Short communication

Heat recovery from air in underground transport tunnels

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Abstract

The performance of a typical air source heat pump could be increased dramatically by a relatively stable air temperature with a high humidity, even during the peak heating months. In this short communication we show such conditions exist in the underground transport tunnels of the Glasgow Subway system, where we had conducted an annual survey of air flow, air temperature and relative humidity at thirty different points within the subway network. We found relatively stable temperatures and sufficient air movement inside the twin tunnels (average temperature during winter = 15^{o}C, annual variation = 2.6^{o}C; average air flow = 16.47 m^3/h) indicating higher system efficiency compared to a conventional air source heat pump installation. Potential energy and carbon savings are discussed.

Keywords: heat recovery, thermal comfort, air source heat pump.

1. Introduction

The need to find alternative energy sources to replace fossil fuel is now being more important than ever. This is recognised in the UK government legislative obligation of reducing the CO_2 emissions by 80% of the 1990's levels by 2050 [1].

The Scottish Government has set a target for the equivalent of 100% of Scotland's electricity demand to be supplied from renewable sources by 2020[1]. This is complemented by an equally stringent target for an increase in renewable heat generation, as well as an increase in community and local ownership of renewable energy schemes[2]. Air source heat pump (ASHP) systems have shown potential to reduce energy consumption and as a result CO_2 reduction of more than 50% compared with conventional heating systems (electricity, oil, gas) can be achieved[3].

This paper reports a year-long study carried out since June 2014 in the Glasgow Subway system to investigate the possibility of using the air that circulates inside the tunnels for space heating through an ASHP. This could be useful to cut down both energy use and carbon emission since the Subway stations are currently heated with electric radiators where the energy cost and the CO_2 emissions are high.

2. Methodology

The Glasgow Subway tunnel system forms a circle in the centre-west of the city. The entire passenger railway is underground, contained in twin tunnels, allowing clockwise circulation on the "outer" circle and anticlockwise on the "inner". Fifteen stations are distributed along the route length of just over ten kilometres. The river Clyde dissects the circular route, with eight stations in the North and seven in the South as shown in Figure 1.

