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An Analysis of Air Heating During Flow through Ground Passages

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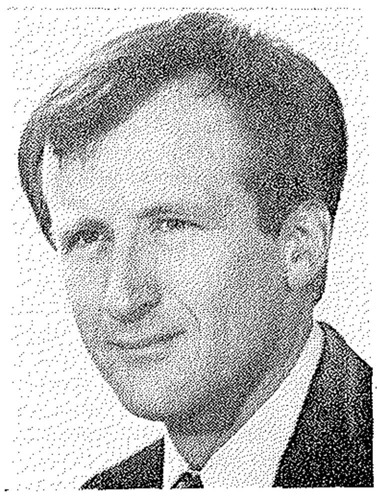
Abstract:
During a 10 day period of below freezing temperatures, air was circulated through an underground tunnel. Under constant airflow rate, rock and air temperatures were observed every four hours at instrumented stations along the tunnel from the portal intake to the exhaust outlet. Tunnel ice formation and the depth of rock temperature cooling in from the tunnel surface were also recorded. The data were analysed to establish the heat flow energy transfer characteristics between the circulating air and the rock. The day to day surface climatic changes were recorded and correlated to the air and rock temperatures within the tunnel. Comparisons were made with theory developed for use in hot underground mining conditions at depth, and a general equation formulated to describe the thermodynamic behaviour of the system. From this empirical base, suitable designs are proposed for ground tubes, or tunnels, to temper winter air for home heating. From the results of the study, the home owner should be able to design a ground passage air-tempering system with sizing appropriate to location and environment.



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AN ANALYSIS OF AIR HEATING DURING FLOW THROUGH GROUND PASSAGES

by

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Summary

During a ten day period of below freezing temperatures, air was circulated through an underground tunnel. Under constant airflow rate, rock and air temperatures were observed every four hours at instrumented stations along the tunnel from the portal intake to the exhaust outlet. Tunnel ice formation and the depth of rock temperature cooling in from the tunnel surface were also recorded.

The data were analysed to establish the heat flow energy transfer characteristics between the circulating air and the rock. The day to day surface climatic changes were recorded and correlated to the air and rock temperatures within the tunnel. Comparisons were made with theory developed for use in hot underground mining conditions at depth, and a general equation formulated to describe the thermodynamic behaviour of the system.

From this empirical base, suitable designs are proposed for ground tubes or tunnels to temper winter air for home heating. The authors propose incorporating a heat pump unit as an energy transfer stage between below ground warmed air and the home heating system. System dimensions are proposed and compared for homes in three climatic areas of the United States and for various soil and rock sub-surface ground conditions. The comparisons are based on both open flow below ground passages and closed loop air flow paths.

From the results of the study, the home owner should be able to design a ground passage air tempering system with sizing appropriate to location and environment.

Introduction

The ground temperature at even a few meters depth from the surface exhibits a profile markedly different to the diurnal or seasonal readings marking climatic changes. The earth tends to act as a thermal blanket. Low heat conductivity of soil or rock slows changes in temperature so that at a depth of as little as 10 m (33 ft) an unfluctuating temperature is reached which characterizes the annual mean condition at the geographic location. Further, at shallow depths of about 3 m (10 ft), conditions are tempered to the extent that variations of only a few degrees throughout the year will be recorded. Gillies and Aughenbaugh (1981)[6] have observed air and ground temperatures at depth to quantify the damping effect that soil or rock cover has on fluctuating air temperatures. The placement of structures partially or fully underground is a method of making use of this natural insulation to achieve tempered or controlled environmental conditions throughout the year.

In the static environment in which little or no air enters or leaves an underground space, thermodynamic theory can be applied to prediction of the closed system psychrometric conditions and a number of studies have been undertaken to empirically verify these relationships. Stauffer (1978)[12], Lorentzen (1978), Boileau and Latta (1978)[4] and Warnock (1978)[14] have observed the effects of heating or cooling underground rooms to maintain conditions above or below the ground virgin rock temperature. In the design of underground housing, however, some account must be taken of air movement from outside. Positive ventilation is necessary to satisfy respiration requirements and in hot humid climates to reduce condensation of moisture on interior walls. The introduction of outside air will change the static environmental conditions within the underground opening. Significant flow rates of air directly into the dwelling at surface temperatures will cause much of the insulated advantage of the tempered environment to be lost. To overcome this dynamic change in conditions as air movement occurs, active air conditioning of surface air can be undertaken through the use of conventional mechanically operated cooling and heating equipment or alternatively passive systems can be incorporated in the underground opening design to assist or replace these units.

