REPORT OF SOCIETY MEETINGS
'COOLING THE TUBE'
Presented by Sharon Duffy BEng, CEng, MCIBSE, MIET
Head of Station Systems Engineering – London Underground
A report of the LURS meeting at All Souls Clubhouse on Tuesday 13 September 2016

Sharon began the meeting by outlining the main points of her presentation: Background, Cooling the Tube Objective, Challenges, Cooling Analysis, Existing Cooling Solutions, New Solutions and Technologies, The Future – Waste Heat Utilisation and Key Successes to Date.

BACKGROUND

A publicity poster for the Bakerloo Line from 1906 was shown claiming to be 'The Coolest Place in Hot Weather'. Sharon doubted whether that would apply on this particularly hot evening! The heating effect in the tunnels was then discussed. When the LU tunnels were constructed the strata in the London Clay had an approximate temperature of 14°C which is the average annual temperature for London. Year on year running of electric trains has heated the clay and caused the surrounding strata temperature to rise. In effect there is an annulus of heat soak around the tunnels which acts as a thermal insulator. A graph was shown for internal and external temperatures on the Northern Line between Chalk Farm and Hampstead for a one month period in summer 2006. Although the external temperature fluctuated between 14°C and 34°C the internal temperature remained constant at about 30°C. This is partly because of the insulating effect of the tunnels, so that when the external temperature drops and cooler air enters, heat starts to transfer out of the tunnels back into the system with a moderating effect keeping the internal temperature fairly constant. The main energy sources (heat produced) of the operational railway are: Braking (conversion of kinetic energy to heat) 50%, Aerodynamic drag and other frictional losses 21%, Motor and drive losses 15%, Train auxiliary energy 6%, Electrical system losses 6% and Passengers 2%. The main Energy Sinks (heat transfer) are: Tunnel walls 79%, Train piston effect (transfers warm air to and from atmosphere by shafts and out through stations) 11% and Mechanical tunnel ventilation systems 10%. Sharon then showed a graph of the Network Heat Input of the main interconnected tube tunnel network. This showed that up to 2006 the heat generated had grown to 300 million KWh per annum, a significant energy input into the system. With regards to heat reduction LU are looking to optimise train operation through more efficient drive systems and the use of regenerated energy where the kinetic energy produced when the train is braking is converted into electrical energy and transferred back into the grid. Also being analysed is aerodynamic efficiency to optimise the train design to reduce drag and thereby reduce the associated energy consumption, and also being analysed is the motor drive and electrical system design to minimise losses and make them more energy efficient.

COOLING THE TUBE OBJECTIVE

The challenge is to keep customers cool enough to protect their wellbeing. The plan is to tackle temperatures through innovation and excellence. The objective is to keep the passengers cool enough to feel comfortable. It's not comfort cooling like walking into an air conditioned environment, instead the Cooling the Tube objective is to maintain the temperatures cool enough so that the passengers don't suffer any health impact. Although it should be noted that the new S Stock trains provide an air conditioned environment that does provide comfort cooling.

CHALLENGES

Sharon showed two graphs. One plotted the enormous increase since the mid-1980s of passenger journeys on LU. The other showed the predicted passenger journey demand for London Underground and Overground (approximately 1,800 million passenger journeys per annum by 2022/3). Demand is predicted to keep growing, even with new transport modes such as Crossrail coming into operation.

COOLING ANALYSIS

Analysis is being done to calculate what cooling is required. LU is looking at what heat energy is being generated by the trains and the train systems. Also how the trains are driven is being analysed. If the train is accelerated to the maximum speed, driven at that speed and then decelerated with a steep braking curve that generates more heat than if coasting was employed in the train speed driver guidance. There also interdependencies on operation, rolling stock design as well as utilising the regenerated energy. There are four main heat factors: (1) Line upgrades – which contribute more trains per hour. (2) Increased passenger demand – up 7% per annum. (3) London is a 'heat island'. Compared to other areas of the UK, due to the density of infrastructure and population, London does not lose much heat, even overnight. (4) Climate change – but this only contributes a small proportion. Tunnel Ventilation Analysis is used as a model for what cooling is required in future conditions. This is a single dimensional analysis, which models complex station and infrastructure geometries into single line diagrams, basically like a circuit diagram. The tunnel ventilation analysis models the operational railway to calculate the resultant temperature and airflows that are induced by moving trains along the tunnels. Although the modelling of an operational railway is complex it calculates an estimate of how much heat is being generated at stations and tunnels. Sharon posed the question "What are the challenges of cooling the network?". One is working with existing historical assets and infrastructure. It is difficult and expensive to introduce more tunnel ventilation systems to the deep tube lines, and even at stations, because of space constraints. The ferric dust generated through operation of the railway, from braking and the wheel/rail interface, also impacts on the air handling equipment.

