The Effect of Shank-Space on the Thermal Performance of Shallow U-Tube Ground Heat Exchangers

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ABSTRACT

Reducing energy consumption in buildings via the use of energy-efficient technologies has become essential. The Ground Source Heat Pump, capable of delivering space conditioning with enhanced energy-efficiency compared to conventional air sourced systems, is one such technology. An important aspect dictating the performance of said technology is the Ground Heat Exchanger (GHE), consisting of a single or a series of U-tubes encased within a borehole backfilled with thermally conductive grout through which a circulating liquid absorbs or rejects heat to the ground. One parameter which may affect the exchanger's thermal performance, is the shank-space, the centre-to-centre distance between the two branches of a U-tube. Generally, in order to ensure the maximum heat transfer surface possible, most of the research carried out has focused on boreholes with depths of 100m and over. Reaching such depths is not always possible and other design limitations, such as, the requirement for limited interaction with the water table, may require that significantly shallower U-tubes are used. Specific research on shallow ground heat exchangers is however limited. To address this aspect, a 3D steady-state CFD model of a U-tube ground heat exchanger was used to investigate the influence of varying shank-space on the thermal performance of two isolated vertical shallow U-tube GHE, one 20m deep and the other 40m deep. To facilitate the computational process, the 3D steady-state CFD model makes use of an innovative approach, whereby the U-junction at the bottom of the U-tube is eliminated. To ensure confidence in the results obtained, the simplified model was validated using available experimental and numerical studies performed for full U-tube models. As expected, the results show that the temperature drop of the circulating fluid varies for different shank-spaces and is lowest for the closest shank-space and highest for the widest shank-space. It is however, observed that this temperature drop is not linear with increases in shank-space and that for both modelled setups, the thermal performance improvement drastically diminishes with increasing shank-space, although with higher values being obtained for the 40m deep borehole. Such results indicate that for shallow U-tube, the temperature drop across the system is more dependent on the length of the pipework than the effect of shank-space.

KEYWORDS

Ground source heat pumps; Thermal performance; Shallow vertical U-tube; Shank-space; Ground heat exchanger; CFD, Validation

INTRODUCTION

In Europe, buildings currently account for 40% of the total energy consumption [1] with 50% of the energy consumed being utilised for space heating and cooling. Increasing energy-efficiency of buildings, including the services utilised for heating and cooling is therefore essential. Curtailing the energy consumed for meeting the demands for heating and cooling can be achieved in a variety of ways. One of the approaches proposed is energy saving through the adoption of energy-efficient technologies [2].

One technology which has been proven capable of reducing energy consumption in buildings is the Ground Source Heat Pump, which is capable of providing heating and cooling with an improved Coefficient of Performance compared to conventional air sourced systems. Using electricity as input, ground source heat pumps utilise the low-temperature geothermal energy present in the ground as a sink where to dump excess heat, or as a source from where to extract the required heat. The fact that below a certain depth, the ground temperature is almost constant throughout the year ensures that a more stable and higher Coefficient of Performance can be achieved all year round [3, 4]. Given that ground source heat is available everywhere, irrespective of climate or location, the ground source heat pumps have become a well-established technology for space heating and cooling worldwide [5].

THE GROUND SOURCE HEAT PUMP – A SHORT REVIEW

A ground source heat pump consists of three principal components: A heat pump which uses electricity to move heat to and fro the conditioned space; an indoor heating/cooling distribution system which conditions the indoor space; and a Ground Heat Exchanger (GHE) [6].

The ground heat exchanger is at the heart of the system, and normally consists of an underground circuit of pipes through which a circulating liquid absorbs or rejects heat from or to the ground. The exchanger can be of the open or closed loop type, based on whether the circulating fluid enters in contact or not with ground, or more importantly be installed vertical or horizontal. Compared to horizontal systems which require a lot of space, vertical systems, are the preferred setup due to the fact that that ground temperatures get increasingly stable with depth. One popular layout of a vertical GHE system consists of a pair of parallel pipes connected at the bottom by a U-shaped connector installed inside a borehole with a typical diameter of 100-150mm and depths of up to 200m [7].

Vertical ground heat exchangers can exist as a single borehole or, more typically, as an array of boreholes depending on the heating/cooling demand. As a general rule of thumb, the distance between adjacent boreholes is usually not allowed to be less than 4.5-6m in order to prevent thermal interactions between boreholes [6, 8].