One passive system for tempering air flow involves passing the intake air through tunnels or buried pipes before it enters the subsurface dwelling. Contact with rock or earth pipe surfaces transfers heat and moisture to or from the surrounding rock mass and adjusts air temperature to subsurface conditions. This study has been undertaken to examine passive air heating for winter home design. While some of the concepts examined have application to passive cooling air tempering for hot climate design, this study does not comprehensively examine this problem. Akridge (1981)[1] maintains that passive cooling has proved to be very difficult compared with passive heating. He maintains that passive cooling techniques for hot humid regions using the earth are nonexistent; the earth can provide sufficient sensible cooling, but the latent load cannot be handled adequately.

In the ventilation of deep mines, consideration has to be given to the transference of heat from hot country rock as air passes through tunnels to ventilate working stopes. Practical engineering criteria used in the design of mine ventilation systems, or where necessary, underground refrigeration units has application to the tempering of intake air to subsurface dwellings.

To study the tempering effect of passing surface air along rock lined passages, a series of tests were undertaken using ventilation facilities at a small mine in dolomite rock at the University of Missouri-Rolla. Experimental results have been collated and compared with thermodynamic relationships and heat transfer equations. From this base, suitable designs are proposed for ground tubes or tunnels to temper winter air for home heating. Plans proposed incorporate a heat pump unit as an energy transfer stage between below ground warmed air and the home heating system. Exercises have been undertaken for homes in three climatic areas of the United States and for various soil and rock subsurface ground conditions. The use of systems based on both open flow below ground passages and closed loop air flow paths have been examined.

Experimental Procedure

The tempering effect of passing air along rock tunnels was investigated by the following in situ test procedure at the mine. A continuous airway 185 m (600 ft) in length from the surface intake to the flow outlet in part of the mine was prepared. This air flow pathway of average dimensions 2 m by 2 m (6.5 ft by 6.5 ft) was through dolomite rock with a depth of rock and soil cover of approximately 10 m (33 ft). A variable speed vane-axial fan powered by a 15 kW (20 hp) motor forced air through the test airway. During the tests, an air velocity of approximately 1.0 m/s (200 fpm) through the system was measured, giving a quantity flow rate of 4 m^3/s (8000 cfm).

To evaluate the effects of changes in air psychrometric conditions over time, study measurements were recorded over a 10 day period. During this period, air temperatures were recorded at regular intervals of four hours at surface and underground stations along the airflow path. Further, airflow rate was checked regularly and rock temperatures taken at the underground test points. At these locations rock temperatures were recorded at depths of 25 mm (1 in), 100 mm (4 in), 300 mm (39 in) and 2000 mm (79 in) from the air rock interface by use of previously installed thermister temperature probes. All tests were undertaken at an approximately uniform airflow rate. Further details as to experimental test procedures are recorded in Smith, Orlandi and Gillies (1981)[11], and Gillies and Aughenbaugh (1981)[6]. In figure 1, a photograph of the mine site and underground data collection point is shown.

Figure 1. Underground data collection station showing air and rock temperature measuring instruments. Ice formation on the floor can be seen.

Experimental Results

The University of Missouri Experimental Mine is not a producing mine, ventilation fans are inoperative for most of the year and natural airflow passing through the workings is slight. Throughout the year, air temperatures in the underground passageways and rock mass temperatures (virgin rock temperatures) are almost constant at about 13°C (55°F). Conclusions drawn from test results are based on measurements taken over the 10 day period from 8 a.m. January 8, to 8 a.m. January 18, 1982.

Climatic conditions during testing, January, 1982

Surface air conditions throughout the data collection period were very cold and were described by one newspaper as leading to the longest prolonged period of "artic" weather of the century (Anon, 1982). Throughout the 240 hour study period, temperatures were consistently below freezing except for two short afternoon periods, and at a number of times were below -20°C (-4°F). Some light snow fell on the fourth day of tests, otherwise conditions were dry.

