EVALUATION OF UNDERGROUND RAILWAY NETWORKS OPERATING SUSTAINABLE COOLING SYSTEMS

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ABSTRACT

Underground railway system usage is growing throughout the developing world and in many cities the underground railway is the most commonly used form of public transport. The heavy use of electrically propelled train carriages within these systems can generate substantial quantities of rejected heat energy. This energy can significantly increase air temperatures within the trains and tunnels. When coupled to high ambient temperatures this can lead to passenger discomfort and health issues. Conventional air conditioning systems have been used in some modern underground railway installations but their operation has had limitations and the units are highly energy intensive solutions. Conventional air conditioning often cannot be included in older systems through heat rejection and unit size problems.

Sustainable cooling systems could easily reduce the overall system energy usage and provide an acceptable environment for passengers. Two novel proposals for cooling underground railways are presented here. The first uses cold groundwater to cool the air in the tunnels. This cooler air is then circulated through the tunnel network using the existing ventilation in combination with the piston effect of the trains. The second novel proposal uses the surrounding soil to store thermal energy during operational hours and then to reject this stored heat during nighttime. This geothermal solution would off set the cooling load to the point that the passengers' thermal comfort would not be negatively affected.

This paper introduces a novel mathematical model that has been developed specifically to evaluate the effectiveness and the implementation of sustainable and low energy cooling strategies when applied to underground railway systems. The expected temperatures are calculated for both the train and the tunnel air, together with a profile of the temperature distribution in the surrounding soil.

Introduction

Underground railway systems can generate enough heat from their operations to raise tunnel and station temperatures as much as 8 to 12K above outdoor temperatures, the greatest differences being at night and in the early morning hours. Passenger discomfort will result in warm weather conditions if the underground railway environment is not cooled.

Ventilating an underground railway environment in which there is to be heavy traffic of electrically propelled rapid transit trains differ from those normally encountered in conventional building services projects. The heat generated by the train motors and electric lighting, together with body heat from passengers, is so great that excessive temperatures would prevail in summer when limited cooling is available. The installation of in-car air-conditioning units adds another major heat source in the tunnel. This heat must be rejected from the tunnel system to make in-car air-conditioning units an effective solution for both the train and the tunnel.

Despite the ground surrounding the railway network being at a constant year round temperature of approximately 15˚C [1], the tunnel network regularly reaches temperatures of 30˚C in summer with train temperatures in excess of 41˚C being reported, [2]. The cooling potential of the ground is not being exploited. In particular the capacitance of the tunnels, the use of cold groundwater and nighttime ventilation cooling has not been utilized. This is partly due to the lack of accurate mathematical modeling to assist the design engineer, [3].

The need in modern society to provide sustainable and low energy solutions to engineering problems is recognised through national and international legislation, [4]. This has produced an expansion in the use of low energy cooling strategies in buildings. Low energy is defined for the purposes of this paper as solutions, which provide substantial cooling power with minimal net energy input required. This could involve the use of groundwater, thermal storage, nighttime and seasonal ventilation and phase change materials, [5][6].

However, few low energy strategies have been used on an operational underground railway. This is largely due to the lack of a dedicated mathematical model to simulate their application in the thermal environment of underground railways, [3]. The mathematical models that are designed for use in underground railways do not currently take proper account of the capacitance, storage and heat sink issues which are associated with low energy cooling systems and are used for assessing peak summertime conditions in systems employing conventional technology, [3].

The enhanced expectations of the modern consumer have led to dissatisfaction with the thermal environment on the underground railway in London, [7]. The London network presents a difficult challenge to the engineer. This is due to two major problems. The first is the age of the system; when the London underground railway was built there was no consideration given to cooling the network. The second problem is the sheer volume of passengers who use the underground railway in London. The network carries over 3 million people around London everyday, [8]. Therefore renovations of the infrastructure must be conducted outside operational hours to prevent excessive disruption. Effective use of the natural heat sink effect would require minimal disruption to install on an underground railway. This would make the use of the heat sink effect an attractive option for delivering cooling to underground railways. Utilizing the heat sink effect of the ground requires accurate mathematical modeling of the whole thermal environment.

