HEATING, PIPING & AIR CONDITIONING

AMERICAN SOCIETY OF HEATING AND AIR-CONDITIONING ENGINEERS

GL03757

Journal Section

The object of the Society is to advance the arts and sciences of heating, ventilating, cooling and air conditioning, and the allied arts and sciences, for the benefit of the general public, to encourage and conduct scientific research, and to cooperate with other organizations having the same or similar objectives.

Earth as Heat Source and Sink for Heat Pumps†

By D. M. Vestal, Jr.* and B. J. Fluker**, College Station, Tex.

SUMMARY — Results of an investigation of the earth at shallow depths as a heat source and sink for the heat pump are presented. Described are the experimental buried coils tested, the testing program conducted, the kind of data obtained, and the method of data analysis used. A buried coil design equation is derived. A discussion is included concerning this design equation.

Fifty-seven tests with both continuous and intermittent type runs were completed. Three separate U-shaped coils of ½-in., 1-in., and 2-in. diameter, each of 160 ft nominal length, buried horizontally 5 ft below the ground surface were tested. Coil operating temperatures ranged from 90 to 130 F where the earth acted as a heat sink while for heat source operation coil temperatures ranged between 20 to 45 F. The circulating fluid rate of flow produced Reynold's numbers from 1000 to 6000. Data from these tests, combined with data from laboratory tests of a wide variety of soils, were studied by dimensional analysis.

An equation evolved from the dimensional analysis studies forms the basis for the development of a heat pump buried coil design procedure. Reference is made to the complete proposed coil design procedure, published separately.

THE ATMOSPHERE, surface and ground water, and the earth itself are three principal media which may serve as the heat source and sink of a heat pump system.

Increased interest in the heat pump as a year 'round air-conditioning system has demanded that quantitative information on each of these media be obtained in order that a designer may make an engineering evaluation of the advantages and disadvantages of each for a particular installation. Each of the media and combinations of them have been studied by other investigators, listed in the Bibliography in the Appendix,‡ but no generalized design criteria were evolved. This paper presents the results from an extensive investigation of the earth at shallow depths as a heat source and sink for the heat pump and gives the buried coil design equation which was developed. Details of the design method based on this work were given previously.[1]

The operating characteristics of horizontally buried coils of ½-in., 1-in., and 2-in. diameter were observed and studied under controlled operating conditions. Data were obtained for both the cases where the earth acted as a heat source, and where it acted as a heat sink. Results were combined with data from laboratory tests of artificially prepared soil specimens and with field measurements of natural soil temperatures into a correlation from which the previously mentioned design equation and design procedure were developed.

Equipment and Apparatus

A plot plan of the field installation where the buried coil testing program was conducted is presented in Fig. 1.

†The data presented here were obtained in experiments conducted for the Texas Electric Service Co., Ft. Worth, by the Texas Engineering Experiment Station cooperatively with the Texas A. & M. Research Foundation.

*Research Engineer, Texas Engineering Experiment Station, Texas A. & M. College System.

**Assistant Research Engineer, Texas Engineering Experiment Station, Texas A. & M. College System.

For presentation at the 63rd Annual Meeting of the AMERICAN SOCIETY OF HEATING AND AIR-CONDITIONING ENGINEERS, Chicago, February 1957.

‡Planned to be included with this paper when published in TRANSACTIONS 1957.

[1]Exponent numerals refer to References.

Construction of the instrument house and installation of the first four coils, A, B, C and D, was begun in the spring of 1949. Each of the coils A, B, C and D was independent of the others and was buried horizontally 5 ft below the ground surface. Experimental work on these coils was initiated in November, 1949.

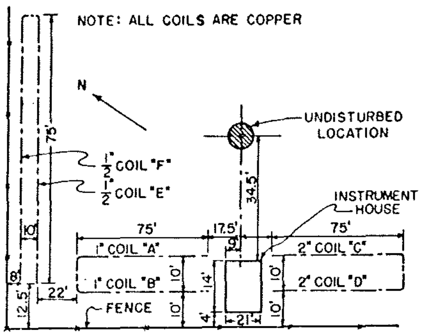

Fig. 1—Plot plan of field installation

When it became evident from data of the first 5 tests of these original 4 coils that the temperature change of the circulating fluid was too small to be measured accurately except at low rates of fluid flow, each pair of coils of like diameter was connected with a 10-ft long crossline. The coil length traveled by the fluid was thereby increased to a nominal 160 ft as shown in Fig. 1. All tests after the first 5 employed the *U*-shaped arrangement.

In the fall of 1951 the ½-in. diameter coils, designated E and F in Fig. 1, were added and were buried at the same depth as the other coils.

A schematic flow diagram of the field installation is shown in Fig. 2. Additional details of the equipment and apparatus employed are given in the Appendix under the heading *Details of Equipment and Apparatus*.

Test Procedure

Procedures followed in starting a test, in extending it over the desired period of time, and in ending it were standardized where possible for the bulk of the buried coil testing program. Early tests in which the fluid was circulated through only one coil 75 ft in length provided the basis for establishing many of the standard operating procedures. Others were modified or became standard as additional experience accumulated.

The general procedure followed in beginning a test run and in placing the buried coil into operation was as follows.