Air temperatures along the airway

The average surface air temperature throughout the test period was calculated to be -10.8°C (13°F). The tunnel air, after moving through an adjustment period when temperatures dropped from the virgin rock temperature of 13°C (55°F) to an intake average level almost 24°C (44°F) lower, reached an equilibrium reflecting almost constant heat flow from the rock mass interior. In figure 2, a typical relationship demonstrating air wet-bulb temperature against station distance along the tunnel is shown. To minimize any effects of temperature adjustment lag, temperatures are average readings for a 24 hour period. As changes in wet-bulb temperature are known from psychrometric theory to be directly proportional to total air energy levels this relationship shows that the heat transfer rate from rock to air is constant along the tunnel length. The tunnel air throughout the study was at all times close to fully saturated, with evaporation and sublimation of water (in floor puddles) and ice occurring along the airway length.

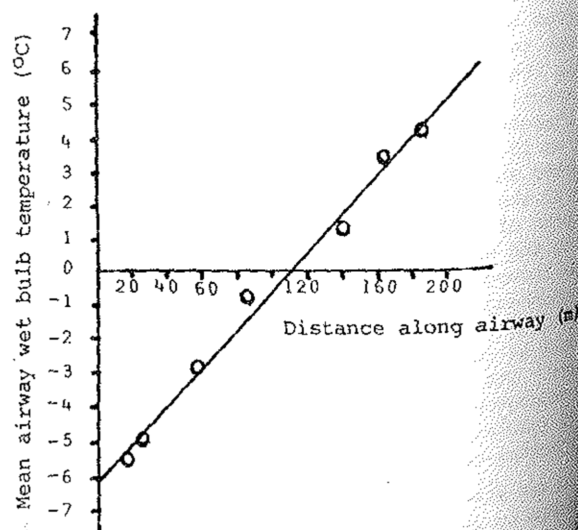

Figure 2. Graph of mean airway wet-bulb temperature at various distances along airway. Temperatures are averaged for the fifth day of study.

Rock temperatures

Temperatures of the rock mass surrounding the tunnel were recorded from previously installed probes sealed in boreholes. From an initial rock temperature of 13°C (55°F) readings dropped sharply for the first few days at stations near the air intake. After the first three days, only minor changes occurred in temperature levels, and these reflected surface climatic warming or cooling periods.

From the rock temperature data it is possible to calculate depth from the tunnel surface to reach rock uninfluenced by the cooling air flow. The rock mass envelope surrounding the tunnel is cooled by the moving air and increases in depth during the first three days of testing to a maximum of 2.0 m (6.5 ft) from the air rock interface. For the remainder of the period, an equilibrium is established where the rock mass envelope at the beginning of the tunnel is cooled to an average depth of about 2.5 m (8.2 ft). Extrapolation shows that a tunnel of about 280 m (920 ft) in length would fully temper the air under these conditions.

The equilibrium situation established reflects the influence on the rock mass of an average temperature throughout the period of -10.8°C (13°F). As previously mentioned the study was undertaken during a period of unusually severe winter weather; it is rare for prolonged below freezing conditions to last more than a few days, even in mid-winter, in central Missouri. Cold periods are normally followed by warm days of above freezing temperatures and this warmer air flowing along a ground tunnel or tube will reduce the heat energy flow from the rock and the depth of the zone of cold rock surrounding the tunnel. Analysis of the ground passage system throughout the year demonstrates that while the envelope layers of rock are cooled in winter, the reverse energy flow path direction is seen in summer with hotter airflow warming the surrounding rock. Under the severe weather conditions experienced during the tests, a comparatively stable rock temperature profile in the envelope was developed after a short period. The conclusion has been reached that the test measurements have experimentally defined the maximum depth of temperature affected rock which is likely to be measured after either a prolonged period of very cold weather or at the other extreme, after abnormally hot summer temperatures. The less extreme air temperatures of spring and autumn will have a less dramatic impact on the rock. In examining the effects of air temperature change throughout the year, it is considered that the rock temperature depth determined experimentally defines a maximum zone of influence appropriate to seasonal air temperature fluctuations which could be expected to occur in the area.

