

## **Improvement of a Two-Dimensional Borehole Heat Exchanger Model**

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### **Abstract**

A dynamic numerical three-dimensional model has been developed to simulate transient fluid transport and heat transfer in and around Borehole Heat Exchangers (BHEs). By applying this three-dimensional model, the dynamics of fluid transport and the transient response of a BHE at short timescales have been examined in detail. The findings indicate that delayed response associated with the transit of fluid around the pipe loop is of some significance in moderating swings in temperature during heat pump operation. Furthermore, the three-dimensional model shows a lower heat transfer rate over longer periods of operation. The more realistic predictions of the three-dimensional model require considerable computing resources so that using the model in annual or super-annual simulations of Ground Source Heat Pump (GSHP) systems is not practical. There is, therefore, a need for a computationally efficient simplified model which can capture the most significant dynamic features of the detailed three-dimensional model. This paper presents an improved two-dimensional BHE model which can meet these needs.

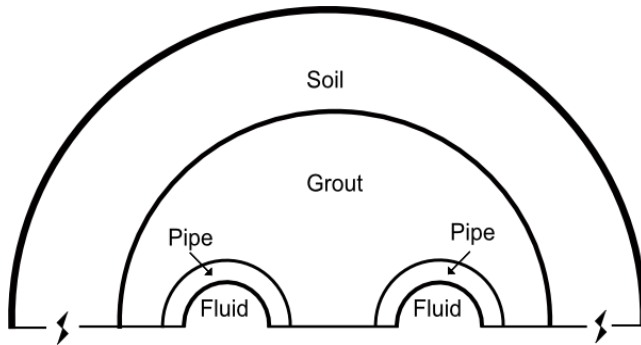
**Keywords:** ground source heat pumps, borehole heat exchanger models, dynamic response simulations

### **1. Introduction**

Ground Source Heat Pump (GSHP) systems are among the most efficient to provide heating and cooling for buildings. Buildings account for over 40% of total energy consumption in the UK, and in turn are responsible for almost half of the UK's carbon emissions. For domestic buildings, heating and hot water account for over 80% of the total energy consumption. For non-domestic buildings, heating and cooling account for around 25% of energy consumption in air-conditioned buildings and 35% of energy consumption in naturally ventilated buildings. Therefore, improving energy efficiency in heating and cooling systems can make a huge impact on targeting carbon emission reduction in buildings. GSHP systems use the ground as a heat source or a heat sink to extract or dissipate heat, depending on the operation of the systems, by circulating fluid inside ground heat exchangers. The main advantage of using the ground is that, the temperature of the ground is much more constant than ambient air temperature, and it is higher in the winter and lower in the summer, which makes the coefficient of performance much higher than other systems, for example, air source heat pump systems. Due to its high coefficient of performance, a GSHP can save 40% of carbon emission when compared to a conventional gas boiler.

There are different types of ground heat exchangers used in GSHP systems, and the most common one is vertical Borehole Heat Exchangers (BHEs). A horizontal cross-section of half

of a typical BHE is shown in Figure 1. A vertical borehole normally ranges between 50 m to 100 m deep and typically is around 100 mm to 150 mm in diameter. Pipes are formed in a ‘U’ loop and inserted into a borehole. Grout material is then refilled back into the borehole for a seal. A single U-tube (two pipes) and a double U-tube (four pipes) borehole can be installed in each borehole.



**Figure 1 A half cross-section of a BHE.**

Properly sizing the length of the borehole and deciding the number of the boreholes required in the GSHP system is critical to the long and short term performance. More importantly, BHEs cannot be designed on the basis of steady-state calculations but require application of dynamic thermal models that are able to take into account the heat transfer inside the borehole as well as the surrounding soil/rock formation over long timescales.

Models of BHEs have three principle applications:

- 1) To design BHEs. This means sizing the borehole depth, number of boreholes etc.
- 2) To analyze of in-situ ground thermal conductivity test data.
- 3) To integrate with building system simulation, i.e. with the model coupled to Heating Ventilation and Air-Conditioning (HVAC) systems and building heat transfer models to study overall performance.