PARAMETERS EFFECTING SYSTEM PERFROMANCE

The efficiency of a ground source heat pump is dependent on the heat exchange process between the fluid circulating through the piping inside the ground heat exchanger and the ground. The heat transfer rate between the system and the ground is in turn influenced by several geometrical, thermophysical and operational parameters. A thorough understanding of these factors is therefore crucial in enhancing the performance of such a system.

Effect of shank-space on system performance

One of the parameters that affect the performance of a U-tube ground heat exchanger is the shank-space [9], that is, the centre-to-centre distance between the inlet and outlet pipes of the U-tube, as shown in Figure 1.

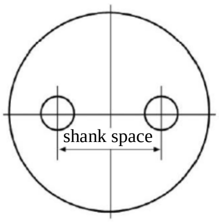

Figure 1. A horizontal cross-section through a U-tube GHE illustrating the shank-space

Literature [10-12] shows that the ideal arrangement of the U-tube inside the borehole (assuming that pipe spacers are used to maintain a constant shank-space throughout the length of the borehole) is when the two vertical pipe branches are as close as possible to the borehole wall, therefore furthest apart. This configuration would result in a low borehole thermal resistance. The issue of variations in shank-space revolves around the phenomenon of thermal short-circuiting and is usually studied in conjunction with variations in other parameters, such as, borehole depth and grout thermal conductivity. Studies found in literature regarding the effects of variations in shank-space on the performance of U-tube ground heat exchanger reveal that the contribution from the shank-space may be highly relevant in certain cases but less important or negligible in others [13, 14].

Witte [13] carried a sensitivity analysis on borehole performance in which the effects of several parameters both in isolation as well as in conjunction with each other parameters where numerically investigated. Witte observed that the effects of variations in shank-space are more prominent for fluid laminar flows, suggesting that the shank-space should be as large as possible in case of laminar flow while for turbulent flows, the shank-space is irrelevant. Zheng *et al.* [14] conducted a numerical analysis using MATLAB on the factors which affect U-tube ground heat exchangers. The study noted that in order to ensure greater heat flow and reduce the probability of thermal short-circuiting, the shank-space should ideally be in the range of 100-200mm. Other literature sources such as that by Cui *et al.* [15] however discuss that the effect of thermal short-circuiting is actually negligible if the shank-space is higher than 60mm.

Most of the research carried out in this area has focused on vertical boreholes with typical depths of 100m and over, as commercially these are the ones which are used, primarily to ensure that enough contact area to reject or absorb the heat is available. However, reaching such depths is not always possible and other design limitations, such as, the requirement for limited interaction with the water table, may require that a system makes use of shallower heat exchangers (up to 50m depth). Specific research on shallow ground heat exchangers is however limited to few studies. One such study is a fairly recent piece of literature by Tang and Nowamooz [16], where the authors study the factors influencing the performance of shallow borehole heat exchangers, including the effect of shank-space. Their study looks at the effect varying-shank space has for one single depth of 20m in different soil typologies.

Effect of spatial arrangement and borehole spacing

In large scale installations there is usually the need to have more than one borehole, even hundreds of them to cater for the length of pipework required to meet a specified heat exchange demand. If land is restricted, the number of U-tubes that can be feasibly installed may limit the ground source heat pump to meet only a portion of the thermal load. When multiple ground heat exchangers are used, they are usually arranged in an array formation called a borehole field. All the boreholes are grouped into smaller arrays, where each array is operated by a single heat pump. In addition to the parameters which affect the thermal performance of a single GHE, such as, the thermal conductivities of ground and grout, shank-space, borehole depth and fluid flow velocity, the thermal interaction between boreholes is another parameter that has an impact on the system overall performance. Therefore, the allocation of sufficient separation distance between boreholes inside an array becomes an important issue [17].

SCOPE OF RESEARCH

In response to the increasing need of utilising shallow ground heat exchangers, the research herby being presented deals with analysing geometric parameters specific to shallow, vertical U-tube ground heat exchangers. Specifically, the aim of this research is twofold. First, it aims to evaluate how the performance of an isolated vertical U-tube ground heat exchanger having a fixed borehole diameter changes with different values of shank-space and (shallow) depth. The second aim complements the first as it is intended to evaluate how the performance of the same ground heat exchanger modelled located centrally within an infinitely-large square array of boreholes varies with changes in borehole spacing.