Preconditioning air for habitable space

To harness the advantages of using preconditioned air systems for ventilating either above ground or subsurface building space, two approaches are proposed.

(a) Air is passed from the outside along a buried pipe or rock lined tunnel and blown directly into the building ducting system; or alternatively is forced through a heat pump unit which allows energy transfer to the building's ventilation system.

(b) A closed-circuit buried pipe or tunnel system is developed for continuous air passage. A heat pump placed in the passageway extracts or dissipates heat from the air and transfers energy to the building. Air in the continuous passageway will never reach the extremes of temperature induced by surface climate, but rather reacts to the load placed on it by the heat pump unit and transfers energy to or from the ground mass.

The system using outside air blown directly into the building has advantages of simplicity and low operating cost. Power costs to run a fan are not high. However a number of disadvantages are presented. Pipe or tunnel length will be considerable if air is to be suitably conditioned in periods of extreme climate. In most climatic locations, a large airflow along the pipe will be needed if sufficient energy is to be available for heating or cooling the house. This will have to be exhausted from the house creating problems of draughts. With a suitable system, air can be tempered to a temperature approaching the V.R.T. Further heating or cooling using mechanical plant will then be necessary to bring conditions to suitable interior comfort levels. Odours, muskiness and dampness from the tunnel will be brought into the building.

Heat pump systems overcome many of these problems as they separate the building air system from that in the buried pipe or tunnel. Pipe lengths in closed circuit systems will be much shorter and pipe diameters smaller. Power to operate a fan will be needed (although in the closed system, as the pipe length is shorter, reduced wall friction will lower power costs), in addition to the cost of running the heat pump. Heat pump energy efficiency (electrical power needed compared with energy output) is stated as the Coefficient of Performance (C.O.P.) and typically, for systems operating across a low temperature difference this is 2.5 to 3.0. Heat pumps operate extremely inefficiently in extreme winter weather and need auxiliary heating boosters, but are ideal for tempered air conditions under steady flow. The principal disadvantages of using a heat pump in either an open or closed circuit system are the costs of operating the mechanical unit, and the lack of fresh air brought into the building. The costs of using a heat pump can be more than outweighed by designing a closed circuit system in which excavation costs of the pipe are markedly reduced. Fresh air intake into an above ground dwelling will generally not be a problem although a special intake for underground dwellings will need to be considered.

Design Requirements for a Dwelling

Results from the study have been interpreted in an attempt to develop design criteria for preconditioning pipe or tunnel systems attached to domestic dwellings. Calculations have been undertaken for heating load conditions and are based on the following assumptions.

(a) The building being heated is a domestic dwelling of 140 m^2 (1500 sq.ft) enclosed floor space.

(b) House construction incorporates modern insulation and heat loss is 85 W/°C (530 BTU/hr - °F).

(c) Air velocity along the pipe is 1.0 m/s (200 fpm).

(d) A heat pump unit is situated at the end of the air passage for regulating heat input to the dwelling to allow the achievement of varying desired interior temperature levels.

Specification of design parameters for this dwelling have been influenced by the dimensions of the model used by Bartlett (1979)[3] in his study of the application of heat pump systems to the heating of a central Missouri home.

The heating of domestic dwellings

From the study of airflow heating under severe winter conditions in the Experimental Mine at Rolla, Missouri, it was found that approximately 150 kW of heat energy was picked up by a flow of 4 m^3/s (8000 cfm) along a 185 m (600 ft) tunnel length. The average outside surface temperature during the ten days of study was -10.8°C (13°F), while at the end of the tunnel the equilibrium temperature averaged about 3°C (37°F) (with a range of plus or minus 2.5°C (4°F)) reflecting surface climatic fluctuations. For comparison with round section tunnels and pipes, the mean hydraulic diameter of the experimental tunnel was calculated to be 2.25 m (7.4 ft).