Analytical models have been developed by making a number of simplifying assumptions and applied to both the design of BHE and analysis of in-situ test data. The cylinder source solution presented by Carslaw and Jaeger (1947) is one of the best-known models in this category. Further simplifying this model, the line source solution (Ingersoll et al., 1954) can also be used for the analysis of in-situ thermal conductivity test data. Although analytical solutions require less computing effort, they are less suited to design and simulation tasks. A number of approaches that have combined analytical and numerical methods have been developed with design tasks in mind. Eskilson (1987) and later Hellstrom (1991) developed a response factor approach – using so called g-function – to design BHE for thermal storage applications. Application of models for system simulation tasks – unlike design tasks – requires the ability to operate at shorter timescales, possibly less than one minute. Therefore, the dynamic response of the borehole should be considered. Yavuzturk and Spitler (1999) extended the g-function model to short time steps which has been implemented in EnergyPlus. Hellstrom (1991) developed the DST model which has been implemented in TRNSYS. However, as variation in fluid temperature with borehole depth can not be considered explicitly, some assumptions have to be made, as it does with simpler models, about the fluid temperatures in the two pipes and the associated boundary conditions. These assumptions can be avoided in a three-dimensional numerical model, which can offer more accurate representation of heat transfer. Several three-dimensional models have been

developed (Zeng et al., 2003, Lee and Lam, 2008, Bandyopadhyay et al., 2008), but none of them have simulated the dynamics of fluid transport along the pipe loop explicitly.

## 2. Model Development

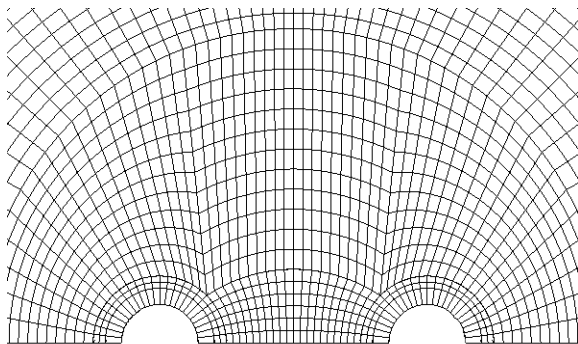
### 2.1 Three-Dimensional Model Development

A dynamic numerical three-dimensional BHE model has been developed that is built upon a finite volume solver known as GEMS3D (General Elliptical Multi-block Solver in 3 Dimensions). This has been developed to simulate the dynamic response of the circulating fluid and transient heat transfer in and around BHEs. GEMS3D applies the finite volume method to solve the partial differential convection-diffusion equation for heat transfer on three-dimensional boundary fitted grids, which can be written as:

$$\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left( \frac{k}{\rho c_p} \frac{\partial T}{\partial x} \right) + S \quad (1)$$

where  $k$  is thermal conductivity,  $\rho c_p$  is volumetric heat capacity, and  $S$  is source term.  $u_j$  is velocity and  $|u_j| > 0$  in fluid cells and  $|u_j| = 0$  elsewhere. Including the convective term  $u_j \frac{\partial T}{\partial x}$  allows fluid transport along pipe loops to be considered explicitly. Likewise, ground water flow can be taken into account by calculating a Darcian flow field or assigning predefined velocities.

Subdividing the solution domain into a finite number of small control volumes, and then integrating the partial differential equation to form an algebraic equation in terms of fluxes at the boundaries of the control volume allows the temperatures and heat fluxes to be calculated. The approach to dealing with non-orthogonal cells and discretisation of the diffusion fluxes is similar to that described by Ferziger and Peric (2002). The Strongly Implicit Procedure (also known as Stone's method) has been employed for solving the equation system arising from discretisation of the partial differential equation for heat transfer. The hybrid differencing scheme has been applied to discretise the convection term of the equation i.e. the term used to represent fluid motion in the pipe. Diffusion fluxes are dealt with using central differencing and the temporal term is discretised using a first order implicit method. The multi-block structured mesh used in this model allows the complex geometries of the BHE to be represented explicitly (Figure 2). The multi-block mesh is also a convenient way to define zones with different physical properties, i.e. the fluid, pipe, grout, and soil. The mesh is essentially extruded in the third dimension (borehole depth) in the three-dimensional model, and further blocks are added to represent the region below the borehole.