This paper describes two novel low energy cooling systems and how they could be used on an underground railway system. The two cooling strategies are described in detail and benefits listed. The paper also introduces a novel mathematical model that can be used to assess sustainable cooling systems on underground railways.

Heat Loads

To understand cooling systems applied to underground railways it is instructive to investigate where the heat energy enters the networks in the first place. Particularly the relative strengths of the heat loads can assist the engineer plan energy management options to be used in conjunction with a cooling system. An underground railway gains heat from a variety of sources. These are shown for the tunnel control volume in Figure 1 and for the train in Figure 2. The major heat source in a system with no air conditioning units is the braking load, which accounts for approximately 70% of the total heat load, [9]. Should an air conditioning unit be included on the system it often produces almost as much rejected heat energy as is produced by the braking system. Some of the loads depend upon the operational circumstances of the underground railway that is under investigation.

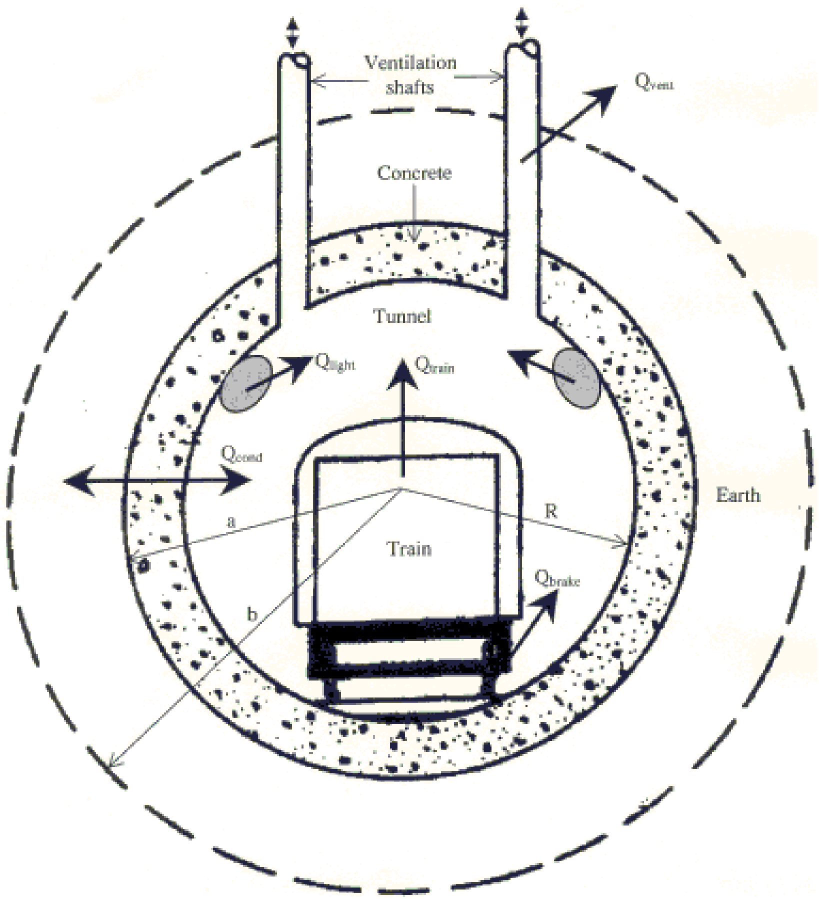

Figure 1 - Heat loads in the tunnel of a typical underground railway [9]

The heat loads are removed through the ventilation systems and via conduction through the ground. These heat removal methods are not always sufficient in the removal of excess heat energy, which leads to excessive temperature build up within the tunnels of the system. As stated earlier air-conditioning systems dramatically increase the heat energy released into the system and this can exacerbate the inherent thermal problems. A low energy cooling system would not, by definition, provide this increase and therefore are an attractive solution to the problem. The two proposals put forward in this paper provide cooling potential without increasing the heat released into the network.