1. Selection of the Coil Pair to be Tested:—Selection of a coil pair was governed principally by the temperature pattern in the soil around the coil pair in question. Sufficient time was allowed between 2 series of tests on the same pair to permit the soil temperatures to approach their natural undisturbed values. The coil testing plan adopted in which a series of 3 test runs were completed on each of the 3 coil pairs in succession gave ample time for soil temperature recovery between series on the same coil.

2. Selection of the Coil Inlet Fluid Temperature to be Maintained Constant Throughout the Test Run:—For coil condenser type runs, the coil inlet fluid temperature was selected between the limits of 90 to 130 F while for coil evaporator runs the limits were from 20 to 45 F. In each type of test, the range included coil temperatures anticipated in the operation of an actual buried coil heat pump installation used for comfort space conditioning. Selection of either a condenser or an evaporator test was governed, as would be the case in an installation used solely for comfort space conditioning, by the seasonal variation of the outside air temperature. That is, circulating fluid temperatures in the winter months were selected in the lower temperature range to simulate coil evaporator operation while those selected for the summer months were in the upper temperature range to simulate coil condenser operation.

3. Selection of an Average Reynold's Number and Computation of the Corresponding Rate of Fluid Flow to be Maintained Constant Throughout the Test Run:—Normally, a series of 3 tests in succession were made on the same coil size at the same coil inlet temperature. Only the Reynold's number was varied between tests in a series. Values of 1000, 2500, and 5000, respectively, were approximated depending upon the ability of the controlling devices to hold a constant fluid temperature and rate of flow.

4. Selection of Either Continuous or Intermittent Coil Operation:—Fluid was circulated with no interruption through the buried coils for the duration of a continuous coil operation test. In those tests in which intermittent operation was employed, 3 different cycles were devised lasting 2 hours each. The 3 intermittent cycles were ¼ cycle on, designated Case I; ½ cycle on, designated Case II; and ¾ cycle on designated Case III. Two other cases, IV and V, combined these 3 basic intermittent cycles. Case IV cycle was composed of Cases I, II, and III in succession while Case V cycle was made up of Cases I, III, and II in that order. Each of the latter cases, as tests proved, was equivalent to ½ cycle on, designated Case II, and is reported as such.

The fraction of the cycle *on* refers to the initial part of the 2-hr period in which the fluid was circulated through the coil. During the remaining part of the cycle, the fluid flowed through only the coil bypass line and the particular common circuit involved in order to maintain flow rate and temperature for the next cycle. Switching of the fluid flow from coil to coil bypass line and back to the coil was accomplished by the simultaneous opposite action of 2 solenoid valves whose operation was controlled by an electric automatic on-off timer.

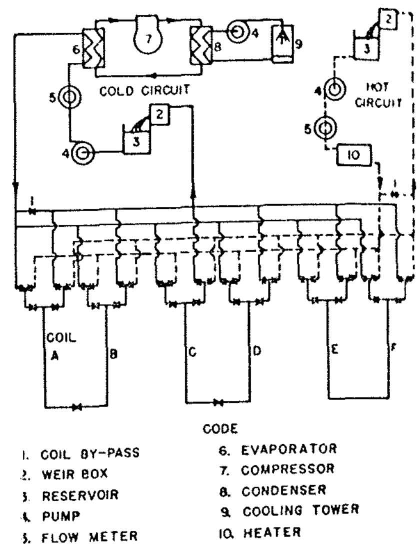

Fig. 2—Schematic flow diagram of field installation

5. Regulation of Valves in the Fluid Circuit to Route the Fluid Through the Desired Flow Path:—Only the manual shut-off valves routing the fluid through the coil pair in the desired direction were initially open. The fluid temperature and rate of flow were brought to their predetermined values by making necessary adjustments while circulating the fluid through the appropriate common circuit and corresponding coil bypass line. These conditions first being satisfied, the coil pair was then put into operation by simultaneously closing the bypass line solenoid valve and opening the inlet solenoid valve to the coil.

Prior to placing a coil pair into operation by the foregoing procedure, soil temperature measurements were made to obtain the before-test distributions in the soil surrounding the coil. The appropriate recording potentiometers were switched on immediately before beginning fluid circulation to record the initial temperatures of all thermocouple junctions located about the coil pair. Each potentiometer then remained in operation for the duration of the test run and the soil temperature recovery period after the end of the run.

Soil moisture content determinations were made also just prior to the beginning of fluid circulation in each test. Borings in the ditch backfill vertically above each leg of the coil pair to be tested were made using a hand auger of either 1-in. or 2-in. diameter. Soil samples were taken at each ½-ft increment to a depth of 5 ft (coil depth). Longitudinal spacing of the borings above the operating coils was 18 in. These borings were continued daily through the duration of the test and soil temperature recovery period.

Additional borings were made before test, 2 ft to either side of the coil leg in the natural soil. The 2-in. auger was used for the side borings which were to a depth of 6 to 8 ft. Soil samples were taken at each ½-ft increment of depth. Only one side boring per week per coil leg of the operating pair was made during the test and the soil temperature recovery period after test.