METHODOLOGY

The research presented in this paper utilises a parametric analysis, whereby a number of parameters were varied to check for their resultant effect on the performance of shallow, vertical U-tube GHE. As discussed the two parameters considered were the shank-space in an isolated vertical U-tube heat exchanger and the borehole spacing in a multi-borehole array having an infinite number of ground heat exchangers similar to the isolated vertical U-tube GHE.

The study sought to identify relative changes in the thermal performance of the heat exchanger triggered by variations in the parameters outlined. In line with this principle and since the Coefficient of Performance of a ground source heat pump is directly related to the temperature difference between the inlet and outlet of the ground heat exchanger, thermal performance losses or gains were assessed by noting the relative changes in the mean temperature difference between the system inlet and outlet (temperature drop) for different values of the variables considered. The effects of the attributes mentioned above were investigated numerically by means of Computational Fluid Dynamics (CFD) simulations. Numerical modelling was carried out in ANSYS FLUENT 16.2 [18] which was used to perform three-dimensional (3D) steady-state CFD calculations in order to simulate the heat transfer process between the fluid and the grout/ground combination, and the resulting temperature distributions for the various GHE configurations.

Computational domain of the isolated ground heat exchanger

A 3D model of an isolated 20m deep U-tube GHE was created using ANSYS. Normally in literature, 3D simulations involve modelling a GHE in its entirety as opposed to two-dimensional (2D) numerical simulations, in which the U-tube GHE is modelled by taking a horizontal cross-section at a particular depth along the length of the borehole where the ground temperature and the temperature of the fluid in the downward and upward pipes are assumed to have reached stabilised values [19]. In this specific case however, the 3D U-tube GHE was modelled as shown in Figure 2, that is, eliminating the U-shaped connector at the bottom of the U-tube.

The motive behind this modification was to simplify the model, consequently reducing the modelling/computation time significantly. The removal of the U-junction altered the nature of the flow that would otherwise have developed in an unbroken loop of pipes and introduced an intermediate outlet (*i.e. Outlet 1*) and inlet (*i.e. Inlet 2*), as shown in Figure 2.

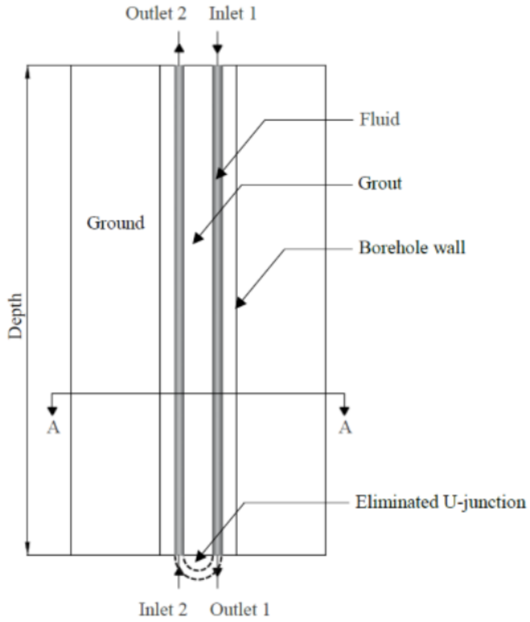

Figure 2. A vertical section through the computational model of the isolated GHE

To ensure the validity of the proposed model, the model was validated using the experimental work done by Borg [20] on a 20m deep ground heat exchanger utilising the same physical parameters as those utilised in this research, and the subsequent (numerical) simulation work done by Sciberras using a CFD model of said setup [21].

A number of checks were performed to ensure that the proposed model, without the U-tube connector was valid, including ensuring that the fluid entering *Inlet 2* develops into a fully turbulent flow within the total length of the pipe, and direct comparison with the results obtained by Sciberras [21] in his model. The hydrodynamic entry length is around 10 times the pipe diameter, that is, 0.36m (internal diameter of the pipe is 0.036m). This means that the flow attains turbulent properties within the first 2% of the pipe length. The second check was a direct comparison with the temperatures obtained by Sciberras. For the same shank-space, in the model proposed in this paper the resulting temperatures at *Outlet 1* and *Outlet 2* were both observed to be less than 0.0007% off from the temperatures obtained by Sciberras' model. This result indicated that the elimination of the U-junction has no significant impact on the simulated temperature profile of the carrier fluid.