Groundwater Cooling

Groundwater Cooling Applied to Underground Railways

Groundwater cooling has been applied in a variety of building services applications but currently no underground railways have used this form of cooling provision. The concept of groundwater cooling is as follows: groundwater is pumped through heat exchangers; hot air in the underground railway network is converted to cool air by passing over the heat exchangers; this cool air is pumped by fans onto platforms via air ducts; trains power the piston effect aerodynamics which circulates the air around the underground railway network; turbines on top of trains suck air to cool trains. A schematic diagram of this arrangement is shown in Figure 3.

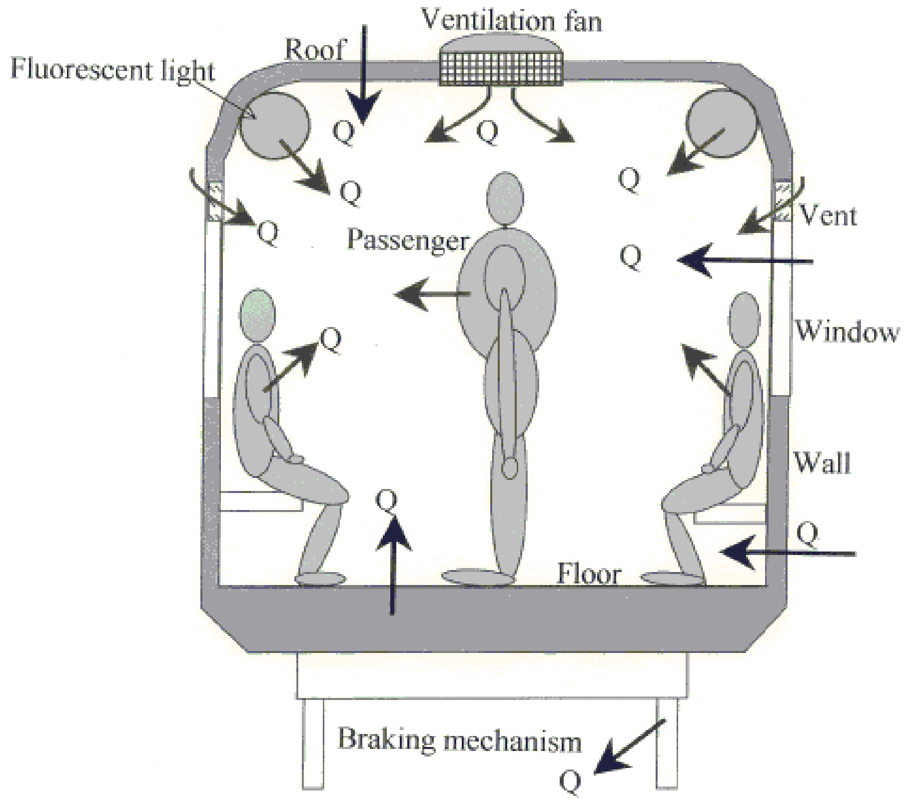

Figure 2 - Heat loads in the train of a typical underground railway [9]

This type of cooling system for use on underground railways was first proposed by Maidment & Missenden , [10]. The proposed methodology was as outlined above. Among the many potential advantages of a groundwater cooling system is a reduction in groundwater levels, and the low energy aspects of this scheme, particularly if the underground railway has to pump groundwater already to prevent foundation damage. An example of such a system would be the London network which pumps 30 million litres of water per day to prevent damage to the network. The fact that the groundwater cooling would provide cooing to the ventilation air means the temperature needs could be met without mechanical refrigeration enhancement of the output air. This avoids all issues of refrigerant ozone depletion and related global warming issues.

