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RÉSUMÉ

La plupart des installations de stockage de la chaleur dans le sol utilisent un réseau de tuyaux en plastique horizontaux ou verticaux pour le transport du fluide caloporteur. En concevant ces systèmes il est généralement admis que les effets thermiques des tuyaux en plastique peuvent être négligés. Ce rapport traite d'une étude effectuée en laboratoire sur les caractéristiques du flux thermique autour des tuyaux caloporteurs en plastique enterrés dans des sols argileux. Outre les mesures du flux de chaleur et le calcul des résistances de contact pour un certain nombre de configurations, cette étude comporte un modèle numérique pour un régime stable, un régime transitoire et le comportement cyclique de plusieurs configurations. On montre aussi que les flux de chaleur sont nettement réduits lorsqu'on utilise des tuyaux en plastique.

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HEAT TRANSFER CHARACTERISTICS OF IN-GROUND HEAT EXCHANGERS

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SUMMARY

Most in-ground heat storage installations use a system of horizontal or vertical plastic pipes to carry heat exchanger fluid. In designing these systems it is generally assumed that the thermal effects of the plastic pipe can be neglected. This paper reports a laboratory study of the pattern of heat flow around fluid-carrying plastic pipe buried in clay soil. Heat flow measurements as well as estimated contact resistances are presented for a number of configurations. In addition, numerical model computations are given for steady-state, transient and cyclic behaviour of several configurations, and it is shown that substantially reduced heat flows are obtained when plastic pipe is used.

KEY WORDS Heat exchange Heat pumps Ground-source heat exchangers

INTRODUCTION

Heat pumps for domestic hot water or space heating applications generally use air, groundwater or natural ground as a source of energy. The air heat source represents the simplest application of a heat pump. Air-to-air or air-to-water systems have been commercially available for a number of years, but the economical feasibility of air source heat pumps in Canada is still marginal and the majority of installations are justified only by the desire for air-conditioning during the summer. Large air temperature fluctations plus the fact that the source air is coldest when the demand for heat is greatest are major problems. Groundwater, which is not usually subjected to any significant seasonal temperature variation, nevertheless has not been widely used in heat pump installations because of the cost of development of a well with sufficient flow (30–50 l/min) and because of restrictions regarding the disposal of the outgoing cold water.

By contrast, use of natural ground as a heat source for heat pumps seems promising and the technology is already widely used, mainly in Sweden and to a lesser extent in other European countries. The temperature of the ground is relatively high and very stable at depths below about 3 to 4 m. The ground has high heat capacity, low thermal conductivity and is an excellent heat source or sink. Furthermore, heat storage is possible on a short-term or seasonal basis. The major problem associated with using the ground as a storage medium or as a direct heat source lies in finding an efficient method of extracting or injecting heat. Heat transfer from a circulating fluid usually employs a system of buried pipes. In most existing applications plastic is selected as the pipe material. Plastics, however, have a low thermal conductivity, typically an order of magnitude less than that of soil. There is therefore a significant drop in temperature between the circulating fluid and the surrounding soil. Other factors influencing heat transfer in buried pipes are the fluid boundary-layer inside the pipes and the contact resistance between the outside wall and the soil. Most current designs of in-ground heat exchangers completely ignore the fluid boundary-layer, losses through the wall, and the contact resistance, in spite of the fact that reduced thermal transfer capability has been observed for buried pipes in clay after cyclic thermal loading.

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Theoretically, this phenomenon can be treated as an increase of contact resistance. Experimental evidence is presented in this paper concerning the significance of contact resistance.

Many engineering applications neglect certain aspects of heat transfer, establishing no rigorous base for the assumed values. The present study attempts to prove that for in-ground heat exchangers it is extremely important to consider all features controlling heat transfer.

HISTORICAL BACKGROUND

The concept of an in-ground heat exchanger system for heat pump application is not new, for use of the ground as a heat source was introduced in a Swiss patent by Zoelly in 1912. Only after the Second World War, however, was the concept revived with the development of the classical theory for ground-pipe heat conduction by Ingersoll and Plass (1948).

In the late forties and early fifties there was considerable effort in the U.S. and Europe to pursue heat pump development to the commercial stage, but because of the availability of cheap energy these systems were not economically competitive. Interest dwindled and was ultimately limited to research, with emphasis on determining the heat extraction rates for actual installations. Griffith (1952) reported extraction rates of 30 to 60 W m^{-1} for copper pipes buried at a depth of 2 m in 'moist soil' in England. His results demonstrated that for a high-conductivity pipe material the extraction rate is almost independent of pipe diameter for internal diameters in the range 19 to 25 mm. Penrod (1954) published heat extraction rates in the range of 20 to 50 W m^{-1} for 25 mm diameter copper pipes buried at a depth of 1·5 m. And similar extraction rates were obtained by Vestal and Fluker (1956) for copper pipes 13 and 25 mm in diameter buried at a depth of 1·6 m in various solids in Texas; heat extraction rates up to 104 W m^{-1} were achieved with larger 50 mm diameter copper pipes. Similar results have been published by Freund and Whitlow (1959) and Smith (1956) and, more recently, by Sumner (1976) and Bose, Ledbetter and Partin (1979). Horizontal as well as vertical configurations of in-ground heat exchanger systems using 9·5 mm OD copper pipes were investigated by Goulburn and Fearon (1978). They arrived at a figure of 30 W m^{-1} heat flux per tube for a horizontal system, but found 40 to 50 W m^{-1} per tube for vertically placed heat exchangers.

In recent years the trend has been to use plastic pipes. Plastic was introduced for economic reasons, justified by the argument that resistance to heat transfer is much greater on the ground side than on the heat pump side. It will be demonstrated, however, that extraction rates show a significant drop due to poor thermal conductivity of the plastic pipe. Bose, Ledbetter and Partin (1979) used 10·16 cm polyethylene pipe buried 1·2 m deep in a serpentine array. Heat transfer rates in the range of 20 to 50 W m^{-1} were obtained throughout the winter. Metz (1979) used 3·8 cm flexible polyethylene pipe in various experimental configurations; and Rosenblad (1979) described an array of 19 vertical PVC pipes, 10 m long, of 90 mm OD and wall thickness of 2·4 mm used as a ground heat exchanger.