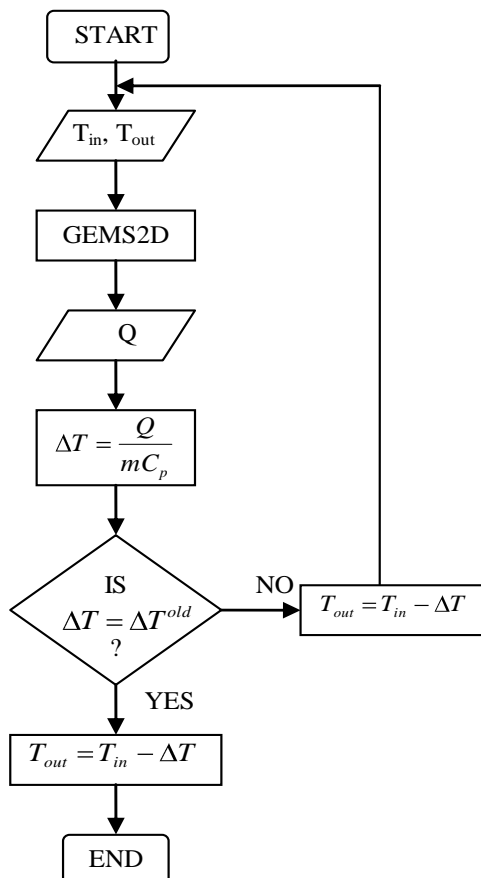


**Figure 2** A horizontal cross-section of boundary fitted mesh showing half a borehole and surrounding soil.

## 2.2 Two-Dimensional Model Implementation

A two-dimensional implementation of BHE model, equivalent to the three-dimensional model of one metre depth, has been used to highlight the differences between model predictions that are due solely to three-dimensional effects and dynamic fluid transport. The two-dimensional model necessarily employs some of the simplifications of other existing models. One important issue in defining a two-dimensional model is relating the model boundary conditions to the inlet and outlet fluid temperatures. In reality, and in the three-dimensional numerical model, the tube nearer the inlet has a higher temperature than that of the outlet. The temperature differences between the neighbouring tubes causes some heat to flow between the tubes rather than from the tubes to the ground. Preliminary calculations suggest this is approximately 5% of the total BHE heat transfer rate (He et al., 2009a). A three-dimensional model can account for the variations in this inter-tube heat flux along the length of the borehole but some assumptions about the differences in pipe temperature have to be made in any two-dimensional models.

One of the approaches is to assume one pipe of the model having a temperature the same as the inlet. The second pipe in the model is assumed to have the same temperature as the outlet. The temperature boundary condition applied to the second pipes is calculated in an iterative manner so that the fluid heat balance is consistent with the heat flux. In this case, the pipe temperatures in the model really reflect conditions near the top of the borehole where the difference in temperature between the pipes is greatest. This can be expected to result in over estimation of the heat flux between the tubes. This iteration method is illustrated in Figure 3.

