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Aims and Objectives – Conduction Shape Factors for Tunnel Heat Exchangers with Isothermal Inner and Outer Boundaries

By

[redacted]

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1. Introduction

1.1 Energy Consumption and CO_2 Emissions in the UK and Europe

As fossil fuels and other natural resources continue to decline in availability, governments around the world are looking towards sustainable energy as a viable alternative (Paez, 2017). In the UK, there seems to be a shift towards generating energy using sustainable methods such as wind, solar, bioenergy and hydropower (Edwards, 2018). Although fossil fuels still account for 80.1% of the UK's energy supply, this is a record low. Electricity generation using fossil fuels is also on the decline with a 27% decrease from coal power, a 4.6% decrease for gas power, and an increase of 19.5% in generation using renewable sources (Department for Business, Energy & Industrial Strategy, 2018). This establishes that there is a significant push for renewable energy in the UK.

It has also been the case that CO_2 emissions from fuel combustion, overall, have decreased in countries that are part of the European Union. In 2016, it was found that combined EU CO_2 emissions from fuel combustion had decreased by 12% since 2000 (IEAa, 2018). The UK showed a noteworthy decrease of 29% in the same time period. Although coal is still the largest source of global CO_2 output at 44%, emissions produced by it decreased by 300 $MtCO_2$ with a large fall of 49% occurring in the UK (IEAa, 2018).

However, while the reports that these statistics were cited from provide good data on energy consumption and CO_2 emissions in the UK, there seems to be very little to no obvious data on geothermal energy. This kind of energy can provide heating, cooling and power generation from hydrothermal resources and power outputs can remain stable and unaffected by changes in the climate (IEAb, 2018). What is most interesting is that when CO_2 emissions are divided by region and sector, 41% of European emissions were attributed to electricity and heat production. Furthermore, 37% of these emissions (1.8 $GtCO_2$) were attributed to European buildings (IEAa, 2018). This provides a situation where geothermal energy could potentially be effectively utilised in order to reduce national, as well as global, CO_2 emission levels.

1.2 Geothermal Energy and its Utilisation

Geothermal energy is quite simply heat originating from the Earth itself and is stored below ground and derives from the Greek words 'geo' and 'therme' referencing the Earth and stored heat, respectively (U.S Energy Information Administration, 2017). Between 1990 and 2017, geothermal production of electricity, for example, has not experienced much growth in terms of energy production. Nonetheless, it has experienced an annual growth of 2.2%, from 28.6 TWh in 1990 to 51.8 TWh in 2017 (IEAc, 2018).

Utilisation of this energy slowly but continually has gained interest from the civil engineering industry and, hence, has made advances in technology to exploit geothermal activity situated in the ground as a result (Adam and Markiewicz, 2009). One example would be using ground heat exchangers for heating and cooling residential households. The following is an acceptable definition for the term 'thermal heat exchanger':

- **Thermal Heat Exchanger**: A device that can pass heat from a fluid (e.g. liquid or gas) into a secondary fluid whilst simultaneously preventing them from coming into direct contact with each other (Woodford, 2018).

There are two main types of ground thermal heat exchangers systems:

I. **Open**: the process whereby air from the outside flows through a pipe going into the ground, where it is either pre-heated or pre-cooled, before being fully heated or cooled by and air conditioning unit. After that, the air enters the building in question for heating or cooling needs.

II. **Closed**: the process whereby a heat carrier medium is circulated in an array of piping buried underground. What happens is that this heat carrier medium transfers the heat from the ground into the building in winter, and vice versa in the summer, via a heat pump (Florides and Kalogirou, 2007).

Regarding closed-pipe systems, while horizontal pipe arrays (whether it be in series, parallel or trench as shown in Figure 1) require less digging and are cheaper to install, vertical ground heat exchangers, depicted in Figure 2, require less piping overall because in the summer, the earth is cooler and, conversely, warmer in the winter (Florides and Kalogirou, 2007).