A large number of ground-coupled heat pump installations exist, particularly in Sweden and Germany. Since the list is very long only a few can be mentioned, not necessarily in order of importance. Many Swedish projects are listed in the *Nordic Symposium on Earth Heat Pumps* (Rosenblad, 1979) and by Hellström (1979); and some of the German installations have been described by Rudolf (1979), Rouvel (1975), Reiman (1980) and Schinke and Mostofizadeh (1981). In most of these projects high-density polyethylene tubes are used in horizontal configurations, but several projects used vertical systems of return U-shaped pipes that suggest a trend towards vertical heat exchanger systems.

A fairly large number of mathematical models have been developed for analysing the entire system, including buildings, heat pump and ground heat storage with heat exchangers or with solar collectors. A comprehensive list of these computer programs according to degree of sophistication was published by Ball (1981). He concluded that in spite of research efforts no sutiable general guidelines for design of a ground-coupled system could be developed. There are still uncertainties regarding heat transfer in dry soils, the long-term effects of cyclic thermal loading on materials and over-all heat transfer (particularly the increase of contact resistance between the soil and the walls of heat exchangers) and the effect of moisture migration. The present paper focuses particularly on heat transfer through the walls of buried pipes, including contact resistance.

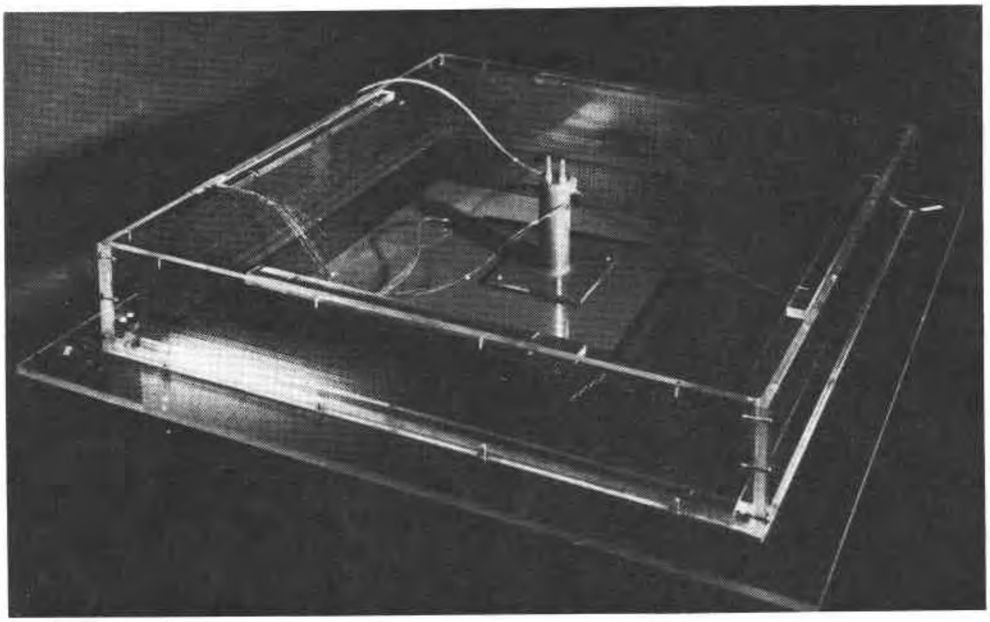

Figure 1. Experimental set-up

APPARATUS

The experimental apparatus consisted of a square plexiglas container 0·9 m × 0·9 m × 0·15 m (Figure 1) filled with soil, the heat exchanger being tested, a temperature bath for conditioning the circulating fluid and the data acquisition system. A thin metal perforated wall placed 2 cm from the plexiglas walls inside the container served as a water reservoir to maintain the soil in a saturated condition. The container was filled with remoulded clay, moisture content 82 per cent by weight. Filling was carried out by hand in layers of approximately 1 cm, special care being taken to achieve reasonably homogeneous conditions. The heat exchanger of each of five systems to be considered (Figure 2) was placed in the centre of the container.

(1) single PVC pipe; OD = 5 cm, wall = 0·25 cm, $K = 0{\cdot}14$ W/(m°K)
(2) same as (1), surrounded by a ring of saturated sand; OD = 10·0 cm,
(3) single PVC liner tube; OD = 5 cm, wall = 0·09 cm, $K = 0{\cdot}10$ W/(m°K)
(4) single-density polyethlene pipe; Swedish, OD = 1·6 cm, wall = 0·15 cm, $K = 0{\cdot}25$ W/(m°K)
(5) pair of pipes, as in (4), 15 cm apart.

Circulation of fluid within the pipes was achieved by placing a venting system in the middle of the pipe (Figure 2), leaving a space at the bottom for the return flow. All the plastic pipes were instrumented using thermocouples located as follows:

(1) within the fluid (fastened to the dividing membrane)
(2) on the inside of the pipe wall
(3) outside the pipe wall, embedded in a groove
(4) outside the pipe wall but glued to the wall, and
(5) outside the pipe wall, leaving the thermocouple tip just freely touching the wall.