Whilst the groundwater cooling scheme would be applied to the tunnels this will lead to cooler trains. This is because there is a direct relationship between the tunnel temperature and the train temperature. This direct relationship has been shown both with the authors' model and data taken from operational underground railway networks, [11]. The cooler trains will improve passenger thermal comfort particularly during the summer months.

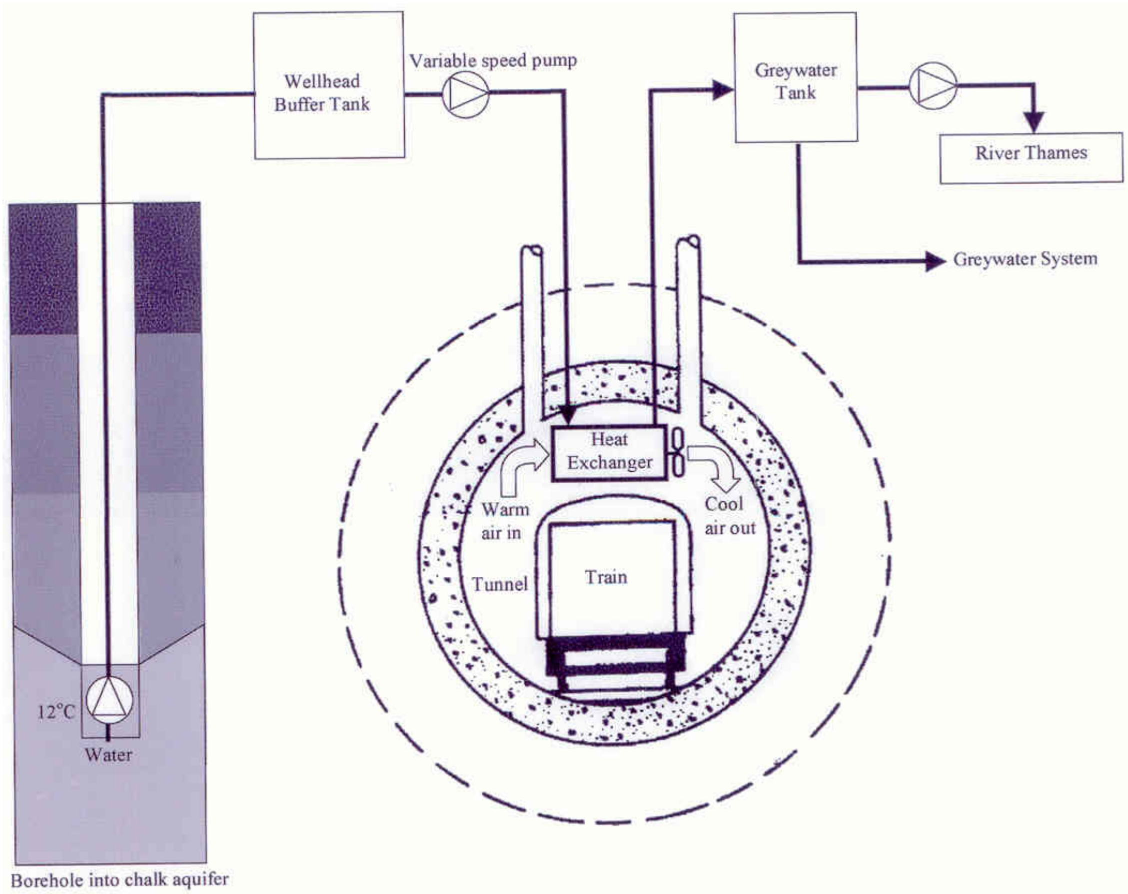

Figure 3 - Schematic diagram of the groundwater system as installed onto an underground railway

Geothermal Cooling Coupled with Seasonal Ventilation

What is Geothermal cooling?