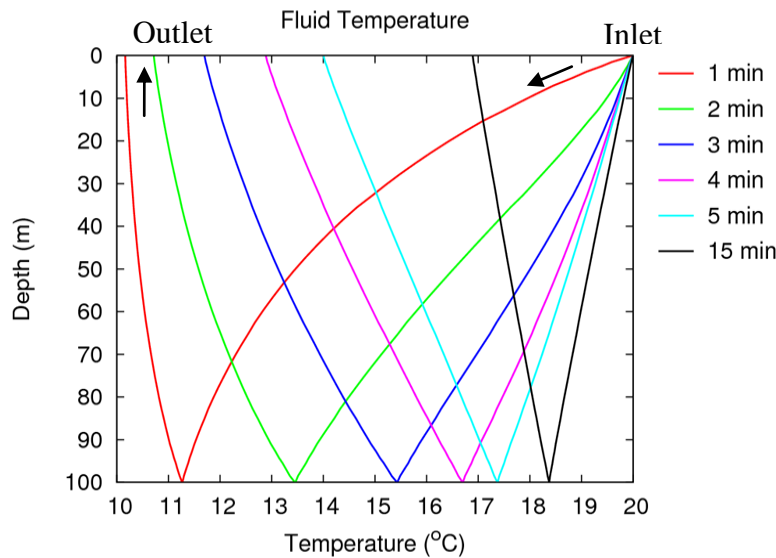


**Figure 3** An illustration of the iterative procedure used to calculate the outlet temperature of a 2D BHE model.

### 3. Simulation Results

#### 3.1 Single Step Response

A single step of heat flux has been applied as the inlet temperature to test the dynamic response in the circulating fluid using the three-dimensional model. Figure 4 shows the fluid temperature profile along the borehole depth in the first few minutes. The non-linear distribution of the temperature can be clearly observed, which contradicts to the assumption of linear distribution of fluid temperature along the borehole depth, made in all two-dimensional models.



**Figure 4 Fluid temperature profile along the borehole depth in the first few minutes.**

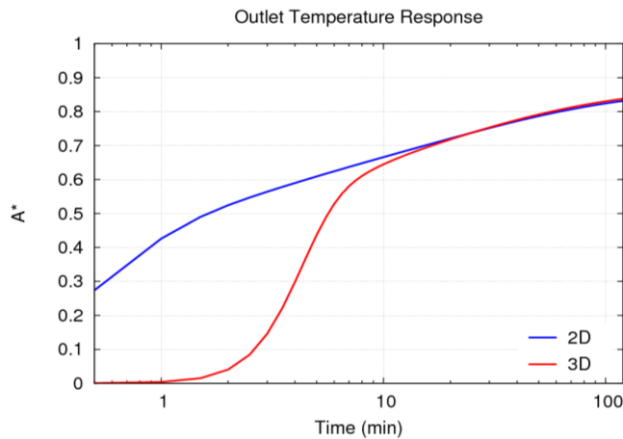
The change of the outlet temperature can be normalised by considering the ratio of change between the outlet and initial temperature, and the inlet and initial temperature, which can be expressed as:

$$A^* = \frac{T_{out} - T_{initial}}{T_{in} - T_{initial}} \quad (2)$$

where  $T_{in}$  is inlet fluid temperature,  $T_{out}$  is outlet fluid temperature, and  $T_{initial}$  is initial ground temperature.

The results of the two-dimensional model and the three-dimensional model are shown in Figure 5. The responses are shown on a logarithmic horizontal scale where the simulation has been carried out over duration of 120 minute. In the case of the three dimensional model the nominal fluid transit time is 200 seconds, the differences in response predicted by the two-dimensional and three-dimensional models prevail over the first 10 minutes. The temperature response predicted by the three-dimensional model is much slower than that is predicted by the two-dimensional model in this period. This is because; the response of the two-dimensional model is governed entirely by the transient conduction of heat through the pipe wall and grout. But in the three-dimensional model, not only are the thermal mass of the pipes and grout taken into account but also the effect of the dynamics of the circulating fluid. This is a question of both the thermal mass of the fluid itself as well as its transport along the pipe and heat loss through the pipe wall. The response is not just delayed according to the notional transit time (200 s) but can be seen to be significant for several times this period – up