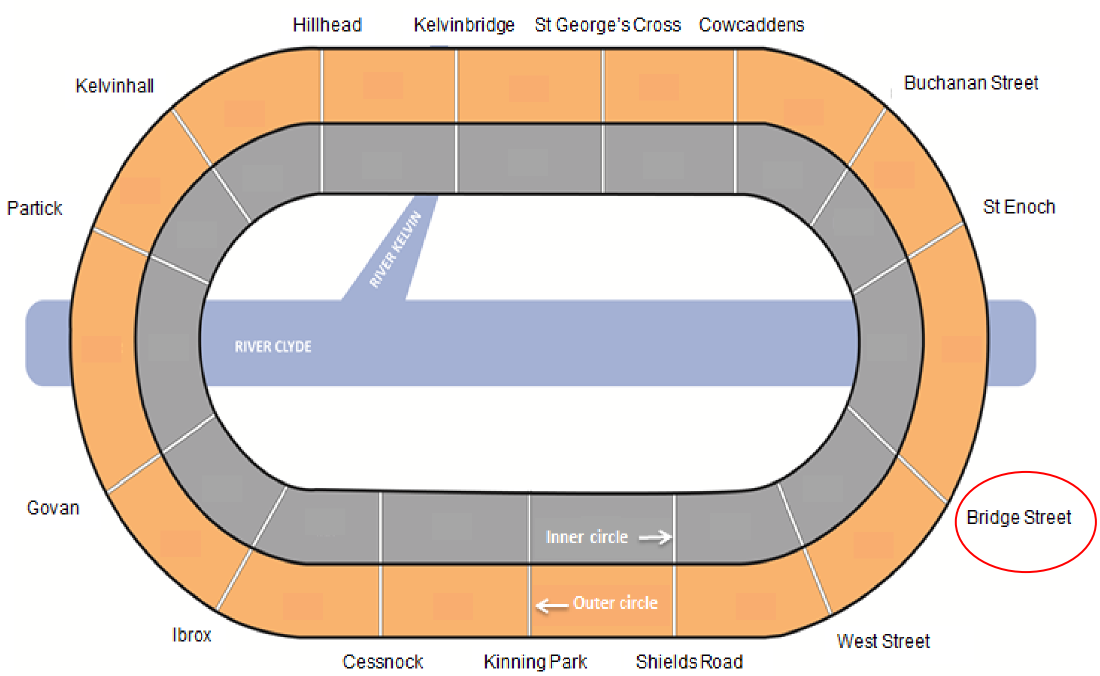


Figure 1: A typical Glasgow Subway map

Note: Case study station highlighted with a red circle

2.1 Proposed heating system

The proposed heating system is a conventional air source heat pump (ASHP) but unlike in a standard installation, utilises the air from within the built confines of the subway platform (as opposed to the outside air) as shown in Figures 2 & 3. In a conventional set-up the external heat exchange coil recovers heat from outside air; however, under colder conditions (such as those prevailing in Glasgow) the efficiency of the ASHP is likely to be low. In the case of our installation, it was hypothesised that a higher efficiency could be achieved, given the relatively warmer conditions inside the subway tunnels and platform. In order for this to work at high efficiency, two conditions need to be present: relatively stable and warm air temperatures and sufficient air movement to ensure continuous operability. Given the enclosed nature of the platform/tunnel area it was surmised air temperatures will be relatively warm and stable. In terms of air movement, although no forced air ventilation system exists in any station, the air is constantly in motion and at relatively high speeds due to the movement of trains as well as from the natural air movement between the platform and the surrounding atmosphere in the concourse level.

Figure 2: A typical Glasgow Subway's platform

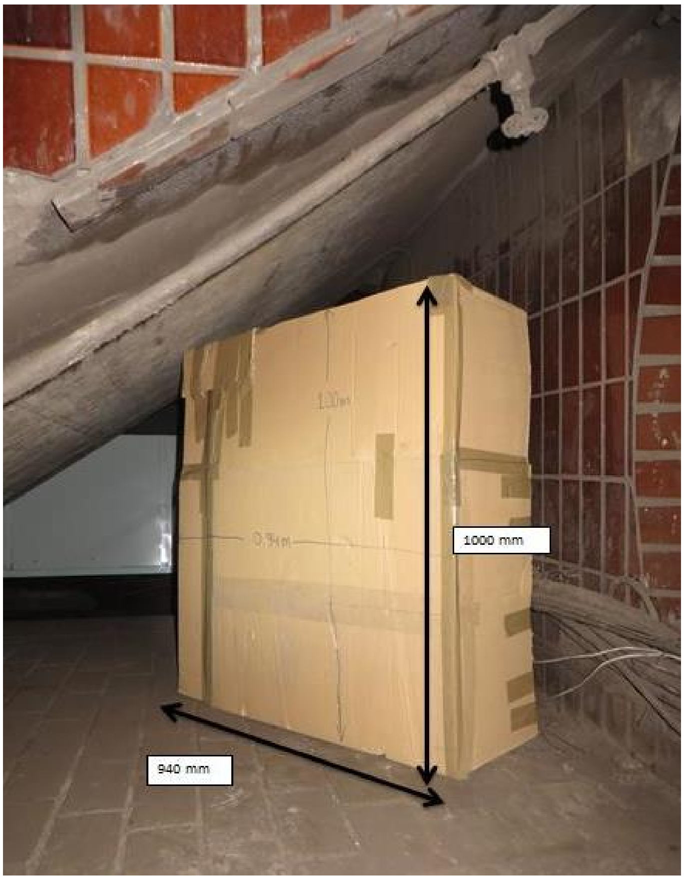


Figure 3: A mock-up of the proposed heat pump condenser below the platform's stairs