Geothermal cooling relies on the use of the near constant temperature of the ground to provide a stable heat source that is utilised through energy exchange between the earth and the space to be cooled. The constant temperature of the ground found in London is close to the correct temperature for a heat pump to operate at maximum efficiency. This has the advantage of increasing the overall system efficiency. A standard building services geothermal cooling system would consist of a working fluid being moved through a buried pipe. This fluid would then be passed through a heat exchanger and release the coolth into the conditioned space. This form of system would not be particularly easy to implement on older underground railway systems due to unit size although it could prove useful for new and spacious current networks. The proposal using geothermal cooling that this paper presents relies on heat pipes buried in the earth surrounding an underground railway tunnel.

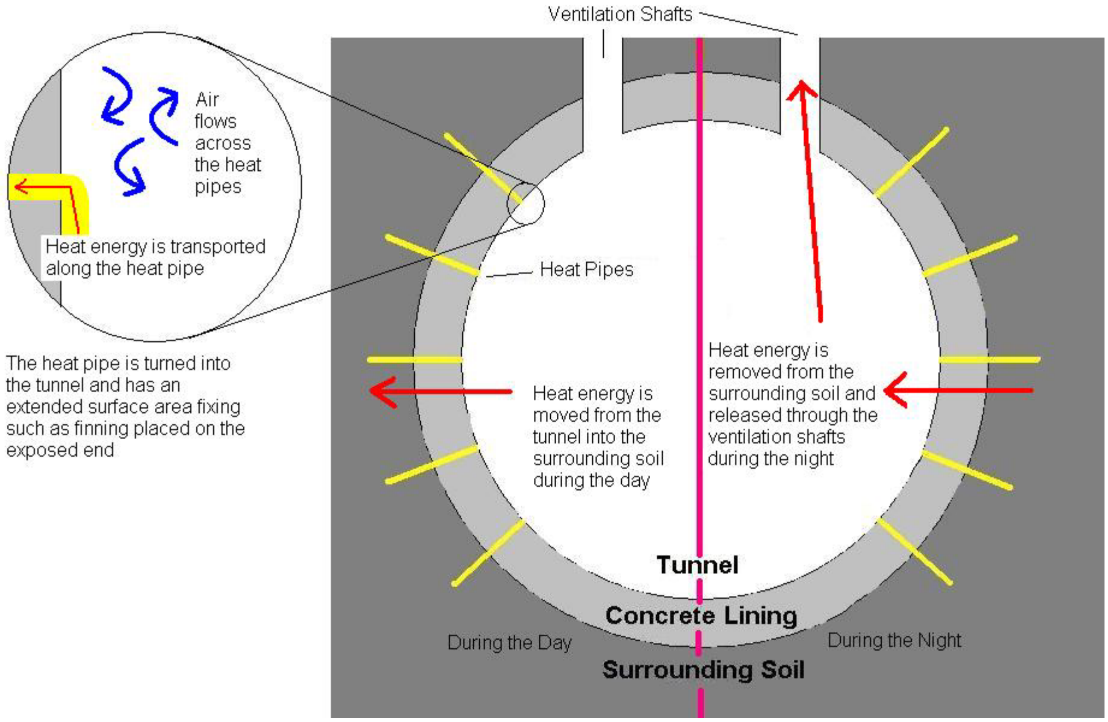

Figure 4 - How the heat pipe solution would be incorporated

A heat pipe is a simple device that conducts heat at constant temperatures over potentially considerable distances. The heat pipe has no moving parts and consequently is very reliable if the heat pipe is not compromised. A hole would be bored into the earth that surrounds the underground railway tunnel and a heat pipe will be placed in the hole. A heat pipe is a sealed slender tube containing a wick structure lining the inner surface of the heat pipe. A small amount of working fluid is contained within the heat pipe in its saturated state. A heat pipe comprises 3 sections, they are known as the evaporator, condenser and adiabatic respectively. In the evaporator section heat is absorbed and the working fluid vaporizes. In the condensing section the vapour is condensed and heat energy is rejected. The final section is the adiabatic section and in this section the fluid and vapour travel in opposite directions through the wick and core respectively. The heat that is absorbed by the heat pipe removes heat generated within the underground railway tunnel and releases this heat deeper into the surrounding soil than usually happens. The main effect of this is to increase the surface area used for heat transfer and the volume of earth used to dissipate the heat energy. This alters the thermal topography that surrounds the tunnel.