EXISTING COOLING SOLUTIONS

The cooling systems that have been completed to date are:

Ground Water Cooling

This was introduced at Victoria station utilising water that was collected in an existing sump. Instead of pumping the water to the sewer some of it was diverted to three air handling units (AHUs) installed on the concourse by the Victoria Line connection to the District and Circle lines. The ground water cooling trial won a Carbon Trust award in 2006. This has since been removed as part of the Victoria station upgrade but there is a revised system designed which will utilise the seepage water collected in the existing station sump. A significant proportion of this sump water comes from the underground River Tyburn source, which used to flow above ground through Victoria. The quality of the water has been tested and it is relatively clean with no contamination from either hydro-carbons or coliforms and it has a maximum temperature of about 18°C. So it is a free cooling water source that can be used to cool the station. An AHU is a cooling coil with cold water pumped through it. Warm air is blown across it and as it passes through the coil, heat is exchanged from the warm air to the cold water, and the resultant cooler air is then discharged from the unit.

Fan Installation

Blue Fans have been installed that deliver an instant cooling effect as you walk past them (convective cooling). Thirty nine are in place at various stations with 94% of passengers rating them as good or very good. Ceiling mounted impulse fans, as used in road tunnels, were also trialled. These weren't as effective and have not been progressed. Comfort cooling has also been installed using mechanical chillers which utilise vapour compression refrigeration systems to chill circulating water. Chillers have been installed in Oxford Circus and Euston ticket halls. New systems have also been installed at Seven Sisters but these do not directly cool the platforms.

Fan and Mid-Tunnel Ventilation Systems (MTVS) upgrades

Thirteen Victoria Line MTVS have been upgraded. The largest fan on the Victoria Line has a diameter of about 2.5 metres and extracts a volume of 100m³ of air per second. Forty out of service fans across the network have been re-instated by Cooling the Tube. A new fan has been installed at Liverpool Street to extract warm air from the tunnels and ventilation has been improved at Holland Park. The MTVS on the Victoria Line had been installed when the line was built. A lot of MTVSs have been cleverly hidden across London. Sharon showed an image of one in the middle of a Georgian Terrace and one that appears to be a folly in a public garden but is in fact a MTVS discharge shaft.

How does an exhaust MTVS work? It's a very large ventilation fan which extracts warm tunnel air and then discharges it to atmosphere. By doing that it generates a negative pressure beneath the fan. The natural balancing of the negative pressure induces make-up air to be drawn in to the tunnels. Cooler outside air is drawn into the operational railway, via draft relief shafts, tunnel portal and through station entrances. As the cool air passes through the stations and tunnels, heat is transferred to the air warming it before it is discharged to atmosphere, thereby cooling the system.

Platform Air Handling Unit (PAHU)

PAHUs have been installed above the platforms at Oxford Circus and Green Park stations. PAHUs are AHUs complete with a very large water cooling coil. The PAHUs are mounted on the crown of the platform tunnel and they weigh approximately 3.5 tonnes when the cooling coil is charged fully with water, which is referenced as a wet cooling coil. Six axial fans induce warm air from the platform tunnel to be drawn across the cooling coil, at the rear of the PAHU and then the cooler air exiting from the cooling coil is discharged from the front of the PAHU onto the platform.