The temperature distribution of the clay soil was measured at 40 locations around the heat exchangers by thermocouples mounted on wooden supports. The thermal conductivity of the clay was measured periodically by two conductivity probes permanently embedded in the clay. The measured values remained essentially constant throughout the experimental programme [0·84 W/(m°K)]. Moisture content was measured next to the heated pipe as well as near the outside boundaries. These measurements were

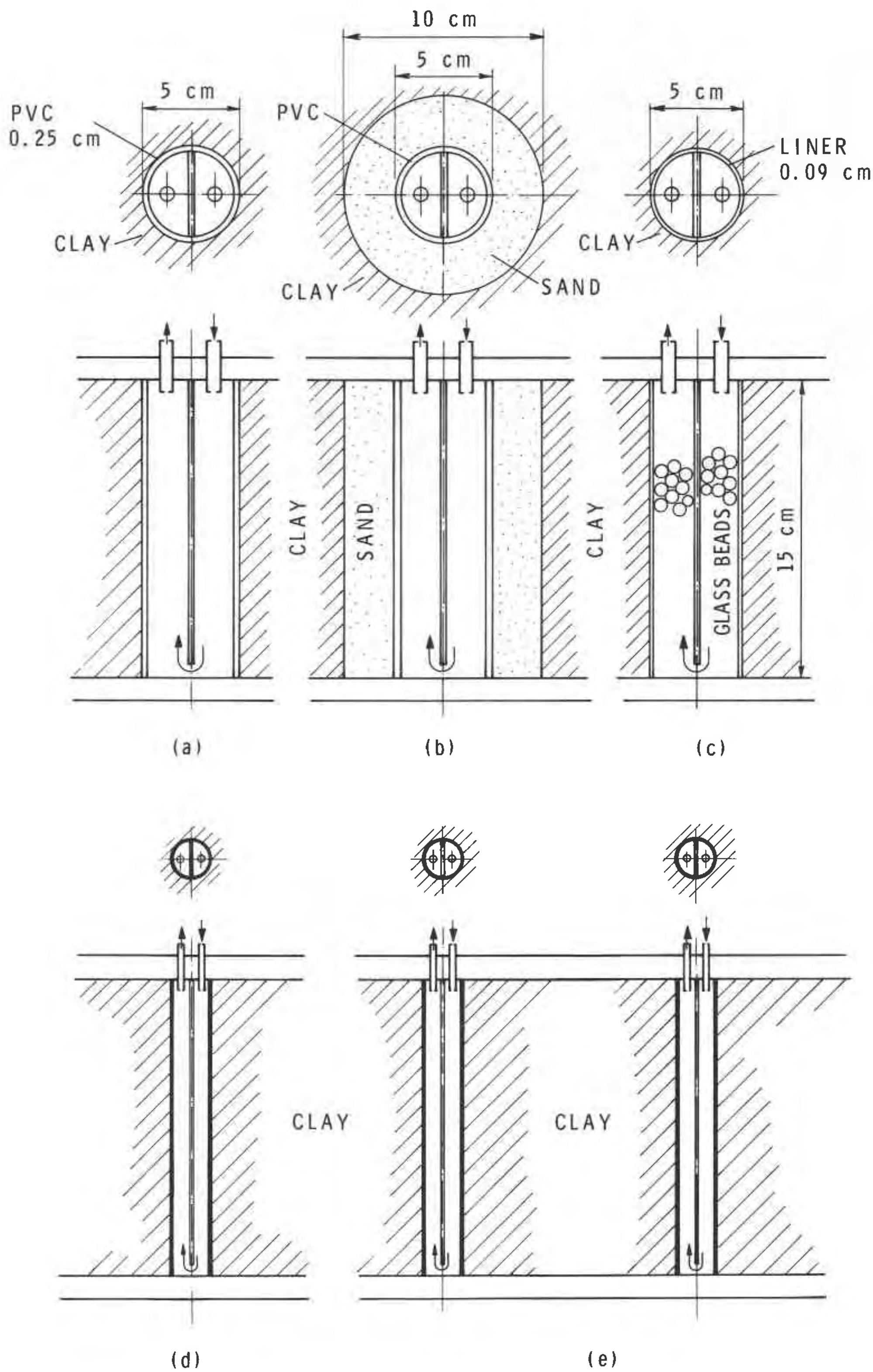

Figure 2. Heat exchangers in test apparatus

repeated after 10 days of heating when steady state had been reached, but no appreciable change in moisture content was observed. It was concluded that for the soil type and test conditions thermally activated diffusion was negligible. It should be pointed out, however, that for a more rigorous analysis, including contact resistance, the moisture migration may not be negligible. This is particularly true in cases of cyclic thermal loading and more permeable soils.

ANALYSIS

The temperature drop $(T_f - T_s)$ between the fluid circulating inside a pipe and a point in the soil at radius r (Figure 3) can be described using the theory of steady-state heat conduction:

$$T_f - T_s(r) = \frac{Q}{2\pi}\left| \frac{1}{h_f r_0} + \frac{1}{k_p}\ln\frac{r_1}{r_0} + \frac{1}{k_s}\ln\frac{r}{r_1} + \frac{R}{r_1} \right| \quad (1)$$

The terms on the right side of equation (1) represent the effect of the fluid boundary-layer, the thermal resistance of the pipe wall, the thermal resistance of the soil, and the contact resistance between the pipe wall and the soil.

The effect of fluid velocity on heat transfer through the fluid boundary-layer has been demonstrated by Nievergeld *et al.* (1980). For all the tests reported in this study the temperature of the fluid was high