It can be established that finding the temperature profile with respect to depth is very important when designing ground heat-pump systems. The literature is not short on findings relating to this field of research. Bharadwaj and Bansal (1981) found the ground temperature distribution for the following four situations:

- Dry sunlit surface
- Dry shaded surface
- Wet sunlit surface
- Wet shaded surface

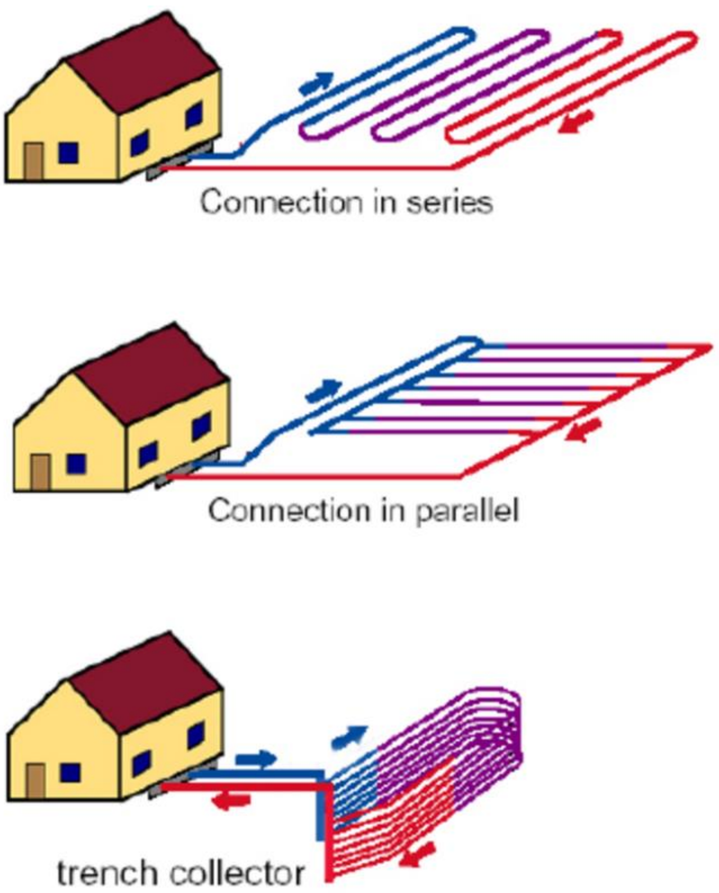

Figure 1 – Different horizontal pipe arrays for closed heat exchanger systems (Florides and Kalogirou, 2007)

The temperature distribution in the ground was found using solar radiation data on a typically hot day in summer and a typically cold day in winter. It was concluded that wet ground surfaces, whether they were sunlit or shaded, were better at maintaining necessary temperatures.

Popiel *et al.* (2001) conducted a ground temperature varation study in the city of Poznan, Poland on two differing surfaces: car park and lawn. They found that their data was in good accordance with what is known as Bagg's formula. Conclusively, it was recommeded, based on the results, that horizontal GHEs should be placed 1-2m below the ground surface.

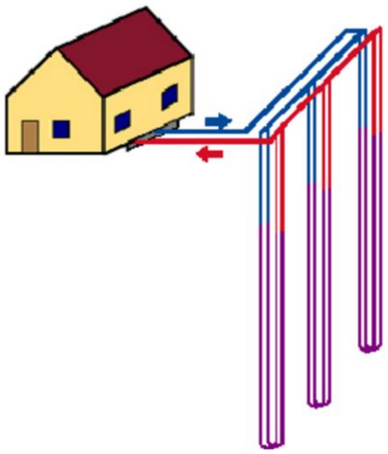

Figure 2 – Vertical pipe array for closed heat exchanger systems (Florides and Kalogirou, 2007)

Florides and Kalogirou (2007) conducted research on the variation of temperature in the ground in Cyprus. They found that below a depth of 5m, the temperature of the ground is fairly constant in both the summer (August) and winter (January) seasons. Civil engineers can install an arrangement of pipes, usually at depths ranging from 5-10m, into the ground and pump fluid through these pipes to act as a medium for the heat to travel through. The heat from the ground to warm the house in winter and, inversely, extract heat from the house and pump it back into the ground to cool the house during the summer.

Badache *et al.* (2015) added a periodic sky temperature variable to their research to better predict the temperature variation in the ground in terms of depth and meteorological data. Their data was validated using meteorological data obtained from multiple US sites.