Considering these two checks, it was assumed that omitting the U-junction does not have significant repercussions in terms of overall temperature difference between *Inlet 1* and *Outlet 2*, and given the relatively small shank-spaces being investigated in this research (and typical of U-tubes), such an assumption was considered to hold true for all subsequent simulations involving different shank-spaces.

The computational domain for the isolated ground heat exchanger, shown in plan in Figure 3 consisted of four sub-domains; two fluid sub-domains representing the carrier fluid flowing within the two branches of the U-tube, and two solid sub-domains representing the infilled grout and the surrounding ground whose adopted volume had the shape of a three-dimensional box (cuboid) measuring 60m x 60m.

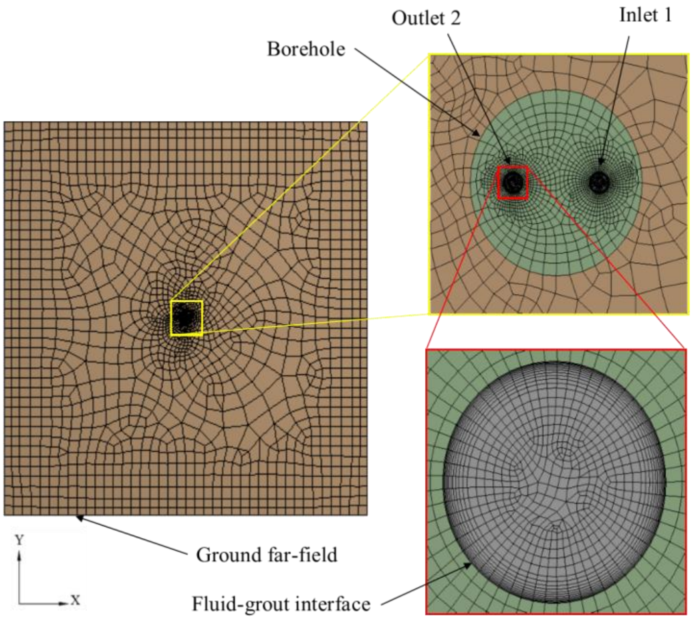

Figure 3. Top view of the 3-dimensional mesh with enlargements

The borehole, which was positioned along the centroidal axis of the ground volume, had a fixed diameter of 300mm and extended to the bottom surface of the ground domain. Being one of the parameters whose value was varied as part of this research, two values for (shallow) depth were considered, specifically 20m and 40m. The pipes were modelled having an outer diameter of 40mm and a wall thickness of 2mm. The physical properties of the ground, backfill material, pipe material and the carrier fluid are summarised in Table 1.

Table 1. Material properties of the components forming the GHE

Component	Material	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Dynamic Viscosity (kg/sm)
Fluid	Water	0.60	998	4182	0.001003
Pipe	LDPE	0.33	940	1900	n/a
Grout	Concrete	6.5	2327	880	n/a
Ground	Calcium Carbonate	2.25	2800	856	n/a

Establishing the boundary conditions

Inlet 1 was assigned a velocity-inlet boundary condition and the temperature of the fluid was set at an initial 313K. The velocity-inlet boundary condition was used as the flow inlet boundary condition because the fluid velocity magnitude and direction together with the temperature at that location were known. The fluid was set to flow at a rate of 10ltr/min (0.167m/s), the flow rate utilised by Borg [20] in his field experiments and Sciberras [21] in his numerical approach. Likewise, the secondary inlet (*Inlet 2*) was given the same boundary condition as *Inlet 1* except that the temperature of the fluid was set to be equal to the temperature of *Outlet 1*. This was achieved by means of an automated user defined function that used the iterative results of the temperature of *Outlet 1* as the input temperature of *Inlet 2*.

The two outlets (*Outlet 1* & *Outlet 2*) were set as pressure outlets specified by a static pressure of

0Pa and a backflow total temperature of 300K. The top surface of the ground and grout domains were assigned as a wall and set to allow a heat transfer by convection with a heat transfer coefficient of 4.345W/m2K and a free stream temperature of 303K. The bottom surfaces of the solid domains were specified as being adiabatic. The far-field ground surfaces were also set as adiabatic boundary surfaces.