Design domestic heating power requirements are factors which vary from place to place for the "standard" home, and it has been ascertained that a 10 kW capacity plant is adequate for winter heating of the standard central Missouri home. While efficiency of conventional surface heat pumps used alone to heat in winter is very low, units placed at the end of a tunnel long enough to bring the air temperature to 10°C (50°F) would provide possibilities of efficient operation. A unit placed at the end of an extended version of the tunnel in the study which could warm air to 10°C (50°F) would have a C.O.P. of about 2.5 (the average temperature of the air passing across the evaporator unit would be 6°C (43°F) with the inlet air cooling from 10°C (50°F) to 2°C (36°F) as it passed across the exchange fins. A cooler outlet temperature would, of course, be possible although problems from frosting occurring on fin surfaces would be increased).

For supplying the design heating load of 10 kW for a Missouri home, a heat pump operating with a C.O.P. of 2.5 over the above temperature range will draw 4 kW of electrical power while transferring 6 kW of heat from the tunnel air. Saturated air in the experimental tunnel, in cooling from 10°C (50°F) to 2°C (36°F), releases some 85 kW of energy or enough heat for a maximum of 14 home heat pumps.

These calculations have been undertaken using data from an open tunnel system. However, if a closed system is developed where the air on leaving the pump evaporator fins is recirculated, then a shorter length of tunnel will be required to heat air to 10°C (50°F) and increase air enthalpy by 85 kW. This length can be calculated to be about 105 m (350 ft).

In most circumstances, it will be more practical for smaller pipe systems to be incorporated in the design of individual houses than for groups of houses to be tied to one large system. With individual tunnels, diameter and size can vary and system flexibility is increased. Maintaining an air flow velocity of 1.0 m/s (200 fpm) through the individual tunnels gives an air quantity of 0.30 m^3/s (600 cfm) for each system sufficient for heat absorption. Using proportionality equations, the pipe diameter necessary to pass this air flow quantity is 0.62 m (2.0 ft).

These calculations have been made from assumptions based on empirical data collected in a system where the air was picking up moisture as it moved down the tunnel and so remaining in a saturated or near-saturated condition. Within a closed air system in which water ingress from surrounding rock is eliminated by sealing, saturated air will not be present throughout the system. As the air passes across the heat pump evaporator fins, condensation will occur with cooling and air humidity on leaving the unit will be that of saturated air at the cooler temperature. Air will be recirculated through the system and on later passes through the heat pump, little condensation from the drier air will occur.

Unsaturated air requires less energy to heat up or cool down than saturated air across the same temperature range. For the design calculations on the Missouri home, unsaturated tunnel air (with a dew point of 2°C (36°F) will absorb 3.15 kW of energy in increasing temperature from 2°C (36°F) to 10°C (50°F), or about half the energy level of air exposed continuously to free water. In this situation, an earth tempering air system will have to pass about twice the flow rate of air to achieve the same energy level change and if air velocity is held constant, pipe diameter will have to be increased.

A general energy transfer equation for ground tunnels

While an empirical examination has been made of the energy flow characteristics of a below ground air tunnel and results used to quantify design parameters for a Missouri home, the development of a general equation from these results to explain the energy exchange phenomena is necessary if results are to be used for other geographic locations. A general equation is found to be a function of a number of factors including the following.

(a) The psychrometric properties of air and the level of air saturation.
(b) Geographic location, climate and the virgin rock temperature of the area.
(c) Rock or soil thermal properties and ground water levels.
(d) The ground pipe system and the characteristics of any heat pump unit in use.

The derivation of a general equation is complex. Details are set down in Gillies, Elifrits, Erten and Aughenbaugh (1983)[7].

Goch and Patterson (1940)[8] have applied develop- ed mathematical theory to the general problem of energy flow into a tunnel driven in a hot rock mass. They have proposed a method which makes use of tabled values calculated to simplify the solution of complex functions incorporated in any rigorous solu- tion of the heat conduction process.

The general design of a below ground air system for an average dwelling has been undertaken on the following basis. Results have been calculated using the general empirical formula developed by the authors, and accuracy compared with those obtained using the formula developed by Goch and Patterson. Specifications are given for pipe diameter and length for a system at a sufficient depth that temperature variation from the geographic annual mean is at a minimum. To illustrate application under different conditions, the following situations have been exam- ined.