Chilled Water System

This has been installed at Oxford Circus. A chiller is a mechanical vapour compression refrigeration system, which is similar to the system within your refrigerator at home, but instead of cooling a food compartment, it cools a refrigerant to water heat exchanger. Cold water is generated and is pumped down to the station PAHUs. Heat is transferred from the warm air to the water in the cooling coils and the resultant warmer water is pumped back to the chiller to transfer the heat to the refrigeration system via the through the refrigerant to water heat exchanger.

Borehole Cooling System

This has been installed at Green Park station and uses cooling borehole water that is abstracted and reinjected via boreholes from and to the chalk aquifer which is located under London. There are five boreholes in the Royal Park, there are two abstraction and three reinjection boreholes. Borehole water is abstracted from the aquifer approximately 150 metres below ground level, and the abstracted borehole water temperature is about 13°C. The abstracted borehole water is then pumped via a primary circuit to the station to a water to water heat exchanger.

Within the station there is a closed secondary water circuit which circulates the secondary cooling water to and from the PAHUs and heat is transferred to the primary borehole cooling circuit via the water to water heat exchanger. The warmed borehole water exits the heat exchanger is then pumped back to a reinjection borehole to be reinjected into the chalk aquifer. The reinjection boreholes are located at approximately 350m distance from the abstraction boreholes to prevent thermal contamination of the abstraction water temperature. In terms of the chalk aquifer there is no net change in water volume; the only resultant impact is that heat is transferred into it. The use of the cool borehole water within the chalk aquifer is a form of free cooling.

Green Park Borehole Cooling Case Study

London Underground required that the Green Park station platform temperatures are maintained at the pre-line upgrade thermal conditions during warm weather, following the Victoria and Piccadilly Line upgrades. Based on the tunnel ventilation system modelling the station requires 800kW of total cooling capacity – 400kW for the Victoria Line platforms and 400kW for the Piccadilly Line platforms. No cooling is required on the Jubilee Line platforms as they were below the specified temperature. The borehole water cooling system design meets the required cooling performance and provides 800kW of total cooling capacity.

Hydrogeology

3D ground water models of the chalk aquifer and overlying strata in the central London area were produced in collaboration with the British Geological Survey team and the Environment Agency. Results showed that the injected warm borehole water caused thermal contamination between the reinjection borehole and the abstraction borehole. To reduce the impact of this the reinjection boreholes are sited approximately 350 metres from the abstraction boreholes. Over time the temperature of the abstracted water may be impacted as well, but modelling shows that the temperature is predicted to only increase by a manageable 2°C over 60 years, therefore this is a sustainable system at Green Park.

An alternative mitigation to the risk that the abstracted water temperature increases is to find a third party to connect to the primary borehole water system via a heat exchanger and transfer the heat from the warmed borehole water prior to it being reinjected into the chalk aquifer, i.e. waste heat utilisation. A third party waste heat utilisation system could reduce the borehole water temperature down from 23°C to the lowest temperature of 6°C, which would in fact result in the charging the aquifer with cooler water and thereby extending the life of the borehole cooling water system. There is passive provision for future waste heat utilisation included within the design.

Primary Borehole Water Distribution Circuit

The Environment Agency has granted a licence for water to be abstracted from and reinjected to the deep level chalk aquifer below Green Park. Each abstraction borehole has a submersible pump mounted on the end of the abstraction pipe work, which is located 25 metres below the rest groundwater level (i.e. to allow for draw down). Water is pumped up to surface level and circulated from the boreholes to the station plant room via distribution pipe work buried in trenches in the park. The aquifer is a source of potable water therefore the system has been designed not to have any adverse environmental impact.

Boreholes

The boreholes are 300mm diameter holes drilled to a depth of 50 – 60 metres into the upper chalk. Steel borehole casings are installed from the surface level, through the entire thickness of the London Clay and Lower London Tertiaries, to six metres into the chalk and sealed within the borehole annulus with grout. The casings penetrate to a level far enough into the chalk to prevent sand ingress, whilst maximising the exposure to the most productive part of the chalk aquifer. The boreholes were acidized (the acid is neutralised by the reaction with the chalk) to open up fissures in the chalk and cleaned, then the borehole hydraulic performance was tested. All the boreholes have water temperature, conductivity and level sensors.