Tests and Data

Of the 57 tests completed on the buried coil installation, 25 were simulated coil condenser type runs while 32 were simulated coil evaporator runs. The tests varied from 5 to 90 days duration. Both intermittent and continuous flow were investigated over a range of Reynold's numbers from 1000 to 6000 except for 2 runs which were below 1000 and 2 whose values were well above 6000. Fluid inlet temperatures investigated covered the range from 90 to 130 deg for simulated condenser type runs and from 20 to 45 deg for simulated evaporator runs. A mixture of ethylene glycol and water was circulated through the coils in all tests.

In Table 1 are listed all simulated coil condenser type runs with a summary of their operating conditions and results. Similarly, the coil evaporator type runs are tabulated in Table 2.

The run designation is given in column 1 of Tables 1 and 2. The initial buried coil test, a condenser type run, was designated run D-1 where D specified the coil tested and the numeral 1 indicated an initial test. Modification of the run designation was required for complete identification when the tests were changed from one coil of 75-ft length to 2 coil legs in series of 160-ft total length. Where 2 letters appear first in a run designation, those letters denote the coil pair tested, the first letter indicating the upstream leg. The numeral indicates the number of runs of that type operation involving a particular coil pair that have been made. A letter H following the numeral indicates a *hot* or condenser type run while a C indicates a *cold* or evaporator type run. Intermittent fluid flow where employed is denoted by the final letter I and a case number indicating the cycle of intermittent operation as defined earlier.

Column 5 gives the mean operating temperature of the coil during test. This temperature is the average of all arithmetic averages of the coil inlet and outlet temperatures at each computation of an instantaneous rate of heat transfer, q.

Column 6 is the computed mean Reynold's number of the circulating fluid in the coil during test. Each of the Reynold's numbers given are computed using the inside coil diameter, the average rate of fluid flow

during the run, and the average fluid viscosity. The latter quantity in turn depended upon the average coil operating temperature given in column 5 and the average ethylene glycol concentration of the fluid.

Column 7 gives the difference between the mean coil operating temperature and the mean thermally undisturbed soil temperature at coil depth for the period of the test run.

In column 8 is given the mean values of a thermal coefficient of the soil immediately surrounding the operating coil. An experimental method, called the heat meter method,[1,3,4] was used to measure the thermal coefficients. Tests on 14 soils covering a wide range of soil types were completed in which thermal coefficients and thermal moisture migration data were obtained and correlated. The resulting correlation, was used to compute the soil thermal coefficients given in Tables 1 and 2.

In addition, column 10 in Table 2 gives the maximum radius of soil freezing in inches which was observed at the midpoint of the up-

Table 1 — Summary of Simulated Condenser Type Runs

(1) Run No.	(2) Days Fluid Circulated	(3) Date Fluid Circulation Stopped	(4) Avg Fluid Inlet Temp °F	(5) Avg Fluid Temp °F	(6) Avg Reynold's No.	(7) Avg Temp Diff, °F	(8) Avg Soil Thermal Coefficient Btu/hr (sq ft) (°F/ft)	(9) Ultimate Rate of Heat Transfer Btu/hr Per ft	°F Per ft
FE1H-I									
Case I	4.00	7 Jul 52	117.5	106.3	5443	26.4	0.79	64.0	2.42
Case II	2.00	9 Jul 52	118.4	108.0	5507	27.0	0.79	54.0	2.00
Case III	1.00	10 Jul 52	118.4	109.3	5012	28.3	0.78	42.0	1.48
FE1H	7.00	4 Sep 52	123.3	119.3	6861	32.0	0.77	15.3	0.48
FE2H	7.00	11 Sep 52	122.7	121.6	31397	35.0	0.76	15.0	0.43
FE3H	15.25	10 Oct 52	120.9	119.3	16774	35.9	0.75	18.0	0.50
1BH	17.00	11 May 50	120.0	114.8	2050	49.9	0.65	50.0	1.00
BA1H	7.00	18 May 51	130.1	115.7	2210	39.8	0.75	47.1	1.18
BA2H	7.00	30 May 51	130.1	120.2	3790	41.6	0.72	47.6	1.14
BA3H	7.00	6 Jun 51	130.1	123.8	6400	43.4	0.71	47.8	1.10
BA4H	15.00	8 Aug 51	99.3	95.9	2310	8.2	0.89	10.0	1.22
BA5H	7.00	15 Aug 51	99.5	98.4	3480	9.5	0.88	2.0	0.21
BA6H	7.00	22 Aug 51	100.4	100.0	6260	11.7	0.88	2.0	0.17
BA1H-I									
Case I	14.08	10 Jun 52	120.2	110.3	5532	36.6	0.73	95.0	2.60
Case II	5.92	16 Jun 52	120.9	114.3	5473	39.5	0.72	68.0	1.72
Case III	5.00	21 Jun 52	120.7	116.0	5414	39.8	0.72	47.0	1.18
D-1	30.00	16 Dec 49	120.0	111.2	1009	40.5	0.71	46.1	1.14
1DH	30.00	4 Mar 50	120.0	112.1	1050	50.8	0.63	57.0	1.12
1CH	20.92	27 Jun 50	120.0	115.3	1150	42.9	0.69	46.0	1.07
DC1H	5.77	12 Jun 51	130.1	117.1	1590	32.8	0.75	52.0	1.59
DC2H	7.00	22 Jun 51	129.7	122.7	2900	39.3	0.73	46.0	1.17
DC3H	7.00	29 Jun 51	129.9	126.5	5950	40.1	0.74	47.0	1.17
CD1H	9.71	9 Jul 51	130.1	121.5	1700	34.2	0.76	36.0	1.05
CD2H	7.00	16 Jul 51	130.3	124.3	3180	40.7	0.73	40.2	0.99
CD3H	15.00	31 Jul 51	129.6	126.9	6470	40.9	0.73	41.0	1.00
DC4H	16.00	7 Sep 51	100.4	96.8	1250	4.0	0.90	15.0	3.75
DC5H	17.00	24 Sep 51	109.4	107.6	2468	12.0	0.82	22.0	1.83
DC6H	21.55	10 Oct 51	110.8	109.0	5256	13.8	0.81	15.0	1.09
DC1H-I									
Case I	19.00	5 Aug 52	115.7	110.8	5979	28.8	0.78	90.0	3.13
Case II	7.08	12 Aug 52	118.4	115.3	5647	31.6	0.77	61.0	1.93
Case III	6.00	18 Aug 52	119.8	117.9	6062	32.8	0.77	35.0	1.07