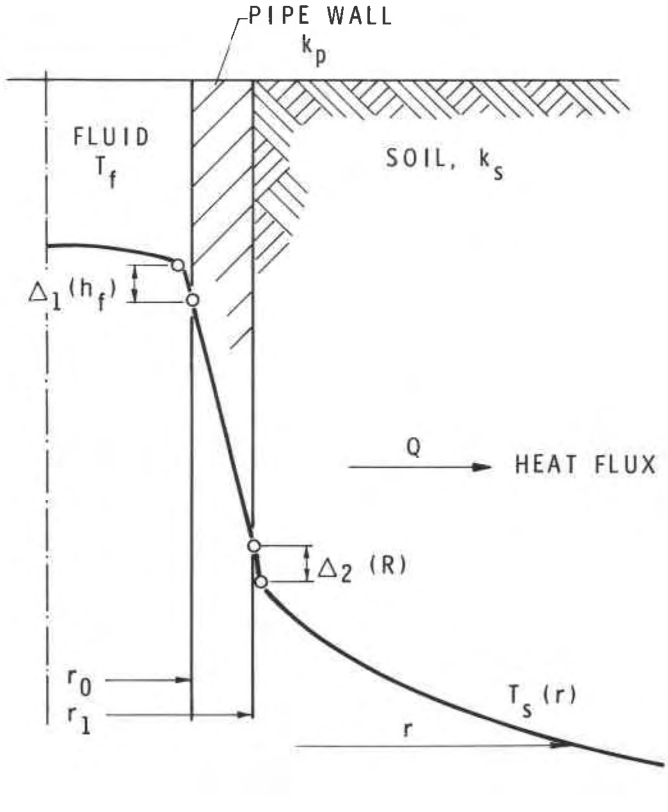

Figure 3. Schematic diagram of temperature profile through buried pipe

Table I. Effect of fluid boundary-layer (Nievergeld *et al.*, 1980, $k_p = 0{\cdot}43$ W/m°K, $k_g = 2{\cdot}0$ W/m°K

Heat resistance composed of	Fluid temp °C	Fluid velocity m/s	Heat transfer coefficient W/m²K	Q W/m	Percentage of Case 1	Percentage of Case 2
Soil, Case 1	—	—	—	1·70	100	—
Soil and tube wall, Case 2	—	—	—	1·18	69·4	100
Soil and tube wall and fluid		0·2	106	0·70	41·2	59·3
	0	0·5	1104	1·11	65·3	94·1
		1·0	2245	1·14	67·0	96·6
		0·2	102	0·69	40·6	58·5
	−12	0·5	118	0·73	43·0	61·9
		1·0	1329	1·12	65·9	95·0

(around 25–26°C for heating runs and 9–10°C for cooling runs), as was the velocity of the fluid in the heat exchangers, so that the measured temperature difference due to the boundary-layer was within instrumental error (~0·05–0·15°C). It was concluded, based on Nievergeld's results (Table I), that the first term in equation (1) could be neglected. It is expected that the heat transfer coefficient will depend on the temperature and velocity ranges, with the possibility of non-linear behaviour in the transient state.

The second term in equation (1) represents the pipe wall resistance. Although it is easy to include an appropriate temperature drop in the design of a heat exchanging system, it is surprising that most published models as well as most applications neglect this effect. For metal pipes the assumption of negligible temperature drop through the walls is appropriate, but for plastic tubing the drop is too great to be ignored.

The last term in equation (1) is due to the thermal contact resistance between soil and pipe. Smith (1956) may have been the first to report this phenomenon for buried pipes coupled with a heat pump. He suggested the use of an apparent thermal conductivity, k_a, for soil that would take into account both inside and outside heat transfer coefficients. By using field experimental results and the steady-state equation, Smith arrived at ratios of k_a/k ranging from 0·466 to 0·960. A similar analysis is reported in this paper, using data obtained under much better controlled laboratory conditions.

RESULTS

In the numerical model developed for the design of a complete system, including building, heat pump, in-ground heat exchangers, solar collectors, etc. a simplified scheme for treating heat flow in the ground has to be chosen. Some of the existing models are based on heat flux characteristic curves relating, as a function of time, the heat flux from a heat exchanger (single pipe, double return U-pipe, coaxial return pipe, etc.) to the temperature rise in the circulating fluid. The actual time-dependent behaviour of the system is then usually modelled as a quasi-transient process. Such a simplified approach is attractive, but comparison with an actual system or with more sophisticated calculations should be made in order to confirm its appropriateness. Introducing more approximations into the characteristic function, for example, neglecting the fluid boundary-layer, the thermal resistance of the pipe walls, the contact resistance between pipe and soil, or all of these effects together, leads to an accumulation of errors and, possibly, unrealistic design. As these assumptions are common to many current models, the emphasis in the work presented here has been to obtain experimental evidence of their importance. In particular, contact resistance has been examined because it has been observed in the field that this phenomenon not only exists but increases in importance with time, especially under cyclic thermal loading.