In order to test this hypothesis we undertook two sets of measurements: air temperature and humidity on the platforms and tunnels and, air flow within the platform/tunnel areas. A twelve-month series of measurements of air temperature and relative humidity in the platforms as well as the tunnels, were undertaken since 1st June 2014 to explore the seasonal variations of the air temperature (Tiny Tag, TGP4020, range = -40^{o} to +125^{o}C, accuracy = ±0.35^{o}C in the 0-60^{o}C range) and humidity (ELMA, DT 171, range: 0-100 RH, accuracy: ± 3% RH). Background weather conditions (temperature, humidity, atmospheric pressure and rainfall) were simultaneously monitored at a city centre location (Glasgow Caledonian University's meteorological station). In total, the underground temperature and humidity has been monitored in 30 different places inside the Subway system (fifteen locations on the platforms and fifteen spots inside the tunnels between two consecutive stations) as shown in Figure 4.

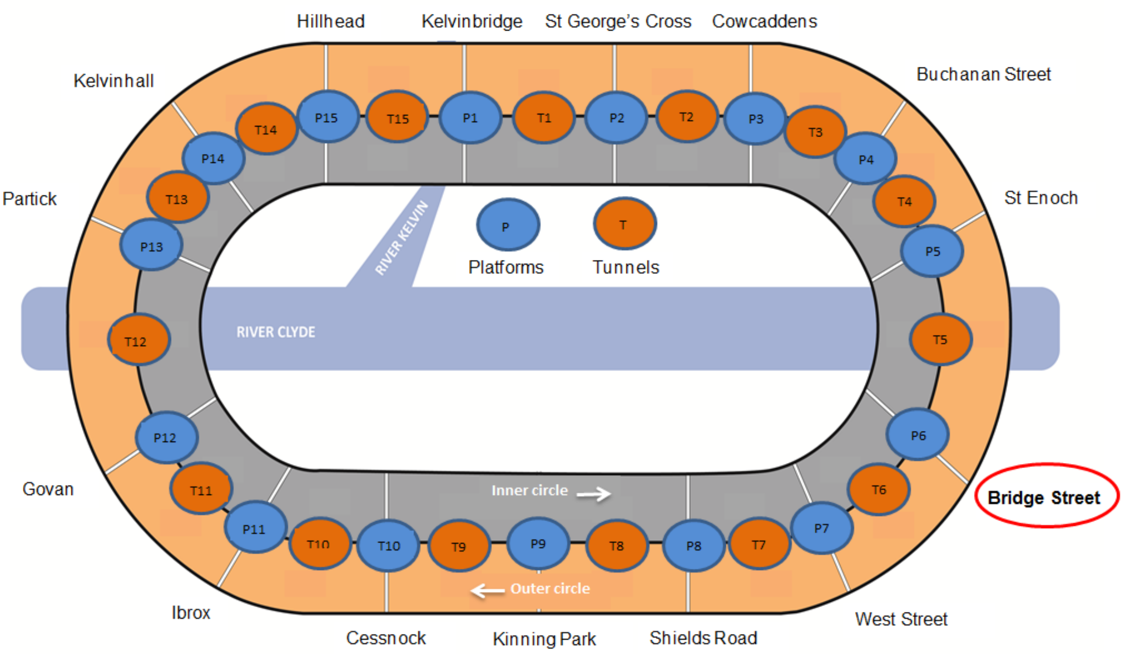


Figure 4: The thirty measuring points inside the Glasgow Subway system

Note: Case study station highlighted with a red circle

Between the two tunnels and at approximately every twenty five meters there are cross-passages which allow the air movement from one tunnel to the other. For this reason half of the tunnel measurements have been conducted on the "inner circle" and the other half on the "outer circle". The readings were taken approximately in the middle of each tunnel section.