(a) Calculations have been performed for both the case where the air entering the heat pump evap- orator is fully saturated (such as in an open pipe design or under wet conditions) and for a sealed closed system in which the air has a relative humidity of 50 percent.

(b) Three U.S. continental locations have been sele- cted as sites for study:
  (i) Freeport, Illinois which exhibits sev

winter conditions and mild summers.

(ii) Rolla, Missouri where both moderate winters and summers are recorded, and

(iii) Birmingham, Alabama as a center where winters are mild while summers are hot.

Information on area ground temperatures, winter climate (given as the average temperature on the coldest winter day) and the design requirements for a dwelling's heating requirements are given in table 1.

Table 1. Design conditions for various locations

Location	Freeport, Il.	Rolla, Mo.	Birmingham, Al.
Ground V.R.T., °C	10	13	17
Winter Average Minimum Design Temperature, °C	-28	-18	- 7
Design Domestic Heating Power, kW	12	10	7

(c) Analysis has been undertaken for different sub-surface materials. Commonly occurring rock and soil types are examined and average thermal characteristics as determined by Clark (1967)[5], Touloukian and Ho (1981)[13], Nichols (1976)[10], and Winterkorn (unpublished notes)[15], have been used.

(d) Determinations have been made for systems in which

(i) air is passed through an open circuit passage and is blown through a heat pump unit to facilitate energy change before being exhausted to the atmosphere, and

(ii) air recirculates through a closed system with a heat pump unit placed within the air flow path.

Design dimensions for a domestic ground air tube system.

Design dimensions of an air system suitable for an average sized, well insulated home have been calculated and are set out in table 2.

Table 2. Design dimensions for a ground pipe or tunnel system for three U.S. locations and varying sub-surface materials. Air enters heat pump unit at 10°C (50°F)

* As calculated using derived empirical equation.

** As calculated using Goch and Patterson general equation.

D is airway diameter dimension, L is airway length.

A. Open circuit system in wet ground. Air is saturated.

Ground Material	Freeport, Il.			Rolla, Mo.			Birmingham, Al.		
	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)
Dolomite	1.38	392*	405**	1.33	309*	337**	1.33	247*	242**
Granite	1.38	292	328	1.33	225	251	1.33	172	177
Sandstone	1.38	372	420	1.33	292	315	1.33	232	226
Sandy soil (moist)	1.38	453	518	1.33	363	395	1.33	300	284
Clay (compact)	1.38	444	501	1.33	354	382	1.33	292	301
Loam (moist)	1.38	422	479	1.33	335	364	1.33	273	287

B. Open circuit system with air at 50 per cent relative humidity.

Ground Material	Freeport, Il.			Rolla, Mo.			Birmingham, Al.		
	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)
Dolomite	1.55	380*	377**	1.51	297*	314**	1.61	229*	**
Granite	1.55	283	311	1.51	217	233	1.61	159	178
Sandstone	1.55	361	394	1.51	281	297	1.61	214	225
Sandy soil (moist)	1.55	439	483	1.51	349	366	1.61	278	274
Clay (compact)	1.55	430	472	1.51	341	354	1.61	270	269
Loam (moist)	1.55	409	446	1.51	322	338	1.61	252	259

C. Closed circuit system in wet ground. Heat pump air exhausts at 2°C (36°F).

Ground Material	Freeport, Il.			Rolla, Mo.			Birmingham, Al.		
	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)
Dolomite	0.73	185*	167**	0.66	68*	63**	0.56	33*	31**
Granite	0.73	133	130	0.66	48	47	0.56	24	24
Sandstone	0.73	175	159	0.66	64	59	0.56	31	30
Sandy soil (moist)	0.73	220	193	0.66	78	72	0.56	39	37
Clay (compact)	0.73	215	186	0.66	78	70	0.56	38	36
Loam (moist)	0.73	202	180	0.66	74	67	0.56	36	34