Computational domain of the array of ground heat exchanger

To analyse the effects of borehole spacing (centre-to-centre distance between two adjacent, collinear boreholes) in an array of boreholes, the base model was positioned centrally in a square array having an infinite number of boreholes in the two orthogonal directions. The geometry of the array formation was accomplished by means of a periodic boundary condition applied to the outer edges of the ground domain, as shown in Figure 4. The smallest borehole spacing was chosen to be 5m in accordance with recommendations from literature and was increased in increments of 5m, to 10m and 15m.

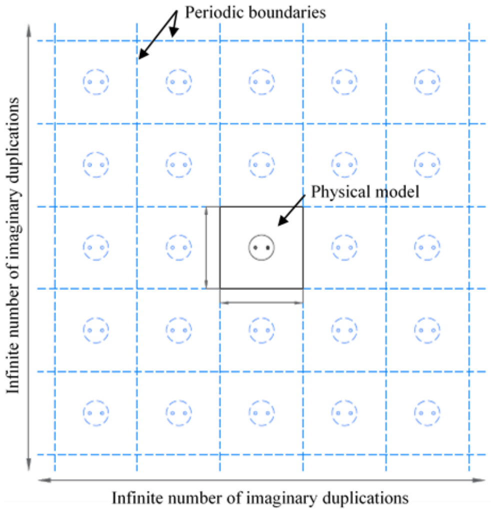

Figure 4. Sketch of the computational domain of the infinite square array

Solution methods

The solver of the commercial code ANSYS FLUENT 16.2 was used to calculate the coupled heat transfer process between the carrier fluid and the solid domains. The Navier-Stokes and energy equations solved are as follows:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

Momentum equations

$$\rho\vec{v}\cdot\vec{\nabla}\vec{v}=-\vec{\nabla}p+\mu\vec{\nabla}^2\vec{v}+\vec{F} \qquad (2)$$

Energy equation

$$\rho c_p\left(\frac{\partial Tu}{\partial x}+\frac{\partial Tv}{\partial y}+\frac{\partial Tw}{\partial z}\right)=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}+u\tau\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}+v\tau\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}+w\tau\right) \qquad (3)$$

Where x, y and z are the Cartesian coordinates and u, v, w are the velocities in the x, y and z directions. $\vec{v}$ is the velocity vector, ρ is the density, p is the pressure, μ is the dynamic viscosity and $\vec{F}$ is the body force vector (here taken to be zero). T is the temperature, k is the thermal conductivity of air and τ is the viscous shear stress.

These governing equations were iteratively solved by the finite volume method with the SIMPLE pressure-velocity coupling algorithm and discretized by the second order upwind scheme. All simulations were initially solved by the standard k-ε turbulence model up till the convergence criteria were met. Following this, the turbulence model was changed to the Shear Stress Transport (SST) k-ω model and iterated until convergence was reached again.

RESULTS AND DISCUSSIONS

Varying the shank-space for a 20m deep borehole

For the 20m deep ground heat exchanger apart from the 150mm used to validate the model without the U-junction, four other different cases were considered, namely two extreme situations in which the pipes touch each other and the borehole wall having a shank-space of 40mm and 260mm respectively, and another set of intermediate shank-spaces located midway, that is, 95mm and 205 mm. The temperatures at the four points of interest for each of the shank-spaces simulated are presented in Table 2.

Table 2. Simulation results for different shank-spaces for the 20m borehole

Shank-Space (mm)	Inlet 1 Temp. (K)	Outlet 1 Temp. (K)	Inlet 2 Temp. (K)	Outlet 2 Temp. (K)	Temp. Drop (Inlet 1 - Outlet 2) (K)	Improvement over previous shank-space (%)
40	313.00	312.58	312.53	312.24	0.76	-
95	313.00	312.58	312.48	312.18	0.82	7.9
150	313.00	312.58	312.47	312.16	0.84	2.4
205	313.00	312.58	312.47	312.15	0.85	1.2
260	313.00	312.59	312.47	312.15	0.85	0.0