Potential for Heat Pipe Cooling

An initial investigation conducted by Ampofo et al. [5] showed that the provision of a tenfold increase of the thermal conductivity of the surrounding soil reduces the temperature experienced in the tunnels and trains of an underground railway by up to 5°C. This initial investigation led to more detailed investigations into the use of heat pipe cooling in underground spaces. The initial work was conducted using FEHT developed by f-chart software [12]. FEHT was used because of the simple interface that the program has as well as the lack of the need for a complicated set up. This means that the program can be mastered quickly and useful results can be extracted quickly.

The initial work conducted was concerned with the most effective method of modelling the underground railway tunnel and the heat transfer around this. The main problem is that the tunnel will never be truly circular in cross section at all points and may indeed not be at any points depending on the design and construction method. Therefore initial studies were conducted to see what effect on the temperature profile of the surrounding ground a change in tunnel shape would have. The results are shown in Figure 5. It can clearly be seen that there is almost no difference in the profile of temperature with relation to the tunnel cross sectional shape. This will enable the modelling of the tunnel to be performed with square tunnels and Cartesian co-ordinates in FEHT.

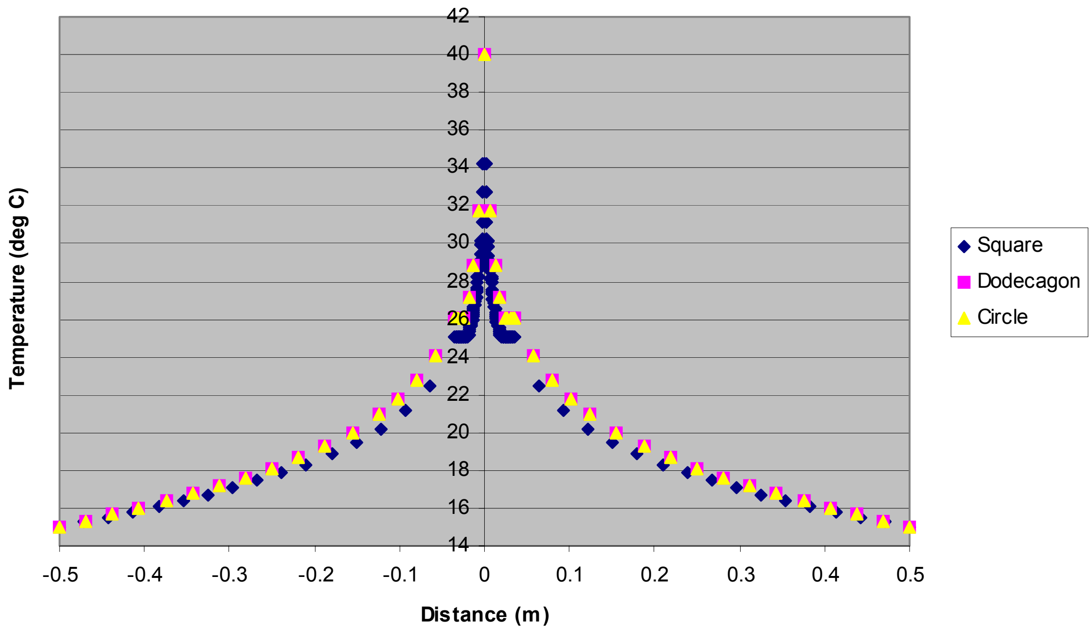

Figure 5 - Comparison of the methods of representing an underground railway tunnel

Once this ability had been established the modelling of the system with and without heat pipes could be performed. The resultant graphics are shown in Figure 6, which shows the effect of 8 heat pipes being installed in a 2D section.