In addition to the above, an air velocity meter was also used during October 2014 to measure the volume of air that circulates inside the tunnels and the Station platforms. This portable air velocity meter (TSI Velocicalc model 9656, range: 0.25-30m/s, accuracy: ±1% of reading, ±0.02m/s) with a rotating vane anemometer attached, (TSI model 995 Ø100mm) was positioned in each platform for more than two hours to monitor the air velocity and the atmospheric pressure.

Figure 5: The portable air velocity meter with the attached rotating vane

In order to compare the energy performance of an ASHP based heating system against the current systems of electric storage heaters, a case study was also conducted at one of the stations on the network (Bridge Street Station, red circle in Fig 1). This station is currently heated by five electric radiators. An energy logger (Fluke 1730, Accuracy at Reference Conditions (% of Reading + % of Full Scale) ± (0.2 % + 0.01 %): was used to measure the electricity input for the heating circuit for a week. The total energy consumption for the five radiators over this period was 0.904 MWh (Figure 6). This translated into 8.07kW average electric power input, considering that the heating period was of 16h/day. (0.904 MWh=904 KWh/7days=129.14 KWh per day. 129.14kWh/16h= 8.07KW).

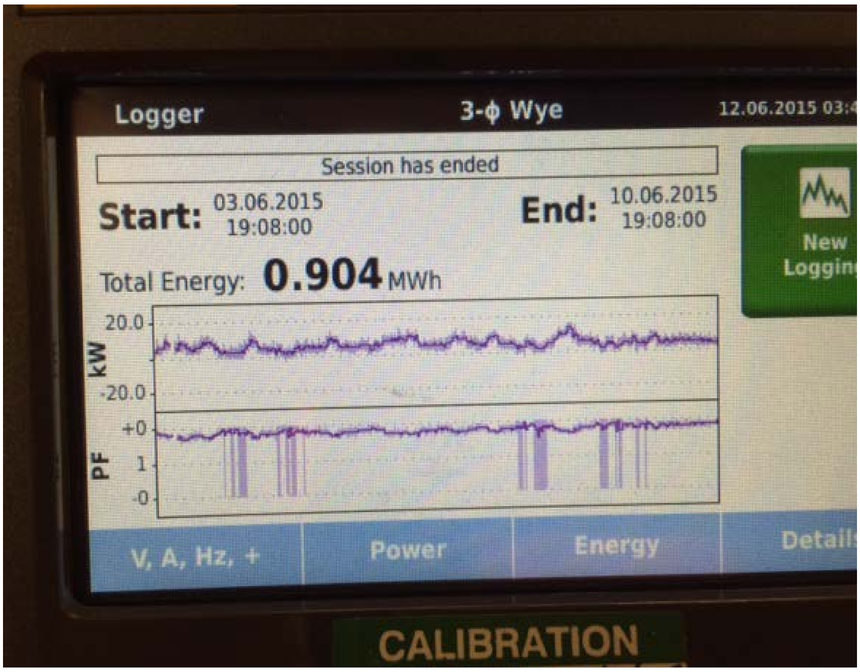


Figure 6: The Energy logger with the overall energy consumption for the current heating circuit

4. Results – proposed installation

Table 1 shows the average monthly temperature & humidity at the case study location (Bridge Street platform and tunnel section no. 6) and Glasgow's background temperature & humidity as measured at the University's meteorological station. Tables 2 and 3 show the seasonal mean temperature and relative humidity variations within the two Subway tunnels throughout the monitoring period. Average temperature variations at the reference station - Glasgow are shown in Figure 6. Table 4 shows air flow measurements at the platforms.

To assess where heat output can be delivered and used, a heat load calculation (in kW) for all the stations has been carried out (Table 5), according the BS EN: 12831-2003.