The temperature drop across the U-tube ground heat exchanger (difference between *Inlet* 1 and *Outlet* 2) between the two extreme shank-spaces investigated was found to be 0.09K, equivalent to an 11.8% difference. As one can expect, the temperature drop increases with increasing shank-spacing, however, this increase was found not to be linear. As the shank-space increases from 40mm to 95mm, the temperature drop increased by 7.9%, whereas with the 150mm shank-space the temperature drop increased only by 2.4% compared to the 95mm shank-space. The change in temperature drop was then found to diminish drastically beyond the 150mm shank-space. In fact, for the 205mm and the 260mm shank-spaces resulted in no change at all, indicating that between the 150mm and 205mm, the ground heat exchanger reaches maximum performance and further increases in shank-space would not yield further improvement.

Figure 5 shows the variation of the fluid temperature along the centreline of the fluid domains, with borehole depth. The fluid temperature varies more or less linearly with pipe length for all shank-spaces but at slightly different gradients. A larger shank-space also produces a slightly shallower gradient. It can also be observed that variations in shank-space only primarily affects the upward moving fluid domain (*pipe2*), as the decrease in temperature in the downward moving fluid domain (*pipe1*) is practically equal for all five shank-spaces.

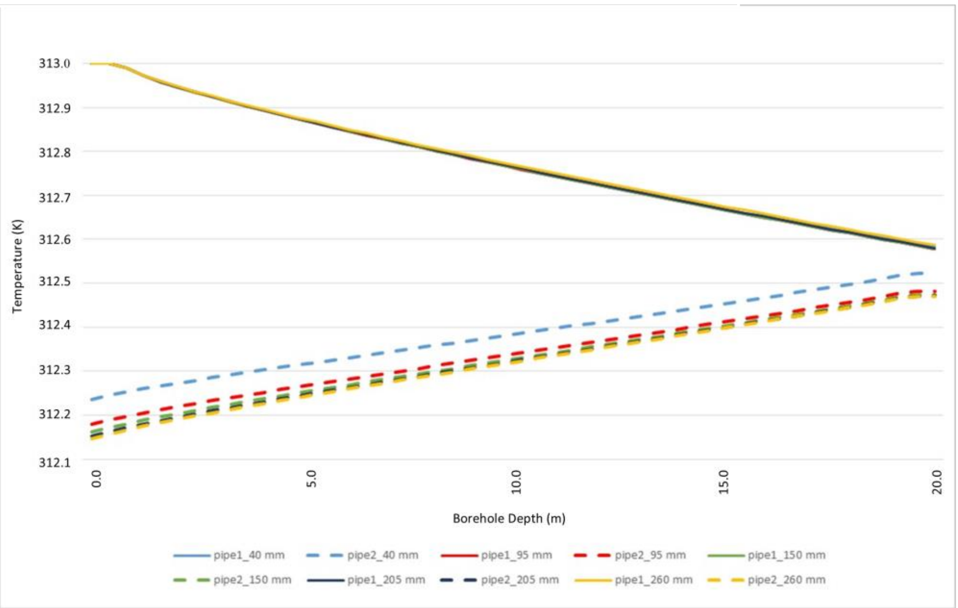

Figure 5. Variation of fluid temperature with depth for the five shank-spaces investigated for the 20m borehole

The temperature distribution within the GHE components on three horizontal x-y planes located at different depths for the five simulations outlined above are presented in Figure 6.

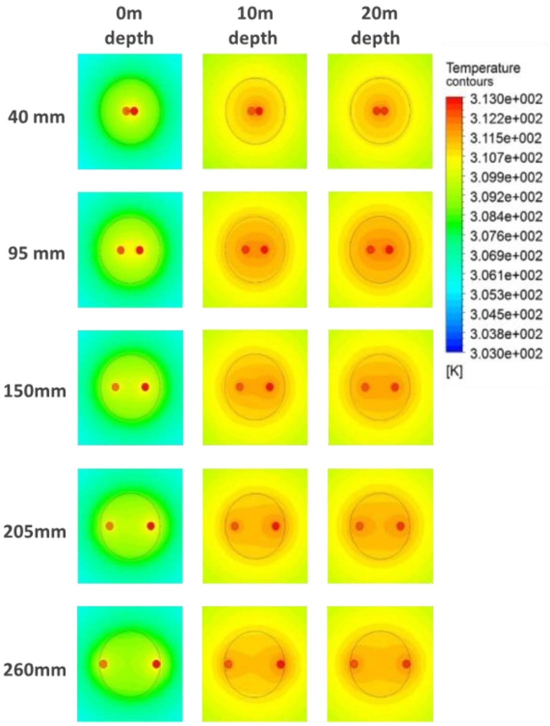

Figure 6. Temperature distributions at three different locations along the borehole depth (20 m) for the five different shank-spaces simulated