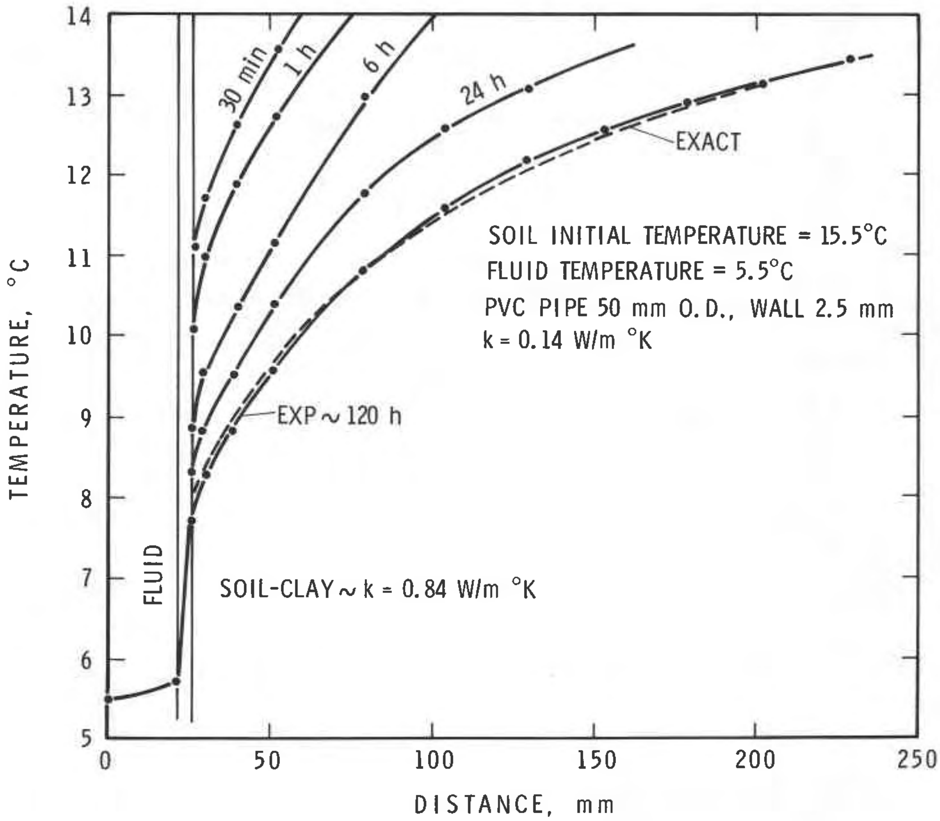

Figure 4. Temperature distribution versus time

Experimental programme

Four pipes (Figure 2) were tested by imposing a temperature difference of 10°C between thermally stabilized soil and the circulating fluid inside the pipes. All the pipes were cooled or heated until steady state was reached. Typical time dependences of the temperature distribution and observed heat flux are shown in Figures 4 and 5, respectively.

Contact resistance (Table II) was estimated as follows: first, heat flux was calculated for the soil, given its thermal conductivity and the steady-state temperature distribution. Since, for steady-state, the analytical solution is a logarithmic function, the temperature versus logarithm of distance is a straight line. By projecting this line back to the pipe, the pipe surface temperature can be calculated (Figures 6–8). Using the previously obtained heat flux for the soil (equal to the flux through the pipe) and the known pipe thermal conductivity, the temperature drop through the pipe can be calculated. The difference in pipe surface temperature, obtained by comparing the temperature profile approaching from the soil and the pipe sides, respectively, is the temperature drop due to contact resistance.

Although precise values of contact resistance could not be obtained, the results do indicate the approximate value to be expected. Table II shows that for steady state the heat flux, in contrast with contact resistance, is invariably larger for heating than for cooling. This result is in agreement with what might be expected, in view of the difference in thermal expansion of the plastic pipe and the soil.

The contact resistance for sand (Table II) was less than that for clay. As sand grains are much larger than clay particles, the resulting contact area for sand is much smaller than that for clay. The contact resistance, may, however, also depend on the thermal conductivity of both materials at the interface. The contact resistance for the PVC linear was not measurable (Figure 8), probably due to the flexibility of the liner.