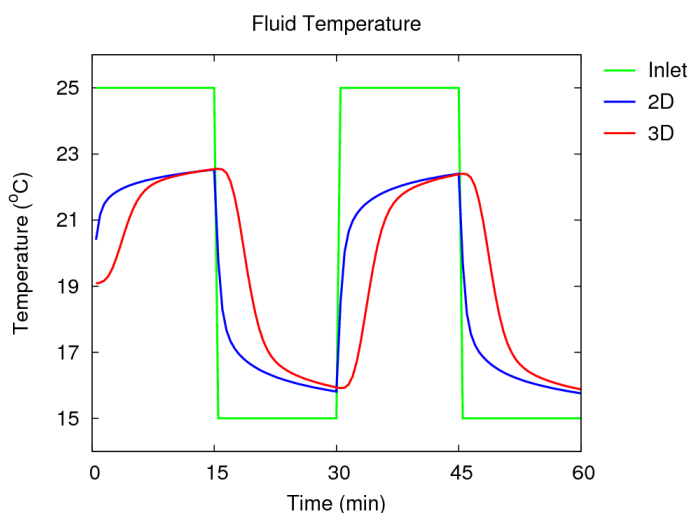
to approximately 10 minutes in this case. Beyond this timescale, the response predicted by the two-dimensional model is very similar to that of the three-dimensional model.



**Figure 5 Comparison of outlet temperature response to a single step change by the 2D and 3D models.**

### 3.2 Periodic Step Response

The practical significance of the dynamics of the fluid transport can be investigated by applying periodic step changes in borehole inlet temperature. This has been done using step changes that might be typical of the on-and-off operating intervals of a heat pump. Assuming the heat pump cycles twice per hour with the inlet temperature changing between 25 °C and 15 °C, and the far-field ground temperature is 10 °C, the predicted outlet temperatures by the two-dimensional and three-dimensional models, in response to the changes of the inlet temperature, are shown in Figure 6. The outlet temperature predicted by the two-dimensional model necessarily shows an instant response to changes in inlet temperature. This is representative of all models that are formulated on a one or two-dimensional basis. On the other hand, the outlet temperature predicted by the three-dimensional model shows a delay in response to the changes, which could significantly change overall system behaviour when interaction with heat pump control system (i.e. cycling) is considered (Kummert and Bernier, 2008). More detailed studies on coupling the three-dimensional model with the heat pump model have been published in a previous conference paper (He et al., 2009b).



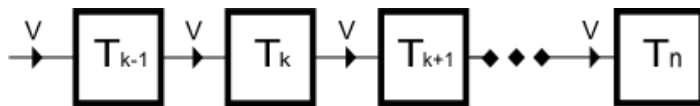
**Figure 6 Comparison of outlet temperatures by 2D and 3D models of periodic step changes.**

## 4. Improvement of Two-Dimensional Model

### 4.1 Methodology

The differences highlighted by the comparisons between the two-dimensional and three-dimensional models indicate that one crucial improvement can be made for the two-dimensional model is to include the dynamics of the fluid transport in the model. One of the straight forward ways is to do so is to have a pipe model to simulate the fluid transport inside the pipes of the borehole, and the transient heat transfer between the fluid, pipes, grout and the surrounding soil is to be calculated by the two-dimensional model.