The case study location (Bridge Street Subway station) has been chosen for the pilot installation of the first ASHP in the platform level which will provide the space heating and the domestic hot water for the station. This station has one of the higher heat loads between all the fifteen stations, besides the two stations with the largest heat load (Govan and Partick). Of the other stations with large heat load, Hillhead Subway station (6.6 kW total design heat load) has been already renovated, and St. Georges Cross Subway station (5.2 kW total design heat load) has been chosen for a similar case study with a water source heat pump (WSHP) which will be reported later.

The design heat load for a building entity is calculated as follows:

HL,i= T,i + V,i +RH,i [W] Eq.1 (BS – EN 12831:2003 § 8.1)

Where:

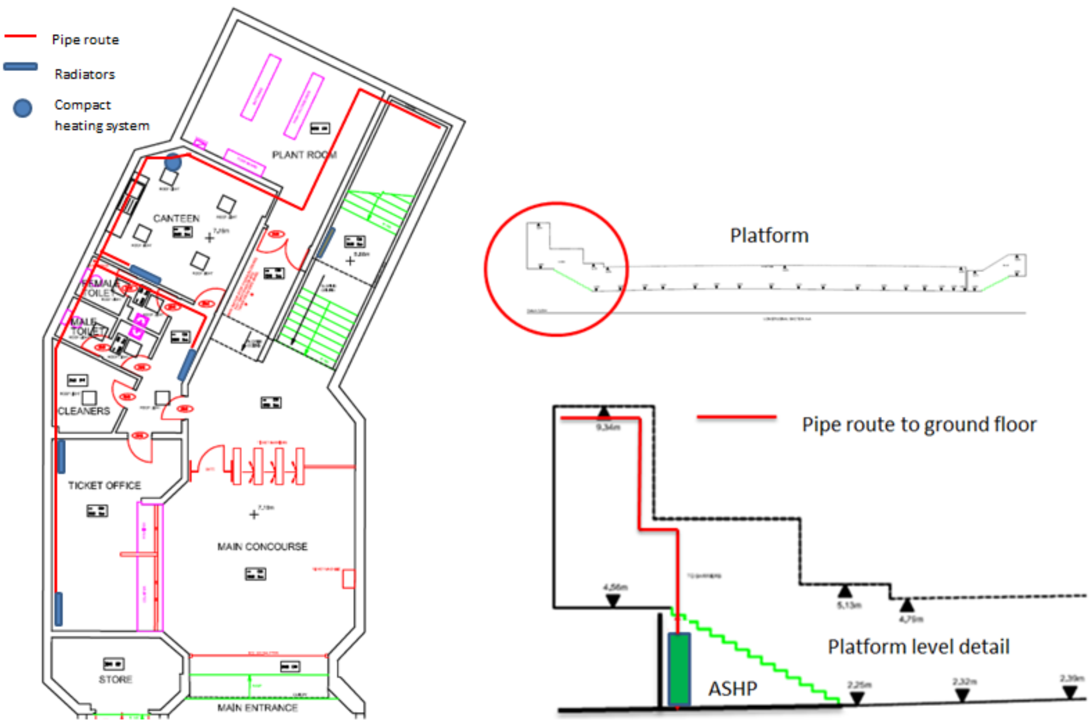
HL,i =total design heat load for a heated space (i), in Watts (W);

T,i =design transmission heat loss for heated space (i), in Watts (W);

V,i = design ventilation heat loss for heated space (i), in Watts (W);

RH,i = heating-up capacity required to compensate for the effects of intermittent heating (i), in Watts (W);

A design of the proposed pilot set-up was undertaken and this indicated that an ASHP of 9kW capacity would be required to meet the Bridge Street Subway station's heating and domestic hot water (DHW) demand. This was based on the station's heat load calculations as well as on the energy input measurements for the electric radiators which was 8.07 kW (as shown in the Methodology section). This installation will feed five new low temperature fan coil radiators with water return temperature at 40 ^{o}C (Figure 7) which will be sufficient to heat the station replacing the existing five electric radiators. This system is also expected to provide cooling as a by-product during the summer months. The heat pump that has been selected is a single phase 9kW mono-block unit which can accommodate both heating and cooling [5].