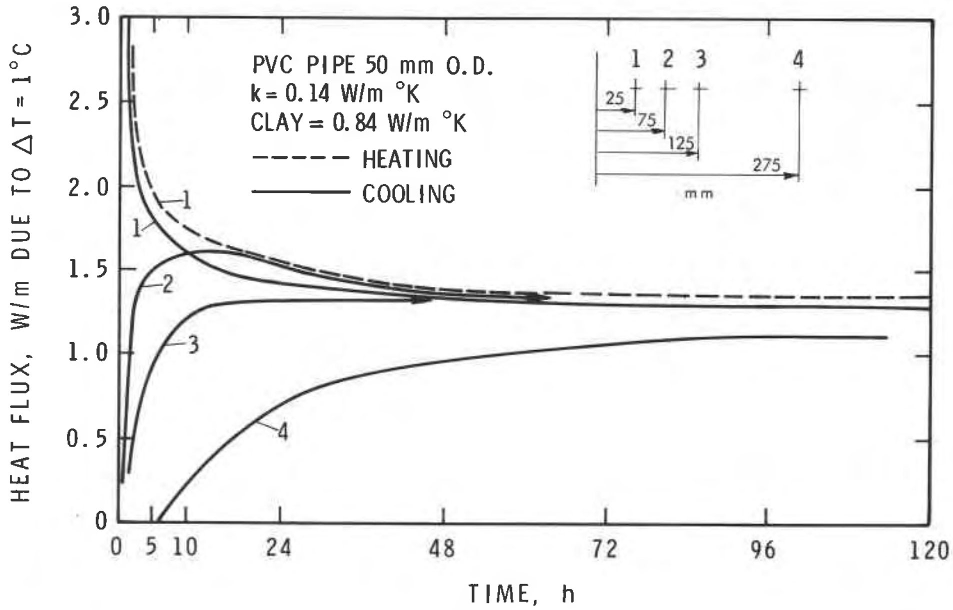

Figure 5. Heat flux in four locations versus time

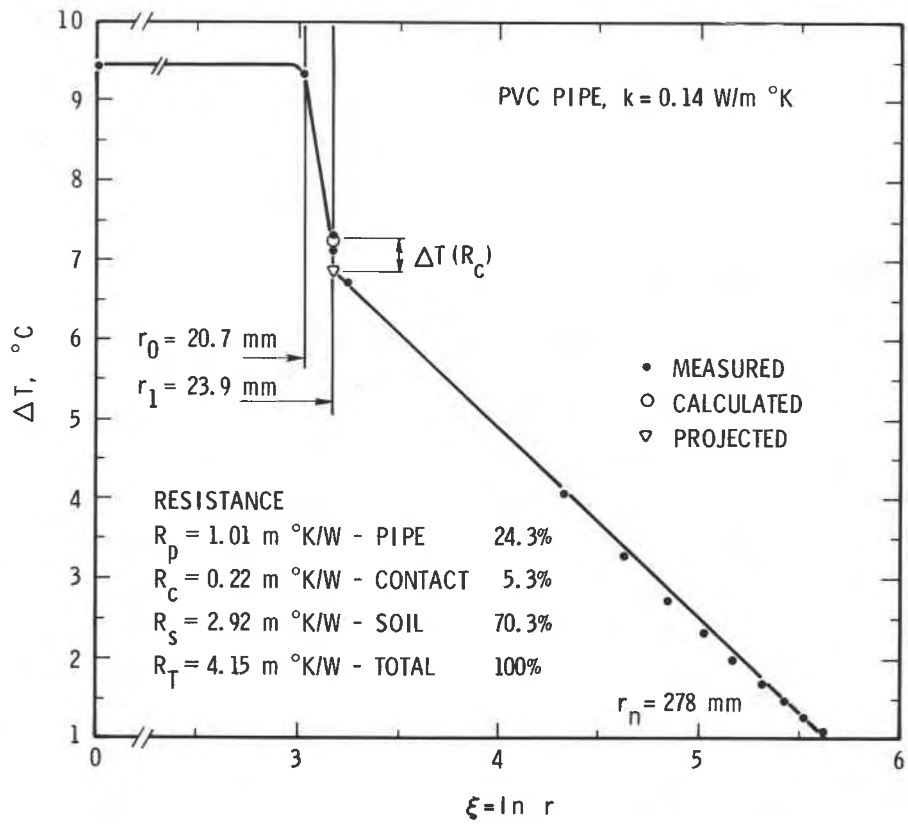

Figure 6. Temperature profile for PVC 4·78 cm OD pipe in clay

Table II. Results of experimental programme

Test	Heat exchanger	Mode	Data	Q W/m	ΔT_0 in Fluid °K	ΔT_1 Wall °K	ΔT_2 Interface °K	ΔT_3 ~25·5 cm in soil	R_p/lm K°m/W	R_c/lm K°m	R_s/lm ~25·5 cm
1	PVC	cooling	value	12·5	0·07	2·06	0·43	5·80	1·01	0·22	2·92
	OD = 4·8 cm	$R_T = 4{\cdot}15$	%		0·7	20·6	4·3 17·3*	58·0	24·3	5·3 17·8*	70·3
	ID = 4·3 cm	heating	value	13·6	0·08	2·18	0·38	6·31	1·01	0·19	2·92
	$k_p = 0{\cdot}14$ W/m°K	$R_T = 4{\cdot}12$	%		0·8	21·8	3·8 14·9*	63·1	24·5	4·6 15·8*	70·8
								sand clay			sand clay
2	Same as No. 1 with ring of sand	cooling	value	15·5	0·14	2·50	0·35	0·76 4·67	1·01	0·14	0·28 2·01
	OD = 10 cm	$R_T = 3{\cdot}44$	%		1·4	25·0	3·5 12·3*	7·6 46·7	29·3	4·1 12·2*	8·1 58·5
	$k_s = 2{\cdot}5$ W/m°K	heating	value	15·6	0·14	2·50	0·30	0·73 4·81	1·01	0·12	0·28 2·01
		$R_T = 3{\cdot}42$	%		1·4	25·0	3·0 10·7*	7·3 48·1	29·5	3·5 10·6*	8·2 58·8
3	PVC liner	cooling	value	15·9	0·13	0·98	—	7·05	0·3	—	2·85
	OD = 5 cm	$R_T = 3{\cdot}15$	%		13	9·8	—	70·5	9·5	—	90·5
	ID = 4·82 cm	heating	value	15·9	0·13	0·95	—	6·92	0·3	—	2·85
	$k_l = 0{\cdot}10$ W/m°K	$R_T = 3{\cdot}15$	%		13	9·5	—	69·2	9·5	—	90·5
4	Polyethylene	cooling	value	9·41	0·09	·25	0·67	6·33	0·84	0·45	4·17
	OD = 1·6 cm	$R_T = 5{\cdot}46$	%		0·9	12·5	6·7 33·8*	63·3	15·4	8·2 34·9*	76·4
	IC = 1·3 cm	heating	value	9·80	0·09	1·31	0·59	6·46	0·84	0·38	4·14
	$k = 0{\cdot}25$ W/m°K	$R_T = 5{\cdot}36$	%		0·9	13·1	5·9 31·0*	64·6	15·7	7·1 31·1*	77·2

Note:
% for ΔT = percentage of total $\Delta T = 10$°K between fluid in the pipe and the outside boundary
% for R = percentage of total resitance R_T between fluid and the point 25·5 cm in the soil
* = percentage of the pipe and the interface together

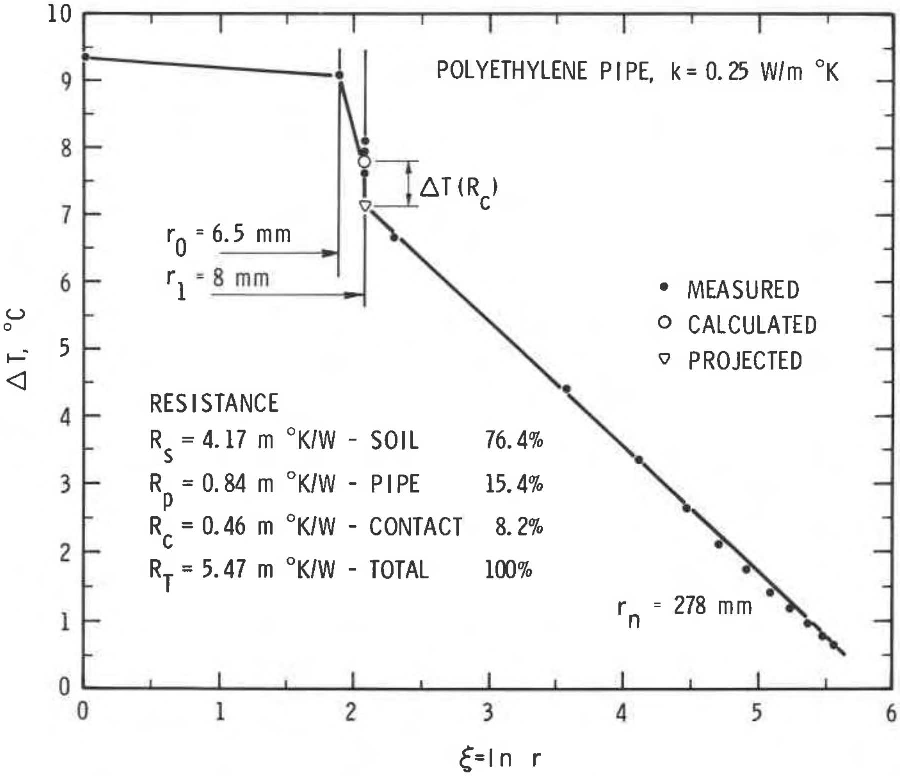

Figure 7. Temperature profile for polyethylene 1·6 cm OD pipe in clay

Because of the difficulty of determining temperatures at well-defined locations on either side of the pipe–soil interface, the values of contact resistance calculated in Table II should not be considered absolutely precise. This study indicates, however, that the problem is real, and that it is necessary to consider its effect, depending on the materials involved

The measurements were also used to calculate heat flux characteristic curves. Figure 9 shows the results for the experimental configurations indicated in Figure 2. It is clear that both the thermal resistance of the heat exchanger walls and the contact resistance must be considered in the design of in-ground heat storage facilities since they do significantly affect the heat flux characteristic curves.