stream coil in runs where the mean fluid temperature in the coil was below 32 F.

Data Analysis

Dimensional analysis was utilized to obtain a correlation of data from the tests. Five preliminary attempts were made before an acceptable correlation evolved from the dimensional analysis study. Variables which were isolated and evaluated during a test run and which were incorporated into the final correlation were:

$$\theta,\ Q,\ \Delta T,\ k,\ \rho C_p,\ L,\ D.$$

As applied to the work of this project the definitions of these quantities are as follows:

- θ = hours of operation elapsed after the beginning of fluid circulation through a coil pair.
- Q = the total instantaneous rate of heat transfer in Btu per hr between the circulating fluid and soil at time θ.
- ΔT = $|t - t_r|$, the instantaneous absolute difference in Fahrenheit degree between the average fluid temperature, t, in the coil at time θ and the ambient soil temperature, t_r, at coil depth (5 ft) averaged over the entire operating period of the run.
- k = a thermal coefficient in Btu per (hr) (sq ft) (deg F per ft) of the soil at the buried coil surface averaged over the entire operating period of the run.
- ρC_p = the volumetric specific heat in Btu per (cu ft) (deg F) of the soil at the coil averaged over the entire operating period of the run. ρ is the wet density of the soil around the coil while C_p is the wet soil heat capacity.
- L = the effective length in feet of the coil or coil pair being tested.
- D = the coil inside diameter, feet.

The final dimensionless grouping of the above variables was

$$(Q/\Delta TkL) \text{ and } (k\theta/\rho C_p D^2).$$

Similar groups were obtained by Hadley,[2] but his definitions of certain of the variables are different from the definitions used here. Differences occur in the definition of the rate of heat transfer, Q, the temperature difference, ΔT, and the time, θ.

Figure 3 is a plot of group ($Q/\Delta TkL$) versus group ($k\theta/\rho C_p D^2$) for all continuous operation simulated condenser type runs. The ordinate of this curve decreases monotonically. The large initial values of the ordinate corresponded to high rates of heat transfer immediately after beginning fluid circulation through the coil pair. An approach to stabilized soil temperature and heat flow conditions was observed as the abscissa increased. The steady-state conditions approached are represented in Fig. 3 by the level portion of the data.

If only the horizontal part of the data in the plot is considered, then the ordinate is independent of the group ($k\theta/\rho C_p D^2$), or

$$Q/\Delta TkL = I \qquad (1)$$

Rearranging the expression, the effective buried coil length is found to be

$$L = Q/\Delta TkI \qquad (2)$$

where

I, called the *intermittency factor*, is a function of the fraction of unit time that fluid is circulating through the coils and is equal to the level value of ordinate approached in the plots of dimensionless groups.

Similar plots of the same 2 dimensionless groups were made for the continuous simulated evaporator type runs and for each of the 3 cases of intermittent operation. Equation 1 was found to apply in every instance with the value of the intermittency factor, I, increasing as the fraction of unit time *on* decreased. Figs. 4a and 4b show the empirical relationship found between I and the intermittency ratio for condenser and evaporator type runs, respectively. Note that an intermittency ratio of 1.0 represents continuous operation.