In more recent years, the application of heat exchanger has turned towards concrete substructures; including slab foundations, bored piles and diaphragm walls; to absorb heat from the ground by embedding pipes within the structures themselves. Adam and Markiewicz (2009) concluded that there are "numerous possibilities for the utilisation of thermo-active concrete elements for heating and cooling purposes" (Adam and Markiewicz, 2009, p. 235). The authors provide useful data showing cooling and heating capacities (kW) and annual outputs (MWh) for various diaphragm wall, bottom slab and bore pile units used for several high-rise buildings in Vienna. For example, the Uniqa Tower utilises 7800 m^2 of diaphragm walls, located 35m below the surface, and has the following outputs:

- Cooling capacity: 240 kW
- Heating capacity: 420 kW
- Annual cooling output: 818 MWh
- Annual heating output: 646 MWh

In summation, substructure units were successfully implemented for floor and wall heating and helped support a conventional cooling system for the Uniqa Tower. But as previously mentioned this is the same result for multiple high-rise buildings in Vienna.

Crucially, however, this paper turns the reader's attention towards the practical utilisation of geothermal energy in tunnels and how using tunnel bores as heat exchangers can be beneficial because a substantially ground volume can be activated for geothermal heat exchange. Additionally, tunnels with a high overburden may have a significantly higher temperature than the surrounding ground, resulting in a better performance of the geothermal system (Adam and Markiewicz, 2009). While detail and illustrations about pipe layout for metro tunnels were presented, the actual data provided was more specific towards sewer tunnels.

Donna *et al.* (2017) studied the thermal performance of diaphragm walls using finite element modelling and, in the paper's abstract, suggested the heat exploitation of retaining walls of tunnels for railway/metro stations. The following parameters are considered in the paper (quoted directly from the abstract):

- Panel width
- Ratio between the wall and excavation depths
- Heat transfer pipe spacing
- Concrete cover
- Heat-carrier fluid velocity
- Concrete's thermal properties
- Temperature difference between the air within the excavation and the soil behind the wall

It was concluded that, in the short term (i.e. after 3 days), the pipe spacing was the factor that had the most impact on the thermal energy efficiency, followed by the thermal conductivity of the concrete and the width of the panel. In the long term (i.e. after 60 days), the difference in temperature between the air within the excavation and the soil behind the wall was the dominant factor, followed by, again, the thermal conductivity of the concrete and the spacing of the pipes.

While the papers cited are relevant in determining the geothermal performance of pipes embedded in substructures and, hence, that geothermal energy can be effectively utilised, neither of them determine how the so-called 'thermal resistance' of the system affects the thermal output. This leads on towards the main scope of this Aims and Objectives document. Analysing heat transfer processes in a thermal substructure system at shorter length or time scales is possible using its thermal resistance. In a substructure heat exchanger, thermal attributes to the thermal resistance between the fluid in the embedded pipes and the heat exchanger wall is a vital performance parameter. Thermal resistance, *TR*, is related to steady state heat conduction rates, *Q*, and the geometry of the system (through a characteristic called the shape factor, *S*) using Eq. 1:

$$TR = -\frac{\Delta T}{Q} = -\frac{1}{\lambda S} \qquad \textbf{Eq. 1}$$

where λ is the thermal conductivity of the medium that pipes are embedded in and ΔT is the difference in temperature between the fluid flowing in the pipe and the outer boundary of the system.

Before analysing the existing literature on the shape factor, here is a definition for the term ‘shape factor’:

- **Shape Factor**: The ratio between the cross-sectional area conducting the heat and the path length (Shafagh, 2019).

Determining the shape factor of any geothermal system can provide useful and practical means for designing heat exchange systems. Firstly, it’s imperative to examine and review what methods have been implemented in the literature up until this point on finding the shape factor for different geometries.

Smith *et al.* (1958) concocted numerical, electric analogue results for the shape factors for concentric square cylinders and made a comparison with existing data for circular cylinders and circles inside, and concentric with, both squares and rectangles. Measurements were accurate to within 0.5%. Balcerzak and Raynor (1961) studied steady-state temperature distribution in prismatic bars of differing geometries. The assumptions that they made were isothermal boundary conditions and the bars were isotropic and homogeneous. Each bar had small circular holes in each of their centres (i.e. the inner boundary was circular).