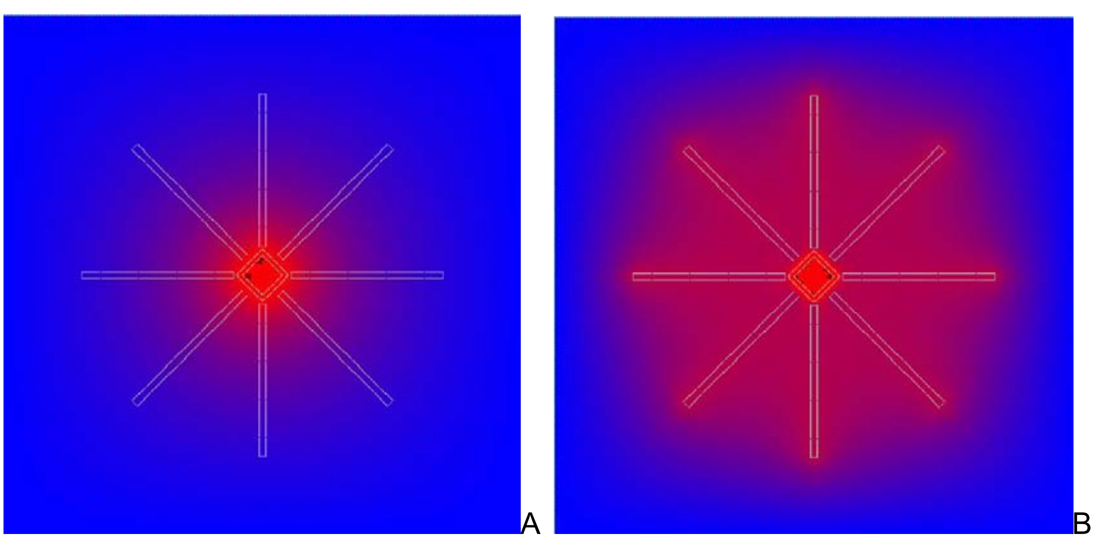

Figure 6 - Comparison of temperature cross sectional profile A: No Heat pipes B: Heat pipes present

The alteration in the thermal topography can be easily seen in Figure 6. The heat pipes increase the area and volume of the surroundings that are used for heat transfer. This lowers the intensity of the heat energy at the centre of the system. To make constructive use of the alteration in the thermal topography the additional volume used to provide a cooling effect must not be allowed to become thermally saturated. To prevent thermal saturation a mechanism of removing heat from the ground must be considered. A useful quality of a heat pipe in this scenario is the fact that it is completely reversible. This means that heat can both be conducted into the ground as well as conducted out. This could allow for heat energy to be stored during the day and released at night. In order to release heat energy gained during the day efficient ventilation during the night is required to move the heat energy out of the underground railways ventilation stacks.

Thermal storage systems are in use in a variety of building services applications and this technology could well be carried over to underground railways and used to provide the network with a year round thermal strategy. The ground could be used to buffer the heat loads of the network during the summer when the tunnel temperatures are higher than during the winter. Providing efficient nighttime ventilation could also back up this seasonal effect with a daily release of some stored heat to the surrounding atmosphere.

The main potential problem is to ensure that the heat pipe is reversed during the non-passenger carrying hours of the system. This will require the ground to be at a higher temperature than the air temperature in the tunnels. Our model shows that when the trains are not running the temperature experienced in the tunnels is below the temperature built up in the ground, provided the tunnel fans are run at current capacity throughout the night. This means that the temperature that would be passed over the heat pipe would be lower than the temperature found in the earth. As long as this remains the case the heat pipe will reverse and the heat will be removed from deep within the earth preventing thermal saturation.

Modeling Sustainable and Low Energy Cooling Strategies

Underground railway thermal mathematical models have very limited application to sustainable and low energy cooling systems mostly because of large inaccuracies in the modeling of the ground and the heat sink effect, [3][11]. These shortcomings mean that the design engineer has no tools to assist with the development of a sustainable cooling scheme. The authors have previously developed a steady state mathematical model that demonstrated the possibilities of using sustainable cooling on underground railways. This model was reported in Ampofo et al 2004, [9] and updated in Thompson et al 2005 [11].