Table 2 — Summary of Simulated Evaporator Type Runs

(1) Run No.	(2) Days Fluid Circulated	(3) Date Fluid Circulation Stopped	(4) Avg Fluid Inlet Temp °F	(5) Avg Fluid Temp °F	(6) Avg Reynold's °F	(7) Avg Temp Diff, °F	(8) Avg Soil Thermal Coefficient Btu/hr (sq ft) (°F/ft)	(9) Ultimate Rate of Heat Transfer Btu/hr: Per ft	(9) Ultimate Rate of Heat Transfer Btu/hr: °F Per ft	(10) Max Radius of Soil Freezing
FE1C	5.00	15 Jan 52	35.6	40.1	1698	25.7	1.00	19.0	0.74	—
FE2C	7.79	23 Jan 52	35.2	36.7	5925	29.0	1.00	21.0	0.72	—
FE3C	8.00	8 Feb 52	30.0	33.8	2206	34.0	1.00	25.0	0.74	—
FE1C-I										
Case I	4.00	12 May 52	44.6	52.3	1785	17.4	1.00	35.0	2.01	—
Case II	2.00	14 May 52	39.2	45.9	1898	24.9	1.00	32.0	1.29	—
Case III	1.00	15 May 52	41.9	47.3	1873	24.3	1.00	27.0	1.11	—
FE4C	5.00	23 Feb 53	23.2	29.3	1213	33.7	1.00	31.5	0.93	—
FE5C	5.00	28 Feb 53	20.8	24.4	2732	38.0	1.00	37.0	0.97	—
FE6C	5.00	5 Mar 53	24.8	26.6	4064	35.2	1.00	35.0	0.99	—
FE2C-I										
Case I	4.00	14 Apr 53	25.7	27.3	4391	40.3	1.00	45.0	1.12	Unknown
Case II	2.00	16 Apr 53	25.4	26.5	4446	41.7	1.00	35.0	0.84	Unknown
Case III	1.00	17 Apr 53	26.6	27.4	4590	41.1	1.00	31.0	0.75	Unknown
BA1C	9.00	2 Feb 51	33.8	40.1	734	25.0	1.00	22.0	0.88	—
BA2C	7.00	13 Feb 51	33.8	38.3	1091	23.9	1.00	20.0	0.84	—
BA3C	7.00	28 Feb 51	33.8	36.7	1640	24.7	1.00	20.0	0.81	—
BA4C	6.00	7 Mar 51	33.8	38.3	4695	25.1	1.00	20.0	0.80	—
BA1C-I										
Case I	7.00	28 Feb 52	33.1	39.4	1475	25.5	1.00	58.0	2.27	—
Case II	7.00	6 Mar 52	33.1	37.6	1442	27.3	1.00	42.0	1.54	—
Case III	7.00	13 Mar 52	33.4	36.6	1442	28.3	1.00	30.0	1.06	—
BA5C	7.00	13 Dec 52	19.9	24.8	1191	44.1	1.00	41.0	0.93	0.00*
BA6C	7.00	20 Dec 52	23.0	24.8	2876	42.3	1.00	39.0	0.92	2.50*
BA7C	10.00	12 Jan 53	24.4	25.2	5216	38.9	1.00	37.0	0.95	3.00*
BA2C-I										
Case I	8.00	30 Apr 53	22.8	24.5	4124	43.9	1.00	104.0	2.37	1.00*
Case II	7.00	7 May 53	19.4	20.8	4124	49.5	1.00	87.0	1.76	2.00*
Case III	7.00	14 May 53	21.6	22.5	4136	48.4	1.00	55.0	1.14	2.75*
1DC	8.00	21 Dec 50	33.8	34.2	245	38.3	1.00	30.0	0.78	—
DC1C	7.00	22 Mar 51	33.8	36.5	1030	28.5	1.00	26.5	0.93	—
DC2C	7.00	3 Apr 51	39.2	41.0	2560	30.2	1.00	34.8	1.15	—
DC3C	8.92	21 Apr 51	40.1	41.0	4700	29.0	1.00	36.5	1.26	—
CD1C	8.96	30 Apr 51	45.5	46.4	1240	22.8	1.00	16.2	0.71	—
CD2C	4.90	5 May 51	45.5	46.4	3090	27.8	1.00	19.2	0.69	—
CD3C	34.00	26 Nov 51	41.0	42.8	5256	20.3	1.00	30.0	1.48	—
DC1C-I										
Case I	17.00	13 May 52	35.2	40.3	1306	25.7	1.00	87.0	3.39	—
Case II	8.00	21 May 52	33.6	36.8	1323	30.6	1.00	56.0	2.18	—
Case III	6.00	27 May 52	34.2	36.7	1315	31.3	1.00	38.0	1.21	—
DC4C	10.00	20 Mar 53	26.1	27.9	1491	34.9	1.00	33.0	0.95	0.00*
DC5C	10.00	30 Mar 53	21.9	23.4	1949	41.0	1.00	31.0	0.76	2.75*
DC6C	10.00	9 Apr 53	21.9	22.5	3741	43.6	1.00	28.0	0.64	4.50*
DC2C-I										
Case I	16.00	7 Jun 53	29.1	31.9	4955	40.2	1.00	91.0	2.26	—
Case II	8.00	15 Jun 53	32.8	34.2	4890	40.9	1.00	69.0	1.69	—
Case III	6.00	21 Jun 53	38.5	39.4	4769	37.5	1.00	57.0	1.52	—
BA8C	90.88	28 Jan 54	21.2	23.0	2345	47.7	1.00	37.0	0.78	4.50*
BA8C-I										
Case I	12.00	9 Feb 54	21.7	23.7	2754	40.1	1.00	83.0	2.07	0.50*
Case II	11.00	20 Feb 54	22.1	23.2	2773	41.2	1.00	45.0	1.09	1.75*
Case III	10.00	2 Mar 54	21.9	25.5	2754	39.7	1.00	31.0	0.78	2.50*