Dugan (1972) worked on finding the shape factor for a hollow, square cylinder cross-section. He used a numerical boundary residual technique and found that when comparing data, from other sources against his own, on the shape factor against the ratio of the radii of the inner and outer boundaries (i.e. R_i/R_o) that solutions started to converge towards each other when $R_i/R_o \leq 0.8$. However, when $R_i/R_o \geq 0.9$, the solutions started diverging away from each other considerably which suggests that older methods of finding the shape factors are most accurate and feasible when the radius/apothem ratio is less than about 0.8 (Simeza and Yovanovich, 1987). The errors involved in the calculations are accurate to within 0.1%.

Laura and Susemihl (1973) incorporated a conformal mapping technique on regular polygon prisms. As a result, through derivation starting with Laplace’s equation, which represented the temperature distribution within the cross-section in question, the following formula obtained was:

$$S = -2\pi \left[\ln\left(\frac{R_0}{a}\frac{1}{A_s}\right)\right]^{-1} \qquad \textbf{Eq. 2}$$

where a is the apothem of a regular polygon, A_s is a parameter with values tabulated in Table 1 of the paper and R_0 is the inner radius.

While these solutions provided much-needed and viable data, the equations used were only specific to whatever scenario was investigated (e.g. circle with a square). However, Kolodziej and Strek (2001) used the boundary collocation method in the least-squares sense for solving appropriate boundary values for the following three cases:

- Hollow prismatic cylinders bounded by isothermal inner circles and outer regular polygons
- Hollow prismatic cylinders bounded by isothermal inner regular polygons and outer circles

- Hollow prismatic cylinders bounded by isothermal inner and outer regular polygons

and produced the following general equation for the shape factor:

$$S = \frac{2\pi}{\ln(1/E) + \ln[k_1 e^{k_2(L-k_3)} + 1]} \qquad \textbf{Eq. 3}$$

where k_1, k_2 and k_3 are constants whose values depend on the nature of the geometry of the cross-section, E is the radius/apothem ratio and L is the number of sides the polygon has.

Nickolay *et al.* (1998) were one of the first to use Finite Element Method (FEM) to calculate heat flow through pipes of differing geometry. The maximum number of elements in the FEM mesh was 6400 in the three cases of concentric squares, circle within the centre of a square and a square within the centre of a circle. What was advantageous about using these cases was that the geometry could be split up into quadrilateral elements which made deriving formulae much easier. When the resulting shape factors were plotted against the ratio of the outer diameter (r_o) to the inner diameter (r_i), denoted as x, the results for all three cases were very promising.

Teerstra *et al.* (2009) developed a two-dimensional, analytical conduction shape factor model for hollow cylinders with non-uniform gap spacing. They succeeded in predicting the dimensionless conduction shape factor formed using isothermal inner and outer boundary conditions. The model was validated using a wide variety of polygonal and concentric cross-sections and the heat flow was analysed as the gap spacing converged towards zero. The root mean square (rms) difference between the data and the model, for most cases, was less than 5%.

The reason that the papers regarding shape factors have been referred to is because they all cover situations where the inner boundary is circular. This is analogous to the scenario that will be covered in this dissertation, whereby the shape factors of circular thermal exchanger pipes in tunnel linings will be investigated. There have been several case studies in the literature where this new technology is being tested and implemented.

Zhang *et al.* (2013) wrote two papers regarding the Linchang Tunnel in China: firstly, finding an analytical solution for the heat conduction and, secondly, on the thermal performance of the tunnel lining during operation. One of the predominant reasons for undergoing this study was to mitigate against damage to the tunnel caused by freezing by extracting heat from the surrounding bedrock. In the first paper, the authors did a factor analysis of the following:

- The ground temperature
- Flow rate of the carrier liquid
- Inlet temperature of the carrier liquid

For economic reasons, they found that the optimal flow rate of the carrier liquid should be 0.8 m/s to account for cost and thermal performance. Higher flow rate means higher running costs, essentially. In addition, the absorber pipes' (i.e. pipes that extract heat from the surrounding bedrock) geothermal energy output linearly decreases as the inlet temperature of the carrier liquid increases.