Bridge Street station proposed layout (ground floor)   Bridge Street station proposed layout (platform level)

Figure 7: Bridge Street Subway station plan

The efficiency of a heat pump usually referred as Coefficient of Performance (COP). COP is the ratio of the delivered heat (H) to the electrical power input (E): COP=H/E. A heat pump doesn't have a fixed COP. The operational conditions and the temperature difference between the source side and the delivery side are the basic factors that define the efficiency of a system. A reduction in energy input (E) due to a lower temperature difference will lead to higher COP.

6. Discussion

Given Glasgow's northerly location, it is common that heating of buildings starts as early as from September. The air temperature in the two tunnels of the subway is relatively stable throughout the year compared to the ambient air temperature (see Table 1). In the wintertime, an ASHP using the air inside the subway system as input will need to raise it from 15^{o}C to a return temperature of 40^{o}C, as opposed to an ASHP using outdoor air (from 0^{o}C to 40^{o}C). Thus, compared to an ASHP installed in an outer environment, the tunnel-based unit is expected to deliver more heat output

The platform level in all fifteen Subway stations is only between 5 to 10 meters below the surface level. The air is being refreshed automatically with a non-forced ventilation system due to the non-existence of any obstacles between each station's platform and the outside atmosphere. If an ASHP unit is installed within a Subway station in platform level, the heat absorption from the unit will not affect the air balance in this platform. Due to the train movement the air flow within each Subway station is constant. An ASHP of 9kW nominal heating power [5] will replace the case study station's heating system to cover the heating demand and DHW (Domestic Hot Water). The five electric radiators that currently provide only heating for the case study station could be replaced by five new low temperature fan coil radiators (return temperature: 40 °C) which will provide heating and cooling for the station. According to the heat pump's manufacturer [5], it is expected that with the same return temperature of 40 °C and inlet air temperature of 15 °C that even during December a COP of more than 4 can be achieved, which means that the energy consumption will be reduced approximately 75% compared to the existing system. Given the current carbon content of UK electricity 0.49kgCO_2/kWh [6] such a reduction in electricity use for heating will lead to 75% reduction in carbon emission (from 0.49kgCO_2/kWh to 0.12kgCO_2/kWh).

7. Conclusions

In this study a number of measurements in Glasgow Subway's system have been taken for more than a year. Air temperature, air humidity and air flow (velocity) have been measured in 30 different points. A new heating system has been designed and implemented in one of the fifteen stations, aiming to reduce the energy cost (electricity) for heating. Using an energy meter; electricity used to power the radiators has been also measured. The aim of the exercise is to identify the energy that can be saved using an ASHP within the Subway system. The following main findings can be deduced from the trial:

1. There is potential to harvest the warm air from the tunnels (which is at a stable temperature throughout the year) to efficiently provide both heat and domestic hot water to a Subway station.
2. This system can cover the space heating, DHW and provide as a by-product cooling during summer months.
3. The energy consumption with the ASHP use is expected to be 75% less compared with the existing electric fired heating system.
4. The CO_2 emissions are expected to be reduced more than 70%. This is expected to be achieved through the reduction of energy input (electricity) for the new heating system.

A full year of monitoring is and is expected to verify the system performance and to confirm the actual energy saving at a station level. The system's energy input and heat energy output will be monitored through an energy logger device. If the energy and carbon savings are confirmed as presented here, further roll out of the heating system may be applicable to other subway stations within the network subject to practical limitations at each station.