Finite-element analysis

In Figure 4 the measurements for steady-state conditions are compared with the exact analytical solution. Agreement is excellent. In order to gain further insight into the behaviour of different configurations of inground heat exchangers a two-dimensional finite-element program for heat conduction was developed. The program uses triangular and quadrilateral linear, or quadratic, curved elements with the usual range of capabilities to handle boundary conditions and material types.

Figure 10 demonstrates the influence of the thermal conductivity of the heat exchanger pipe in a single-pipe laboratory configuration, as simulated by the numerical model. The graphs give the heat flux into the soil next to the pipe computed for a 10°C step-temperature rise imposed at the inside of the pipe wall while the outer soil boundary remains at a fixed temperature.

The higher thermal conductivity of the steel compared with that of the PVC increased the steady-state heat flux by some 34 per cent. An even greater increase was manifested during the first few hours. The dashed lines represent the decreased heat flux due to inclusion of a contact resistance estimated as 15 per cent of the resistance of the PVC pipe wall.

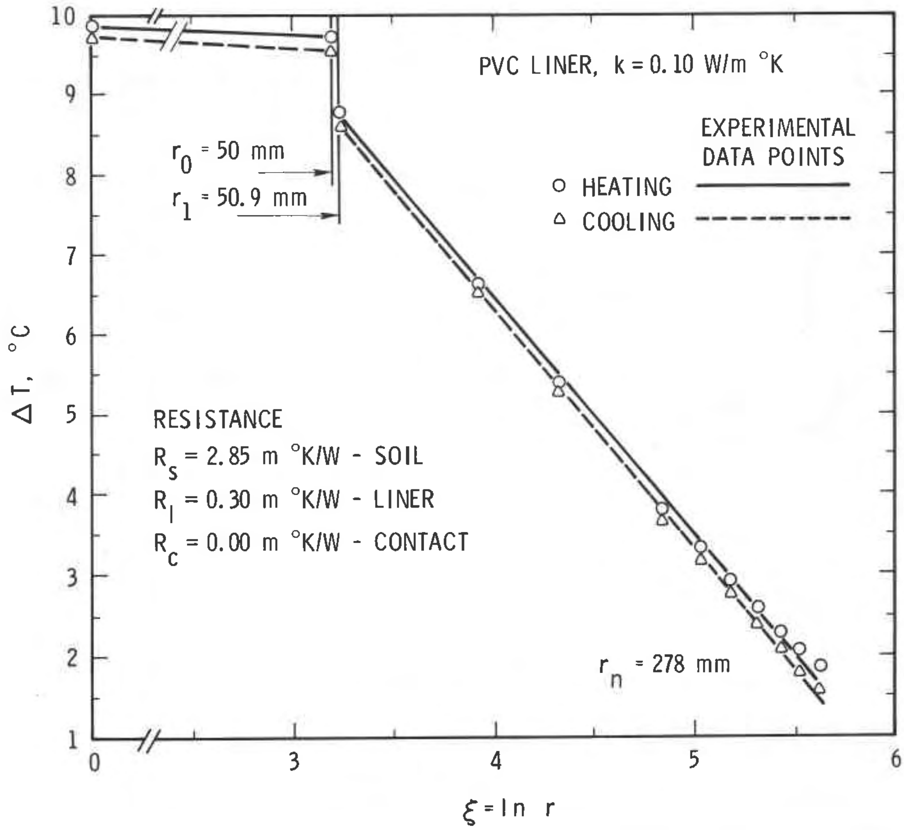

Figure 8. Temperature profile for PVC 5·0 cm OD liner in clay

In view of these results an even greater influence of pipe material on heat exchange rate may be expected for cyclic thermal loading. Figure 11 shows results computed for the same configuration as that of Figure 10, but the inner pipe wall is subjected to a sinusoidal variation with amplitude 5°C and period 24 h. The left half of the graph shows the heat flux in the soil immediately adjacent to the pipe wall; the right half of the graph shows the flux at a distance of 7·5 cm from the pipe. For cyclic thermal loading the effect of the thermal conductivity of the pipe is far from negligible. Changing from PVC to steel boosted the peak heat flux by 73 per cent for the location next to the pipe and by 79 per cent for the location 7·5 cm from the pipe.

Additional model studies will be carried out in the near future to confirm these results as well as to examine more realistic geometrical configurations, including multiple pipe arrays.

CONCLUSIONS

To design an efficient in-ground heat exchanger four factors have to be considered:

(1) thermal properties of the soil
(2) thermal resistance of the pipe wall
(3) contact resistance at the pipe-soil interface
(4) effective fluid-pipe wall heat transfer coefficient.

The results of the present study show that if plastic pipes are used the low thermal conductivity of plastic dictates that heat exchange with the soil will be significantly diminished. Cyclic behaviour, in particular, is dramatically affected.