The Buried Coil Design Equation

Equation 2 formed the basis around which a design procedure for a buried coil heat source and sink for the heat pump was developed. The expression is the result of experimental data compiled from tests

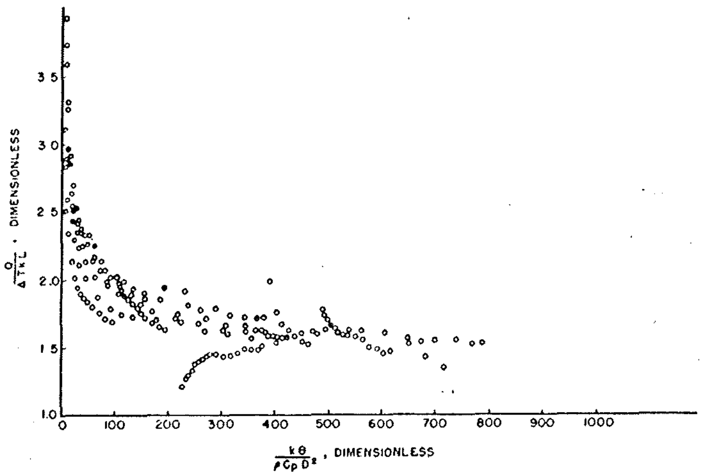

Fig. 3 — Dimensional analysis correlation of data of buried coil condenser runs, continuous operation

on 3 relatively short lengths (160 ft) of buried coil.

The variables Q and ΔT were computed from quantities measured during test while I was an empirically determined dimensionless number. Evaluation of k was by means of an equation which resulted from laboratory tests of artificially prepared soil samples. The equation for k given here without derivation[1,3,4] is

$$k = a\left(\frac{t}{t_r}\right)^{\frac{0.29}{d+1}} (S_r)^{0.29} \quad \text{.................(3)}$$

where

k = soil thermal coefficient corresponding to the stabilized soil condition established during coil operation.

S_r = initial or reference degree of saturation of the soil.

t = average fluid temperature in the coil, Fahrenheit degrees.

t_r = average ambient soil temperature at coil depth, Fahrenheit degrees.

and

a and d = empirical constants.

If the expression for k given by Equation 3 is substituted into Equation 2 together with $\Delta T = (t - t_r)$, the final form of the design equation is

$$L = \frac{Q}{\left[a\left(\frac{t}{t_r}\right)^{\frac{0.29}{d+1}} (S_r)^{0.29}\right](t-t_r)I} \quad \text{......(4)}$$

Thus, a buried coil for the heat pump may be designed from a knowledge of the total coil load, Q, the mean coil operating temperature, t, a reference soil temperature, t_r, the initial degree of saturation of the soil at coil depth, S_r, and 3 empirical constants, a, d, and I.

The design consists of an evaluation of these quantities followed by a solution of the equation for the coil length L. This length must then be modified to suit the particular coil configuration employed[1].

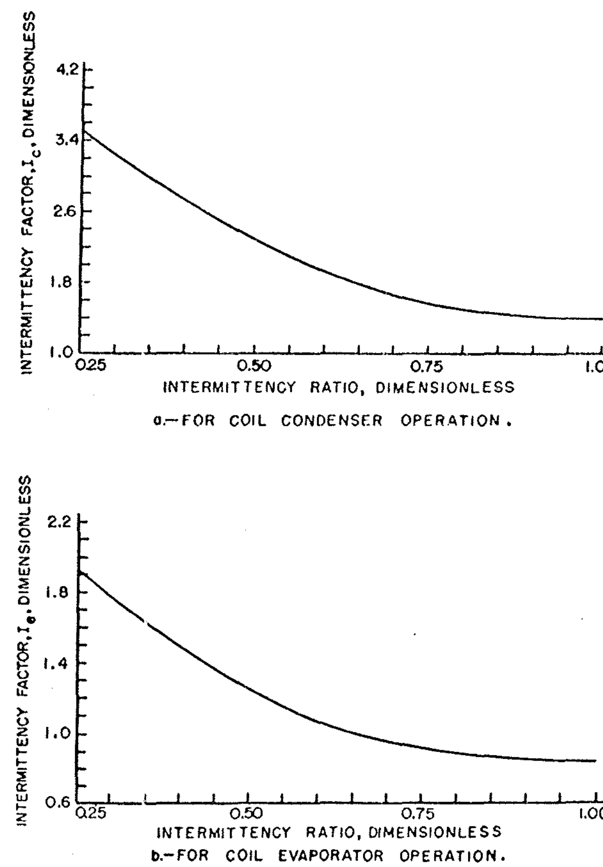

Fig. 4 — Empirical relationships of the intermittency factor with the coil intermittency ratio

Buried Coil Configurations

In practice, the ground surface area under which a coil is to be buried may be too small to permit installation of a coil arrangement where each leg is thermally isolated from the others. A solution to the problem would be to space adjacent coil legs closer than the minimum separation required for thermal isolation. In this case the influence of each leg upon adjacent legs will reduce the rate of heat transfer between soil and fluid per linear foot of buried coil, thus necessitating a greater coil length than that given by Equation 4 to meet a specific load. No experimental investigation of thermal interference was attempted but a theoretical analysis of the problem described in the Appendix served as the basis for including in Equation 4 a ratio to account for thermal interference between coil legs.