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8. References

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9. Tables

Table 1: Average temperature & humidity readings in platform no.6 & tunnel section no.6

Subway Station: **Bridge Street**									
Platform No: **P6** Tunnel No: **T6** Reference: Glasgow Caledonian University Meteorological Station (**GLW)**									
Year	Month	Temp. P6 (°C)		Temp. T6 (°C)	Temp. GLW (°C)	Hum. P6 (%)		Hum. T6 (%)	Hum. GLW (%)
2014	June	17.1		17.3	17.2	80		78	83
2014	July	16.9	17.3	17.5	16.0	77	76.1	75	87
2014	August	16.1		19.0	14.0	75		72	80
2014	September	17.8		21.0	16.2	65		62	72
2014	October	17.3	17.8	18.6	12.9	71	67.3	68	89
2014	November	15.6		16.8	9.0	70		68	81
2014	December	14.8		15.9	6.2	76		72	87
2015	January	14.9	15.2	15.2	2.1	62	70.1	62	85
2015	February	15.1		15.4	5.8	74		75	82
2015	March	14.7		15.5	6.8	60		59	75
2015	April	16.8	16.3	16.9	15.1	60	62.3	67	74
2015	May	17.0		17.2	10.0	63		65	69

Table 2: Seasonal variations in air temperature across the subway network

Season	Kelvinbridge	St George's Cross	Cowcaddens	Buchanan Street	St Enoch	**Bridge Street**	West Street	Shields Road	Kinning Park	Cessnock	Ibrox	Govan	Partick	Kelvinhall	Hillhead
	Subway Stations air temperature (degrees Celsius) - Average of six readings per station per season														
Summer 2014	16.9	16.7	17.0	16.8	17.9	**17.3**	17.2	16.9	17.3	17.0	16.9	16.9	16.9	17.1	17.1
Autumn 2014	18.4	17.1	17.3	17.5	18.1	**17.8**	17.7	17.2	16.9	16.5	16.5	16.8	16.8	17.0	17.0
Winter 14-15	15.9	15.7	15.7	15.7	15.8	**15.2**	15.3	15.1	14.5	14.2	13.4	13.5	14.5	14.6	14.7
Spring 2015	16.0	15.9	15.7	15.7	16.1	**16.5**	16.3	15.2	14.8	13.9	13.6	11.5	15.7	14.9	15.1

Table 3: Seasonal variations in relative humidity across the subway network

Season	Kelvinbridge	St George's Cross	Cowcaddens	Buchanan Street	St Enoch	**Bridge Street**	West Street	Shields Road	Kinning Park	Cessnock	Ibrox	Govan	Partick	Kelvinhall	Hillhead
	Subway Stations relative humidity (%) - Average of six readings per station per season														
Summer 2014	81.8	83.6	84.1	84.3	84.3	**76.1**	76.8	76.1	74.3	72.8	71.6	73.3	73.0	71.5	71.5
Autumn 2014	82.5	78.2	74.6	76.6	76.6	**67.3**	72.3	79.6	77.3	78.5	78.1	75.8	77.5	77.5	77.5
Winter 14-15	81.3	81.5	77.3	76.8	69.2	**70.1**	71.1	73.5	76.6	76.8	78.5	72.3	75.1	73.5	79.5
Spring 2015	78.2	77.2	77.2	76.5	58.2	**62.3**	63.2	71.0	69.5	68.2	69.2	64.2	62.7	61.2	77.0