D. Closed circuit system with air at 50 per cent relative humidity. Heat pump air exhausts at 2°C (36°F).

Ground Material	Freeport, Il.			Rolla, Mo.			Birmingham, Al.		
	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)	D (m)	L (m)	L (m)
Dolomite	0.83	175*	153**	0.75	64*	57**	0.64	31*	29**
Granite	0.83	125	117	0.75	46	43	0.64	22	22
Sandstone	0.83	165	147	0.75	60	54	0.64	30	28
Sandy soil (moist)	0.83	207	177	0.75	76	66	0.64	37	30
Clay (compact)	0.83	202	173	0.75	74	64	0.64	36	33
Loam (moist)	0.83	190	164	0.75	70	61	0.64	34	31

Interpretation of design dimension calculations

Examination of calculated results emphasises the following points. The system diameter is a function of airpath cross section necessary to allow the required heat energy to be absorbed by the air mass flow while maintaining a constant velocity of 1.0 m/s (200 fpm). In colder climates, or in the open circuit system examples where energy requirements are increased, larger diameter systems are required to increase the air mass flow and its energy carrying capacity. Dry air of low relative humidity exhibits a lower enthalpy level than saturated air and so larger diameter airpaths are needed to maintain energy carrying capacity. Design diameter sizes calculated are a minimum dimension and increasing size would allow some margin for discrepancies in domestic heating load or air saturation levels.

The ground pipe or tunnel length is a function of both the required air temperature change and the thermal properties of the surrounding rock or soil material. Again, length dimensions given are a minimum and any additional length incorporated in a system would allow some safety margin. However, once air temperature has increased to the virgin rock temperature level, no further increase will occur and dditional system length will be non-beneficial.

From this discussion it is clear that the para-eters of system diameter and length are largely in-ependent functions: increasing one dimension to compensate for a reduction in the other would not, in general, allow sufficient energy absorption for the particular situation under examination. Comparison of system dimensions for pipe length calculated using the derived general equation, and the Goch and Patterson approach demonstrates very close correlation of results. For the survey, the average discrepancy between results from the two approaches is 2.8 per cent with the maximum discrepancy for results from any one location being 14 per cent.

The results emphasise the size difference in pipe diameter and length between the closed circuit system design. The open system designs demand dimensions capable of handling extremes in climatic condition, although the lag time in temperature change along the air path would reduce the impact of short periods of adverse weather. The air energy changes needed are accommodated by increased volumetric flow through tube lengths. Pipe lengths needed in the coldest climate of Freeport which exceed 400 m (1300 ft) for the various soil types are somewhat impractical for normal residential situations. However, those calculated for the closed circuit systems demand lower volumetric air flow and most designs are of dimensions which are compatible with the size of a normal building lot. Some lend themselves to being buried beneath the outer walls of excavated basements.

Care will be needed in the layout of a system to ensure that effects of interference from other sections of the ground tempering airpath or parallel branches do not adversely affect results. No system branch should be placed closer together than twice the maximum radial length of the temperature affected tunnel rock walls to avoid "overtaxing" the stored energy of surrounding rock.

Results from this empirically based study demonstrate that design calculations for a pipe system are complex and the cost of investment in a suitable subsurface system will not be cheap. However, the potential for obtaining long term savings from installation of a carefully thought out system are apparent and installation of test units to determine long term operating characteristics is warranted.

Conclusions

As air moves through a rock lined passageway temperature changes take place as heat energy transfer occurs within the air and rock mass system. To obtain a better understanding of this process, an in situ study was undertaken to monitor and record the changing conditions at various locations along a 185 m (600 ft) passageway in dolomite rock with regulated airflow.

Calculations have been made to determine design dimensions for use in the planning of systems in different locations and varying subsurface geology. Ground pipe dimension sizes for the different situations have been calculated using an empirically derived general formula and compared with the results from a theoretically based formula developed by Goch and Patterson (1940)[8] for use in the underground mining industry. Correlation of results from these two approaches is excellent.

It has been found that ground pipe dimensions needed to temper air before being passed through a heat pump unit are compatible with the size of a normal building lot for sites where mild winter conditions are experienced. A closed circuit system would appear to offer the greatest economy in excavation cost. Dimensions calculated for an individual residence located in a severe winter area are somewhat impractical using the system constraints under study. Some further investigation into the economics of using a heat pump unit operating at lower air inlet temperatures is warranted. Communities in northern latitudes may find it advantageous to utilize one common large diameter tunnel system for the tempering of air for a number of residences.

Acknowledgement

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