Zhang *et al.* (2014) (i.e. the second paper) investigated the thermal performance of the tunnel lining GHEs (ground heat exchanger). The aforementioned factors were also investigated here with the addition of the distance of the pipes. The dimensions of the pipes were a diameter of 25mm and a thickness of 2.3mm. It was concluded that the distance of the pipes, plus the flow rate and inlet temperature, all had a significant impact on heat exchange rate of the pipes themselves. Wiik (2015) presents preliminary calculations and similar conclusions when discussing geothermal energy utilisation within a city railway loop in Helsinki, Finland. Figure 4 below shows a 3D representation of a tunnel GHE.

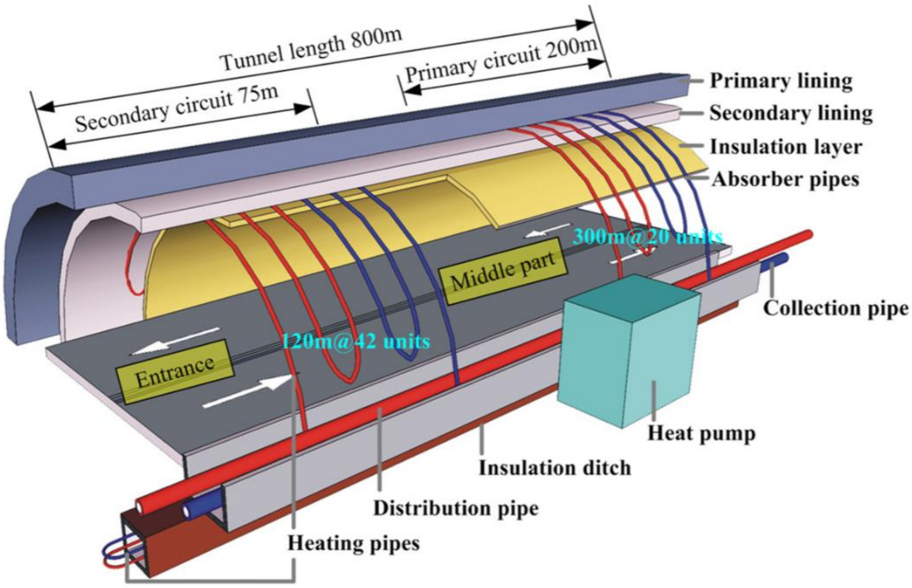

Figure 4 – Tunnel GHE diagram (Wiik, 2015)

Nicholson *et al.* (2014) deals with the design of a tunnel lining GHE (referred to by the authors as a TES system) for Crossrail, UK. This publication is good at identifying where potential excess heat originates from, including the trains' motors, brakes and air conditioning units. It was proposed to use heat generated in the tunnels to heat the 365 buildings that lied within 100m of the route alignment which varied in size and use. Figure 5 shows a real-life image of heat exchanger pipes attached to steel reinforcement for the tunnel lining.

Figure 5 – Heat exchanger pipes attached to steel reinforcement for tunnel lining (Nicholson et al., 2014)

In this dissertation, shape factors for a tunnel lining are investigated where the pipe and tunnel surface are both assumed to have isothermal conditions. The boundary conditions are selected for simplistic reasons and the amount of time given to complete this project. Shape factors for tunnel linings has not been previously addressed in the literature. A schematic representation of the geometry of interest is illustrated in Figure 6.