Due to the relatively small temperature drops obtained in all five simulations, the temperature distribution in the outward radial direction exhibits a typical sharp contrast between the temperature of the fluid domains and the temperature of the surrounding grout and ground domains. This contrast is highest at the top but decreases gradually with depth.

The plots show that for the 40mm shank-space the temperature contours in the region of the borehole cross-section are more or less circular, while with increases in shank-space the temperature contours around the fluid domains take the shape of an oval that encapsulates the upward and downward pipes. This phenomenon is observed throughout the whole depth of the borehole, bar the larger shank-spaces (205mm and 260mm), where the egg-shaped temperature contours start to separate in two, forming two almost independent circular contours around the fluid domains as observed for the 260mm shank-space. The grout temperature in the central part is therefore lower compared to that for the other shank-spaces.

These results confirm the presence of thermal short-circuiting, implying that the pipes are not only exchanging heat with the grout but also exchange heat with one another thus deteriorating the thermal performance of the GHE. Thus, the loss in performance associated with variations in shank-space can be attributed to the effects of thermal short-circuiting. As the entire length of pipe simulated is only 40m long, the temperature drop between the inlet and outlet is also small and thus the thermal short-circuiting effect witnessed in these simulations is small.

Varying the shank-space for a 40m deep borehole

The second set of results obtained for a borehole depth of 40m, shown in Table 3, show similar trends to those obtained for the 20m borehole, although with marginally higher temperature drops. The fluid temperature variation with depth is shown in Figure 7.

Table 3. Simulation results for different shank-spaces for the 40m borehole

Shank-Space (mm)	Inlet 1 Temp. (K)	Outlet 1 Temp. (K)	Inlet 2 Temp. (K)	Outlet 2 Temp. (K)	Temp. Drop (Inlet 1 - Outlet 2) (K)	Improvement over previous shank-space (%)
40	313.00	312.22	312.18	311.78	1.22	-
95	313.00	312.23	312.16	311.72	1.28	4.92
150	313.00	312.24	312.16	311.70	1.30	1.56
205	313.00	312.25	312.16	311.69	1.31	0.77
260	313.00	312.27	312.16	311.68	1.32	0.77

As can be seen from the results obtained, the temperature drop for all shank-spaces is marginally higher than those obtained for the 20m deep borehole. This is to be expected, given the larger contact area available for heat transfer. What is however noticeable as well, is the fact that similarly to the 20m deep borehole as the shank-space increases, the temperature drop increases in a non-proportional manner, with a higher increase between the 40mm and 95mm shank-space compared, to the practically non-existent increase between the 205mm and the 260mm shank-spaces.

When the temperature drops are compared across borehole depth as shown in Table 4, it becomes apparent that the temperature drop between inlet and outlet of the ground heat exchanger is in fact more dependent on the length of the pipework, rather than the effect of increasing shank-space. In this case in fact, the depth based improvement is constant, irrespective of shank-space.