Figure 6: Temperature variations: Glasgow & Subway

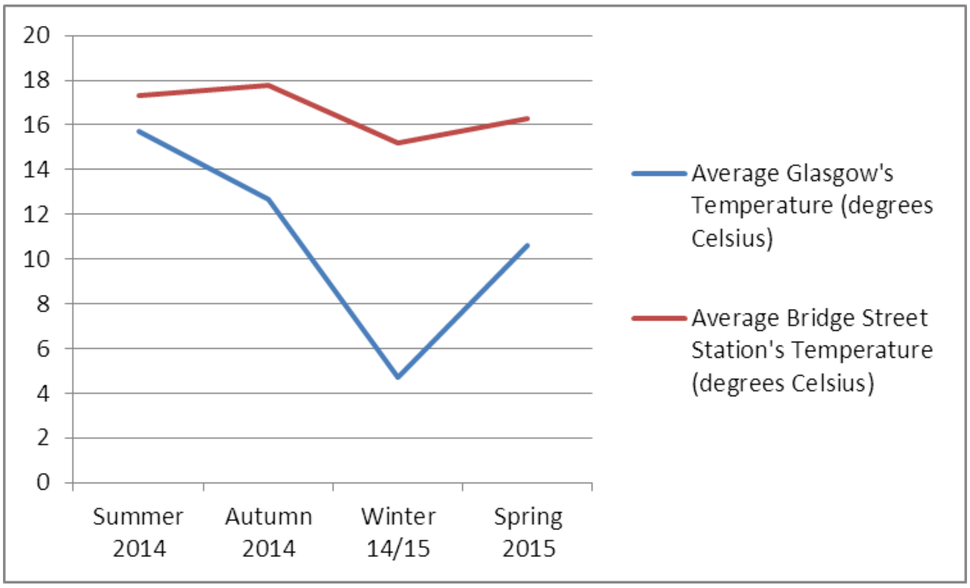

Table 4: Air flow meter readings from the fifteen platforms

Subway stations			
Station name	Approximate platform volume (m^3)	Mean air flow (m^3/h)	Maximum air flow (m^3/h)
Kelvinbridge	1700	15.52	126.95
St. George's Cross	800	12.59	58.91
Cowcaddens	1590	12.03	54.84
Buchanan Street	1240	05.04	38.84
St. Enoch	1400	20.00	158.86
Bridge Street	**820**	**15.82**	**131.92**
West Street	1680	12.46	85.90
Shields Road	1000	24.25	163.25
Kinning Park	750	17.13	126.09
Cessnock	1090	36.11	214.89
Ibrox	1170	15.32	145.72
Govan	2000	20.00	158.86
Partick	1850	11.20	132.38
Kelvinhall	800	12.83	164.29
Hillhead	1250	16.79	88.78

Table 5: Heat loads for the fifteen Subway stations (Carried out in accordance with BS EN: 12831-2003)

Subway Stations name	Total design heat load (kW)
Kelvinbridge	4.8
St. George's Cross	5.2
Cowcaddens	3.4
Buchanan Street	3.8
St. Enoch	4.5
Bridge Street	**5.0**
West Street	4.0
Shields Road	4.2
Kinning Park	3.0
Cessnock	4.1
Ibrox	3.2
Govan	30.3
Partick	45.7
Kelvinhall	2.6
Hillhead	6.6

Table 6: Total heat load for Bridge Street station according to BS EN: 12831-2003

Bridge Street Subway station total heat load					
Room name	Transmission heat load	Ventilation heat load	Temperature correction factor	Heating-up capacity	Total design heat load
	T,i W	V,i W	*f,i*	RH,i W	HL,i W
Ticket office	1147.40	168.44	1.0	261.95	1577.8
Hallway	585.49	41.76	1.0	106.08	733.3
Canteen	687.90	134.48	1.0	258.57	1081.0
M & F WC	536.05	89.56	1.6	50.7	1082.1
Store	398.32	36.60	1.0	42.9	477.8
Total	**3355.16**	**470.84**	**-**	**720.2**	**4952**

f,i*:* temperature correction factor, for rooms heated at a higher temperature than the adjacent heated rooms, e.g. bathrooms.

Table 7: Bridge Street current & proposed system

Bridge Street Subway station total heat load (5kW)							
Heating	Input	Output	Cost / power	Cost / day (16h)	Cost / year (210d)	Carbon dioxide factor ($kgCO_2/kWh$)	By-product
	kW	kW	£/kWh	£	£	Kg	
Current: 5 electric radiators (2kW)	10	10	10X0.12=1.2	1.2X16=19.2	4032	0.49	None
Proposed: ASHP	3	9	3X0.12=0.36	0.36X16=5.76	1209.6	0.14	Cooling