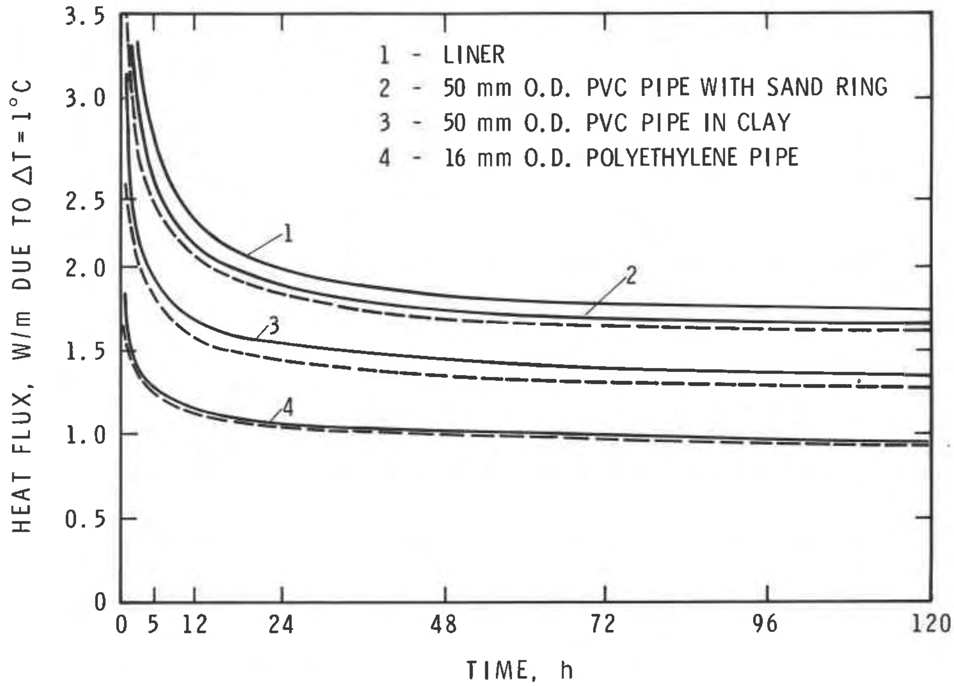

Figure 9. Heat flux characteristic curves for four experiments

In spite of the fact that very little is known about pipe–soil interface contact resistance, owing to the difficulty of measuring and evaluating the effect experimentally, the presence and importance of contact resistance is demonstrated in this analysis. Contact resistance is a significant part of the pipe–soil thermal interaction and more attention should be given to determining its dependence on factors that affect it, particularly for cyclic loading. Physical separation or loss of contact between soil and pipe has been

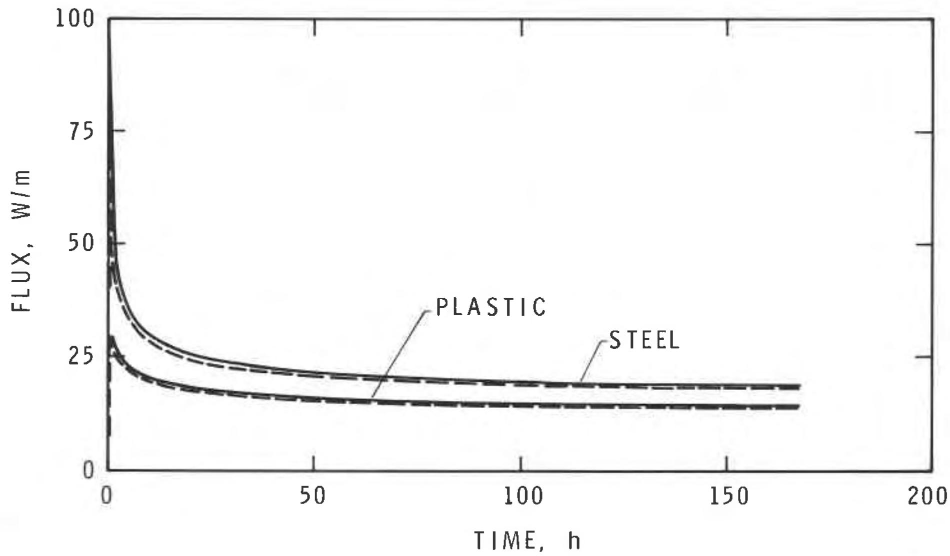

Figure 10. Heat flux characteristic curves for plastic and steel pipes

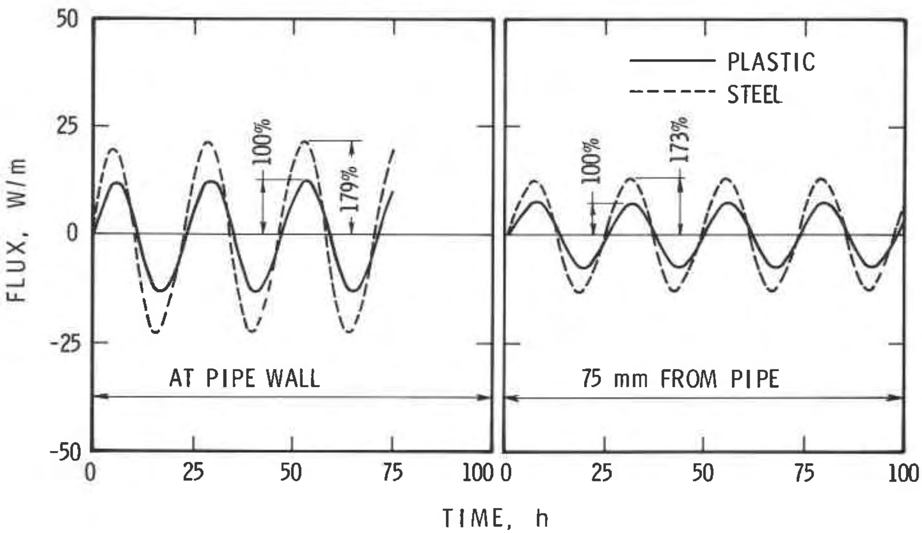

Figure 11. Heat flux due to cyclic loading for plastic and steel pipes

observed in the field; it has resulted in considerable decrease in efficiency of the entire heat storage system. Future research should be undertaken.

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