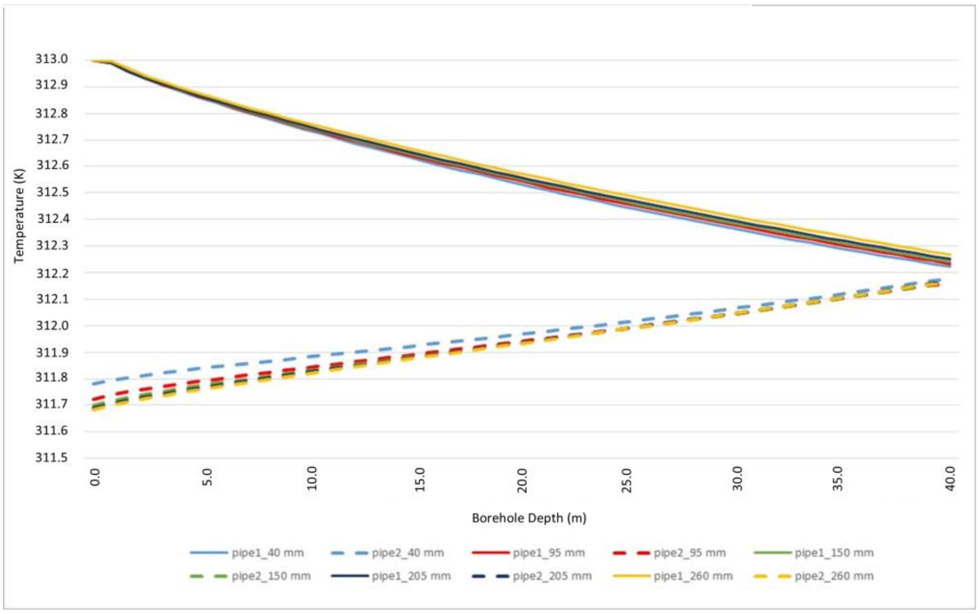

Figure 7. Variation of fluid temperature with depth for the five shank-spaces investigated for the 40m borehole

Table 4. Depth based improvement

Shank-Space (mm)	20m deep borehole Temp. Drop (*Inlet 1 - Outlet 2*) (K)	40m deep borehole Temp. Drop (*Inlet 1 - Outlet 2*) (K)	Depth based improvement (%)
40	0.76	1.22	60.53
95	0.82	1.28	56.10
150	0.84	1.30	54.76
205	0.85	1.31	54.12
260	0.85	1.32	55.29

Effect of borehole spacing

This last part of the research utilised the modelled U-tube ground heat exchanger to understand the effect of borehole spacing on the overall performance. As discussed earlier, an array with an infinite number of boreholes in the two orthogonal directions was modelled. Three cases of borehole spacing were considered, that is, 5m, 10m and 15m. In this case, only one value of shank-space was simulated (150 mm), and the borehole depth was taken as 20m.

Table 5. Simulation results for three different borehole separation distances

Borehole Spacing (m)	Inlet 1 Temp. (K)	Outlet 1 Temp. (K)	Inlet 2 Temp. (K)	Outlet 2 Temp. (K)	Temp. Drop (*Inlet 1 - Outlet 2*) (K)
5	313.00	312.89	312.89	312.81	0.19
10	313.00	312.79	312.76	312.60	0.40
15	313.00	312.71	312.65	312.43	0.57

As can be seen in Table 5, increasing the separation distance from 5m to 10m, the temperature drop increases by 0.21K which represents an improvement of 111%. Increasing the separation distance to 15m the drop also increases the temperature drop, this time however with a smaller increment of 43%.

Comparing the results obtained in this case with those obtained for the isolated 20m GHE, the performance loss due to the 3 boreholes spacing investigated varies between 77.38% for the 5m borehole spacing, 52.38% for the 10m borehole spacing and 32.14% for the 15m borehole spacing, indicating that as expected thermal interference between boreholes occurs, and that a compromise between borehole spacing and GHE performance needs to be studied well before a system is designed.

CONCLUSIONS

The research presented in this paper looked at the effect shank-space has on the performance of shallow vertical U-tube ground heat exchangers. Using the computational fluid dynamic tool ANSYS, two vertical U-tube ground heat exchangers, were modelled, one 20m deep and the other 40m deep. For each system the shank-space was varied between a minimum of 40mm to a maximum of 260mm and the resultant temperature drop between inlet and outlet simulated. Differently to most other modelling approaches involving U-tube ground heat exchangers, the 3D U-tube heat exchanger model was modelled without the U-shaped connector at the bottom of the U-tube. Validation against similar experimental work and numerical analysis involving the full U-tube, however showed that the elimination of the U-junction has no significant impact on the simulated temperature profile of the carrier fluid.

Results for the two depths investigated show that for the smaller shank-spaces investigated (40mm and 95mm), increasing the distance between the two U-tube branches results in improvements of between 4% and 7%, but that once the shank-space increases beyond the borehole mid-point (150mm), improvements are only marginal. On the contrary comparing the results across borehole depth, shows that improvements are constantly in the range of 55%. Such results indicate that for shallow U-tube, the temperature drop across the system is more dependent on the length of the pipework than the effect of shank-space.

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