Values of R and R' which are called configuration factors (see Appendix for the derivation of equations for these factors) were computed for various configurations and are given in tabular form in the proposed buried coil design procedure[1]. The reciprocal of the appropriate configuration factor, depending upon whether one or two coils per ditch are used, multiplied by design Equation 4 will result in a coil length increased sufficiently to make up for the heat transfer reduction due to the effects of thermal interference between adjacent coil legs.

Discussion of Results

The buried coil design equation as given is valid where the soil is unfrozen and also where the soil freezes to some extent during coil operation. The maximum radius of soil freezing observed during an evaporator type run was 4.5 in.

Effects attributable to soil freezing were observed only for a short time at the beginning of a test. All evaporator runs in which the operating temperature was below the freezing point of soil were included in the dimensional analysis plot. Data from these soil freezing runs corresponded closely to data from nonfrozen runs following the initial period during which the radius of soil freezing was increasing.

It may be noted that coil diameter and material do not enter into Equation 4. Data from tests of all 3 coil sizes were included in the final analysis. No distinction between data of different coil sizes was evident, indicating that the effect of coil diameter was negligible. The design equation is considered applicable, therefore, to coil sizes from ½ to 2 in. in diameter. No coil diameter outside this range and no coil of material other than copper was used in the tests.

The rate of fluid flow was such that the average Reynold's number exceeded 1000 in all but 2 test runs. Data from these 2 runs, 1DC and BA1C, were excluded from the plots of dimensionless groups. Because of the increased difficulty in maintaining a constant rate of fluid flow at low Reynold's numbers and in view of the decreased accuracy in recording fluid inlet and outlet temperatures at relatively low rates of flow, the Reynold's number was maintained above 1000 for all other tests. This value is recommended as the minimum to be used in coil design where the data from this work are used.

It must be emphasized that only one fluid was circulated through the buried coils in all tests. A liquid solution of ethylene glycol in water was used exclusively, and the solution experienced no change of phase while traversing the coil. For the results of this work to be strictly applicable to a design problem, the fluid circulated through the coil must be a liquid.

Justification for applying the data to the flow of a boiling or condensing liquid refrigerant as would be the case in a direct expansion system was found in a study of the coil internal and external heat transfer film coefficients.[5,6,7,8] In the coil tests studied where liquid was circulated, the ratio of the inside to outside film coefficient was greater than 10. This difference in magnitude rendered negligible the influence of the inside film coefficient upon the overall heat transfer coefficient. Further, for boiling or condensing dichlorodifluoromethane the average inside film coefficient was computed by the method of Baker, Touloukian and Hawkins[6] and was found to be larger than those determined for the water-ethylene glycol solution assuming the same rate of heat flow per unit inside surface area for both types of flow.

These findings show that the results of this work may be applied to the design of a buried coil where either a liquid or where boiling or condensing dichlorodifluoromethane is circulated. The foregoing analysis also confirmed the fact which was indicated by the dimensional analysis study that no upper limit of Reynold's number should be placed on the data. The inside film coeffcient for the types of flow discussed normally increases with Reynold's number. An increase in Reynold's number would further decrease the already negligibly small influence of the inside film coefficient upon the rate of heat transfer between the fluid and the surrounding soil.

The absolute difference, ΔT, between average coil temperature and ambient soil temperature should be maintained at 25 F or greater in an installation. During runs BA4H, BA5H, BA6H, DC4H, DC5H, and DC6H in which ΔT was well below that value, difficulty was encountered in measuring the small drop in fluid temperature across the coil. Very erratic heat flow values were computed for those 6 runs, and their data were omitted in the final dimensional analysis plot.

Reliability of the result from the buried coil design equation depends upon the evaluation of the factors applying to a particular design problem and also on the accuracy of the measured data used in the dimensional analysis correlation.

An analysis was made of the errors involved in measuring the various quantities in design Equation 2. In the observation of data during a buried coil test, seemingly small inherent instrument errors were encountered in the measurement of coil inlet and outlet fluid temperatures. All thermocouples at the field site were calibrated before installation in a constant temperature bath, the temperature of which was measured with a mercury-in-glass thermometer of known calibration. It was found that the differences, Δt, between junction temperatures of coil inlet and coil outlet thermocouples could be measured correctly to ± 0.18 F (or ± 0.1 C) at the temperature levels employed in the coil testing program. The estimated percentage error in measuring Δt through all the field runs, based on ± 0.18 F was ± 4.0 percent. And the percentage error would appear to be no greater than ± 2 percent in each measurement of the instantaneous rate of fluid flow. For the majority of runs an even smaller error was involved.

Assuming that the error in the value of fluid heat capacity, c, may be neglected, and by examining the equation

$$Q = w\ c\ \Delta t$$

it may be seen that an error in each computation of instantaneous rate of heat transfer, Q, was ± 6 percent.