Secondary Station Cooling Water Circuit

The secondary station cooling water circuit is a closed loop pressurised distribution system complete with platform AHUs. Secondary pumps distribute the cooling water from the station plant room to the Victoria and Piccadilly Line platforms. The cooling water return from the cooling coils in the platform AHUs is pumped through a heat exchanger. The cooling water flow temperature is 15°C off the heat exchanger. The cooling water return temperature is 23°C from the platforms. The platform AHUs deliver 100kW of cooling each, with two units on all of the Victoria and Piccadilly Line platforms. Sharon showed several images of the construction of the boreholes in Green Park and the station plant room with the heat exchanger and pipe work routed to the platforms. The installation of the platform AHUs was also shown.

Supply MTVs Complete with Cooling Coils

Two new MTV shafts complete with cooling coils have been commissioned to serve St. Paul's station and Forest Road (Victoria Line). Effectively these are very large AHUs with a supply fan bringing fresh air from outside and passing over a cooling coil which reduces the temperature. At St. Paul's eastbound there are some louvres where the air is coming out at about 18ºC which charges the eastbound tunnel with cold air. Forest Road should have been commissioned today – 13 September 2016.

NEW SOLUTIONS AND TECHNOLOGIES

In Train Hybrid Cooling

The provision of air conditioning is possible on the new rolling S Stock but on the deep tube lines (Jubilee, Northern, Piccadilly, Bakerloo, Central and Victoria) there is no room in the annular space between the train and the tunnels to locate externally mounted air conditioning units. Also the heat generated by the air conditioning systems would be discharged into the tunnels and therefore contribute to the heat generated within the sub-surface network. In-train hybrid cooling is an option that is currently being evaluated for use for future tube rolling stock. Using this system, when the train is travelling outside above ground a standard air conditioning system can work to cool the cars but simultaneously it is also charging a phase change media. A phase change media stores cooling capacity by changing from a liquid to a solid state and the process can be likened to the cooling system cooling a volume of water to a large block of ice.

When the train goes below ground into the deep tube tunnels the air conditioning system stops and the in-car cooling chilled water system runs through a heat exchanger within the phase change media and heat from the train car is transferred to the phase change media. The change of state from a solid to a liquid is an endothermic process which means that heat energy is absorbed by the phase change media and this process provides the cooling. Then after the train re-emerges to travel above ground the mechanical refrigeration system is switched back on and the phase change material is reformed from a liquid to a solid, and the heat energy is released to atmosphere.

Regenerative Braking and Train Optimisation

Regenerative braking energy converts some of the train’s kinetic energy into electrical energy, and therefore reduces the amount of heat energy produced. The maximum amount of regenerative braking energy can be utilised provided that the train that is braking is in the same substation section as another train that is accelerating at the same time. Therefore the accelerating train can use the electricity generated by the braking train. In addition, there are also technologies being assessed which can store the regenerated electricity such as inverting substations.

Under Platform Exhaust Systems

Ventilation exhaust grilles under the platform capture waste heat from the under car equipment while trains are waiting at the platform. The heat can be exhausted via ventilation system and discharged to atmosphere. There are some LU examples on the network and these systems are being installed on Crossrail.

THE FUTURE – WASTE HEAT UTILISATION

There is an opportunity when constructing tunnels to utilise waste heat generated from the railway by extracting it via absorber pipes embedded in the segmental linings. Low grade heat can be transferred through a heat pump to provide heat for energy efficient hot water or space heating to commercial and residential users near stations. This is a potential revenue stream for LU which could offset energy consumption and reduce the operational cost of running fans for cooling. There is a collaboration project in progress both with the GLA, Islington Council and the EU funded Celsius Project to recover waste heat from the City Road ventilation shaft. This heat will be used within the Bunhill district heating network.

