the main objective of this paper to present a rather simple sketch of the historical background of ground source heat pump technology and to throw some light on its uncertain but promising future. The author has not attempted to make his account complete, but hopes that major trends and contributors have been recognized. It is almost impossible to include all significant research projects and existing installations in the world, but he hopes that this paper will serve as a reminder of the past and a source of suggestions for future research.

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