The authors have now developed a new model called TURTLE (Transient Underground Railway Thermal Load Evaluator), which is an extension of the initial model. TURTLE uses a fully transient infinite heat sink module coupled to a quasi-steady underground railway simulator to give the most accurate reflection on sustainable cooling systems applications to underground railways currently available.

TURTLE is written in EES (Engineering Equation Solver) created by f-Chart software, [12]. This package was used for development of the model because EES will automatically determine the correct order to solve the equations entered. It allows each section of the model to be individually packaged without interdependence problems. This allows easy development of the model in physically meaningful sections. EES allows easy parametric analysis for all variables in the system. Also EES has built in psychometric functions, which allows the easy calculation of humidity and thermal comfort for both the train and tunnel.

TURTLE has been designed to operate on a generic deep line underground railway tunnel section. The model uses the geometric and thermofluid properties of the railway under investigation to determine its solutions. It predicts temperatures, humidities and thermal comfort parameters under year round representative conditions. TURTLE can be used to simulate current operating conditions as well as to investigate the effects possible changes could have upon the network. TURTLE has been constructed to be very general in nature however all the investigations were performed using London Underground data and as such the applicability of the model is restricted until additional validation work has been carried out. When this additional validation has been performed the GUI will be updated to allow for complete customization of the underground railway to be investigated.

Investigations Using Mathematical Models

The two proposals have been investigated using the models developed by the authors, both TURTLE and the initial steady state model. The results presented here are taken from both models though the majority of the work has been performed using TURTLE. Both of these proposals are designed to cool the tunnels and this cooler tunnel air is then circulated into the trains through the ventilation systems already present in the system.

The groundwater proposal has been shown to be capable of providing values of up to 350 kW per km of tunnel depending on the yield of the aquifer. This can lower the temperature experienced in a tunnel and train by up to 8°C. This is achieved with only the energy required to pump the groundwater through the system. The heat pipe system is used to modify the thermal topography of the earth. As this has never been performed in published literature the calculations have been taken assuming a modified thermal conductivity of the earth. The earth is assumed to have had a ten fold increase in thermal conductivity. This results in a decrease in temperature of approximately 3°C.

Method of Cooling	Space Available	Power Available	Capital Cost	Operating Cost	Effectiveness
Groundwater	Yes	Yes	Medium	Low	High if groundwater is available in sufficient quantities
Heat Pipes	Uses existing fans	Yes	Low	Low	Medium. Limited cooling Needs complimentary system
Air-Conditioning on Train	Yes (limited)	Yes (Train power)	Medium	Medium	Medium Power failure to system increases risk of heat stress problems
Air-Condition in Tunnel	Yes	Yes	Medium	High Without structural change	Requires a barrier between cooled area and ambient air to be effective and plausible

Table 1 - Comparison of differing cooling methods for underground railways

A comparison table is shown in Table 1. This contrasts the two proposals and compares them with a standard air-conditioning unit applied to both the train and the tunnel. The space and power comparisons are considered for the London underground network only. The table and results produced thus far are intended to be used as a guide only. Additional investigations and calculations are required before a fully detailed and objective opinion can be derived, however current information points towards ongoing investigations into low energy cooling being worthwhile.

Conclusions

This paper has shown the possibilities of two novel sustainable cooling proposals for cooling underground railways. The two proposals have been shown to effectively reduce the temperature of underground railways without increasing the energy consumption of the railway networks significantly. This point is crucial because a main restriction on the inclusion of an air-conditioning unit is the increase in dissipated heat energy in the railway making the temperatures of the non air-conditioned spaces even less thermally bearable.

The groundwater proposal has been developed into a prototype solution. This will shortly be tested on an operational network to investigate the practicality of the solution. The results of this test could guide future uses of sustainable cooling in underground railways.

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