Tri-Generation

Tri-Generation is combined cooling, heat and power. Trigeneration systems can be employed to generate electricity in a decentralised energy network. An example of a Trigeneration system is the generation of electricity from a gas fired turbine engine, during which the waste product is heat. The heat can then be utilised by third parties such as local residential or businesses. However, the heat energy can also be converted into cooling energy via an absorption chiller for use in a chilled water system. A Trigeneration feasibility study is currently being developed to establish whether it could serve out at Holborn station providing LU with cooling and electricity and the residual heat being exported to local housing, hotels or businesses. Currently, the national grid is running at about 98% capacity, so a decentralised energy network would take some of the pressure off the existing electricity network.

SUMMARY OF KEY SUCCESSES TO DATE

- Oxford Circus chilled water system.
- Green Park borehole cooling system.
- St. Paul's and Forest Road MTV shafts complete with cooling coils.
- Upgraded 13 Victoria Line MTV shafts.
- Restored 50 ventilation fans – doubling capacity of the fan network.
- Restored 10 long-term out of service fans.
- Further designs in development for five long term out of service fans.
- Ground water cooling trial at Victoria.
- Deployment of portable summer fans at many locations.
- Evaluating waste heat utilisation opportunities across the network.

DELIVERED IN THE LAST 11 YEARS HAVE BEEN:

- 24 Fan Systems
- 2 Fan and Coil Systems
- 2 Platform AHUs.

PROJECTED FOR THE NEXT 20 YEARS ARE:

- 18 Fan Systems
- 9 Fan and Coil Systems
- 35 Platform AHUs.

This concluded Sharon's presentation and she invited questions from the audience.

Q. Are you using any new technologies on the Battersea extension?

A. New tunnel ventilation systems are being installed which are smoke control systems. Similar systems have been installed on Crossrail and the Jubilee Line extension. Smoke control systems control the direction of airflow in the emergency event of a train fire. The tunnel ventilation systems would provide airflow in the opposite direction to which people were escaping the train so they would be always moving into fresh air. Tunnel energy segments were looked at but due to programme constraints they are not being incorporated.

Q. What scope is there for reducing the power demands of the train equipment?

A. Development of new rolling stock with energy efficient motors, more efficient systems, the optimisation of the weight of trains, optimising the aerodynamic drag coefficient of the train skin – all these initiatives are being undertaken to reduce the amount of traction energy required. Also a significant amount of work is going into optimising the train operation.

Q. Have you investigated aircraft type turbine heat exchangers for cooling systems?

A. No, but we always interested in other industries for cross fertilisation of ideas and innovations. The biggest constraint would be noise. The shafts in the capital have to have sound attenuators fitted to reduce the noise levels so there is no noise disturbance to our neighbours.

Q. Why have you put platform AHUs on the Victoria Line at Green Park?

A. This was future proofing for the Victoria Line upgrades so that when there is an increase in trains per hour there will be more heat generated.

Q. Why are you putting illuminated advertising screens on the escalators which increase the energy consumption?

A. Cooling the Tube have assessed the heat generated by the new advertising screens and the amount of heat they produce is insignificant when compared it to an average 350kW heat load generated under the train. Also it is important that the revenue gained from advertising on those screens is required by the business.

Q. Will you be changing to LED lights from fluorescent fittings?

A. Yes. We've just completed the PRO-LITE initiative which involved market research across the Global Lighting and Supply Chain and we've now put in place Supply Framework contracts with lighting manufacturers which will result in the rationalisation of the lighting assets that are installed across the TfL network. We have chosen products which are all energy efficient and the majority of them are LED. The energy efficiency of these lighting products meets the criteria for the Enhanced Capital Allowance which is a tax rebate that LU can claim from the HMRC. When LU installs energy efficient equipment it can get a tax rebate of 19 pence per pound on all the associated lighting design, installation, commissioning and procurement costs. The ECA drives good practice in installing energy efficient lighting.

Q. Are the MTV shaft fans running all day and can you use the heat to generate electricity?

A. Yes, the MTV shaft fans are running 24/7. They can't be used to generate electricity because that creates a resistance within the air path which would result in an increase the amount of energy they use and would cancel out the amount of electricity generated. As mentioned previously the heat generated at City Road will be captured by the Bunhill district heating network to help people that are classified as energy poor.

The audience showed their appreciation to Sharon in the usual way for her very informative presentation.

Maurice Lees