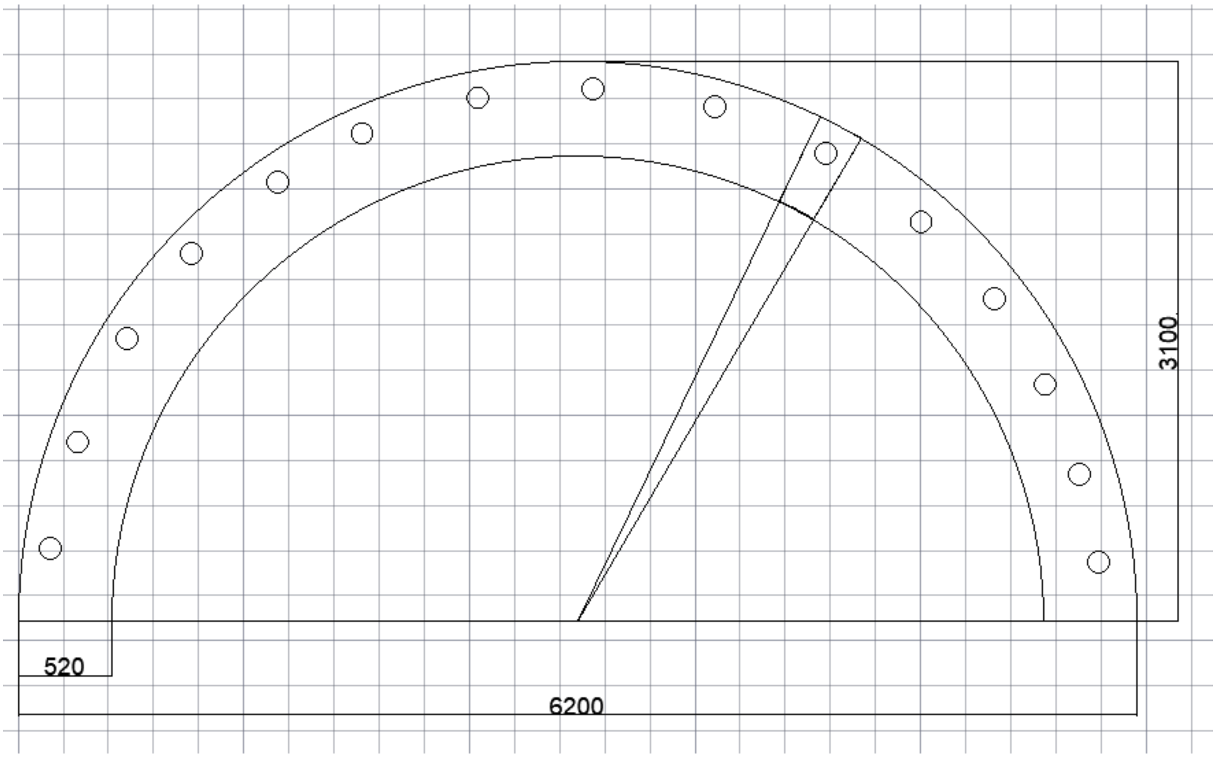

Figure 6 – Tunnel cross-section with dimensions in millimetres

Due to the symmetry of the system, it can be reduced to that existing about a single pipe as shown in Figure 7 and can be further reduced to that shown in Figure 8.

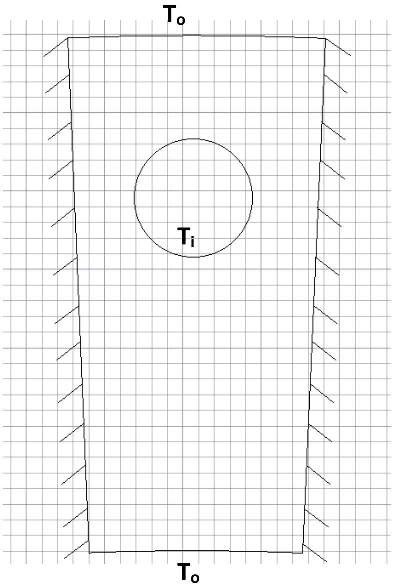

Figure 7

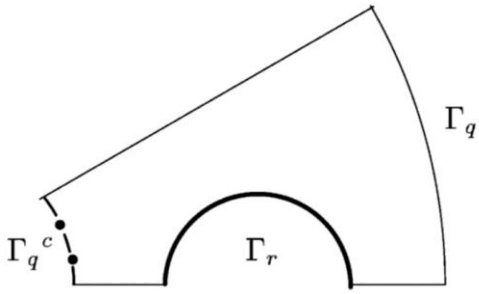

Figure 8 (Hayashi, 2002)

In Figure 7, T_o is the outer boundary condition and T_i is the circular inner boundary condition. It is crucial to find the temperature distribution in the domain shown in Figure 8 to calculate the values of the shape factors. If a relation can be found for the temperature distribution in a doubly-connected region, the shape factor can be calculated from integrating the normal gradient of the temperature over any of boundary surfaces as shown in Eq. 4:

$$S = \int_P \frac{\partial \Phi}{\partial n} dP \qquad \textbf{Eq. 4}$$

where Φ is the dimensionless temperature and P is the length of the boundary. In domains where one of the boundaries is a circle of radius R, Eq. 4 can be readily reduced to that in Eq. 5:

$$S = -\int_0^{2\pi} \frac{\partial \Phi}{\partial R} R d\theta \qquad \textbf{Eq. 5}$$