If Q is correct to ± 6 percent, ΔT is correct to ± 4 percent, and k and L are considered without error, then the estimated error in the dimensionless group $Q/\Delta TkL$ is $\pm$ 10 percent. The analysis is applicable to intermittent as well as continuous coil operation. In obtaining the basic design Equation 2, the dimensionless group $(Q/\Delta TkL)$ was equated to a constant, which was called the intermittency factor I. Thus, the error in I for any one test run is identical to that for the group. An independent check of the average deviation of I from a mean value for all continuous operation runs was computed to be $\pm$ 9 percent. As the fraction of coil operation per unit time decreased this average deviation increased.

For design purposes, the values of I plotted in Figs. 4a and 4b were selected with the intention that the resulting computed coil length be adequate during periods of extreme loads without auxiliary equipment to provide supplementary heating or cooling. The values of I plotted were the most reasonable values near the lower limit of the range of I corresponding to each type of test and cycle of operation.

Coil design for extreme ambient temperature conditions was the primary consideration in evaluating the reference soil temperature. An investigation of published weather station data indicated the greatest need for cooling occurred consistently in the months of July and August and the largest heating requirements were in January and February. The most unfavorable soil temperature conditions were found to occur in the months of August and February.[3] Thus, to perform satisfactorily during those extreme periods the reference soil temperature, t_r, was taken as the mean soil temperature at coil depth during August and February for coil condenser and evaporator operation, respectively.

The development of Equation 2, which resulted from the dimensional analysis of the operating coil data, into the usable buried coil design Equation 4 involved data correlations from laboratory soil heat transfer tests and thermal moisture migration phenomena investigations. These correlations were expressed in Equation 3 for the evaluation of a soil thermal coefficient in terms of the initial soil condition, the ratio of mean coil operating temperature to a reference soil temperature, and 2 constants. The reliability of Equation 3 in actual practice depends largely upon the accuracy with which the properties of the soil at coil depth are known. Emphasis is placed on the fact that standard procedures should be followed by an experienced field crew where possible in making density measurements and in obtaining soil samples at the proposed buried coil site. It is recommended that the soil index properties, liquid limit and plastic limit, which are related to the constants a and d be measured by experienced soil technicians[1].

The refrigeration machine condenser and evaporator capacities are required in the design equation. Also, the heat loss during the winter season and the heat gain during the cooling season of the space to be conditioned must be computed. The procedures recommended to find the heat loss or gain are those of ASHAE. Values determined by these methods, in general, are conservative. Manufacturers ratings at specified operating conditions of a given piece of equipment are normally *safe* values to use in sizing equipment for the job. In actual practice, however, variations in operating characteristics will occur causing a corresponding change in equipment capacity.

Because the accuracy of various site and operating equipment quantities necessary to the design of a buried coil cannot be estimated, the constants in Equation 4 were selected such that the coil length given by Equation 4 will tend to be slightly oversized.

As pointed out previously, no experimental investigations have been conducted to verify the configuration factors. It is thought, however, that these also will produce conservative coil lengths.

Acknowledgement

This paper was prepared by B. J. Fluker while D. M. Vestal, Jr. was on leave of absence. Mr. Vestal acted as consultant concerning questions

Journal Section

which arose during the preparation of the paper.

Acknowledgment is made of the excellent foremanship of J. W. Overall, Jr., in the performance of the test work and in the collection of data described and presented in this paper.

Acknowledgment is given also to those students of the A. & M. College of Texas who assisted in all phases of work of this project.

References

1. A Proposed Procedure for the Design of a Heat Pump Buried Coil, by D. M. Vestal, Jr. and B. J. Fluker (Preliminary Copy, Texas Engineering Experiment Station, College Station, Texas, September 24, 1954).

2. Operating Characteristics of Heat Pump Ground Coils, by W. A. Hadley (*Edison Electric Institute Bulletin*, Vol. 17, No. 12, pp. 457-461, December 1949).

3. A future paper is planned which will present the natural soil temperature data collected by the project. Another paper will be prepared dealing with the soil thermal conductivity work conducted while a third paper will describe the moisture migration studies made. Data for the latter two papers were observed in laboratory tests of artificially compacted specimens covering a wide range of soil types.

4. A Comparison of the Values of Thermal Conductivity of a Dry Porous Material Determined by Various Laboratory Methods, by B. J. Fluker (*Thesis*, A. & M. College of Texas, College Station, Texas, 1953).

5. Heat Transfer Film Coefficients for Refrigerants Boiling Inside Tubes, by Merl Baker, Y. S. Touloukian and G. A. Hawkins (Paper presented at 40th Semi-Annual Meeting of *ASRE*, June 28-July 1, 1953, pp. 21-26).

6. Heat Transfer Rates to Evaporating Freon-12 in a Horizontal Tube Evaporator, by W. F. Witzig, G. W. Penny and J. A. Cyphers (*Refrigerating Engineering*, Vol. 56, No. 2, pp. 153-157, 1948).

7. Vaporization Inside Horizontal Tubes, by W. H. McAdams, W. K. Woods and R. L. Bryan (*Transactions ASME*, Vol. 63, No. 6, p. 545, 1941).

8. Heat Transfer Notes, by L. M. K. Boelter, V. H. Cherry, M. S. Johnson and R. C. Martinelli (University of California Press, 1946, pp. XV-1 to XV-8).