Once the shape factor has been accurately recognised, it can be used to calculate the rate of heat transfer. Shafagh *et al.* (2019) used a semi-analytical boundary collocation least-squares method to calculate and analyse shape factors in rectangular sections with eccentric holes. This is important as eccentricities will occur in this problem.

The equation that governs steady state temperature distribution in the domain illustrated in Figure 8 is the Laplace's equation in plane polar coordinates:

$$\frac{\partial^2 T(r,\theta)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,\theta)}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T(r,\theta)}{\partial \theta^2} = 0 \qquad \textbf{Eq.6}$$

To simplify the analysis, the following dimensionless parameters are substituted in the governing equation:

$$\Phi = \frac{T(r,\theta) - T(r_s,\theta)}{T(r_i,\theta) - T(r_s,\theta)} \quad , \quad R = \frac{r}{\sqrt{a^2 + b^2}} \qquad \textbf{Eq. 7}$$

where radius of the circle, $\sqrt{a^2 + b^2}$, is used as the characterised body length. Thus, the dimensionless formulation reduces the boundary value problem into the following form:

$$\frac{\partial^2 \Phi}{\partial R^2} + \frac{1}{R}\frac{\partial \Phi}{\partial R} + \frac{1}{R^2}\frac{\partial^2 \Phi}{\partial \theta^2} = 0 \qquad \textbf{Eq. 8}$$

A linear combination of the trial functions that satisfies Laplace's equation can be obtained by deploying the method of the separation of variables, as follows:

$$\begin{aligned}\Phi(R,\theta) = A + B\ln R + C\theta + D\theta\ln R + \sum_{n=1}^{\infty}\left(A_n R^{\lambda_n} + B_n R^{-\lambda_n}\right)\cos(\lambda_n\theta) \\ + \sum_{n=1}^{\infty}\left(C_n R^{\lambda_n} + D_n R^{-\lambda_n}\right)\sin(\lambda_n\theta)\end{aligned} \qquad \textbf{Eq. 9}$$

2. Aim

- Calculate and critically analyse shape factors associated with the geometries of tunnel lining using a boundary collocation least-squares technique in conjunction with validating the results through numerical analysis using OpenFOAM. To that end, it is necessary to solve Eq. 9 in the domain shown in Figure 8. It is possible to find the parameters shown in Eq. 7 through applying the specific boundary conditions of the domain in Figure 7. Consequently, a series of solutions will be provided for this problem which can be solved using the boundary collocation least-squares technique. Eventually shape factors are calculated from solving the system of linear algebraic equations. To the best of our knowledge, this is the first attempt in the literature to derive such values for tunnel linings and will significantly improve the application of such heat exchangers.

3. Objectives

- Although I have provided an extensive literature review thus far, it is important to keep up-to-date with any future literature that is published and include it in the literature review.
- Establish thermal equations for the boundaries indicated in Figure 7 by working out a general solution to Laplace's equation in the domain in Figure 8.
- Apply the necessary boundary conditions.
- Adapt the currently developed code by I. Shafagh to suit the domain shown in Figure 8.

- Create the geometry in OpenFOAM and analyse the numerical shape factors using Laplacianfoam.
- Compare results with those found with the general solution and on OpenFOAM software.
- Compare data with that found across the existing literature by calculating the root mean square differences to check for accuracy.
- Validate the data accordingly and check for any possible calculation errors.

4. Work Plan

Month	Oct-18	Nov				Dec					Jan-19				Feb				Mar				Apr					May
Week commencing (Monday)	29th	5	12	19	26	3	10	17	24	31	7	14	21	28	4	11	18	25	4	11	18	25	1	8	15	22	29	6
Literature review																												
Meetings with supervisor																												
Shape Factor calculations																												
Code Development																												
OpenFOAM calculations																												
Data Validation																												
Writing Dissertation																												
Finalising/Submission																												

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