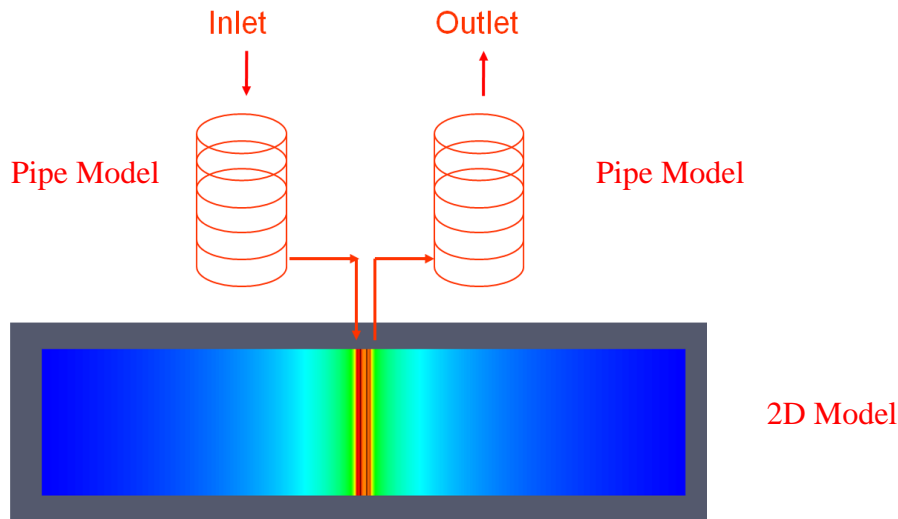
The pipe model to simulate the fluid transport applies the same method that the three-dimensional model uses to simulate the fluid transport. The total length of the pipe is to be discretised into a finite number of cells, and fluid velocity is imposed in these cells in accordance with the system flow rate. Assuming the fluid is well-mixed in each cell; each fluid cell can be represented by a single temperature  $T$  and is connected by the velocity  $V$ . The model can be considered similar to a Compartments-In-Series model(Wen and Fan, 1975), which is widely used in processing engineering. The model is illustrated in **Error! Reference source not found..**



**Figure 7 Illustration of pipe model to simulate the fluid transport.**

However, there is a significant difference between the three-dimensional model and the improved two-dimensional model. In the three-dimensional model, the dynamics of the fluid transport and the transient heat between the fluid, pipes, grout and the surrounding soil are simulated simultaneously. But in the improved two-dimensional model, the fluid transport and the heat transfer are simulated separately. In this way, the total number of cells of the model is much less than that of the three-dimensional model. Therefore, the computing time it requires is reduced dramatically comparing with the three-dimensional model.

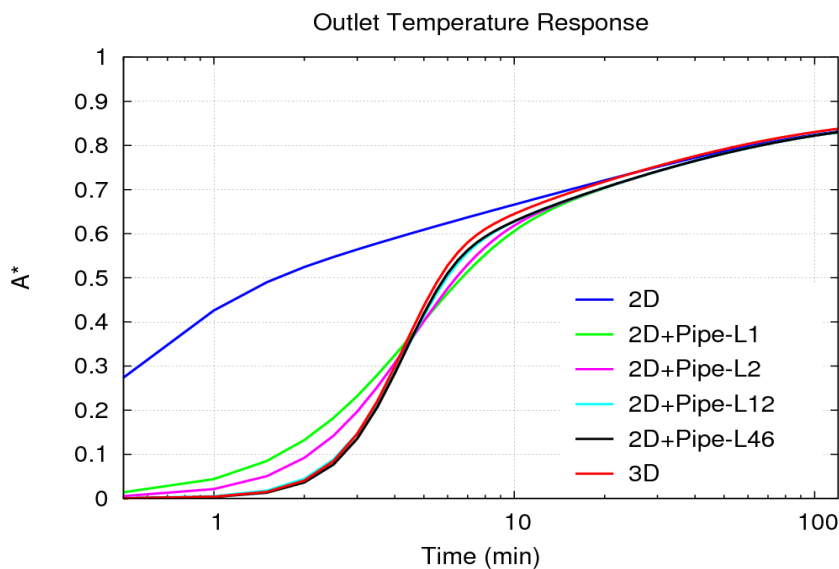
There are many different ways to simulate the fluid transport and heat transfer separately, depending on whether to simulate the fluid transport before or after simulating the heat transfer in the two-dimensional model, or both before and after. Different arrangements have been examined, and the results show that having one pipe model corresponding to the downward fluid, and another pipe model corresponding to the upward fluid, and having both of these two pipe models connected with the two-dimensional model (Figure 8) generates the best results, when compared to the three-dimensional model.



**Figure 8 Diagram of the improved 2D model.**

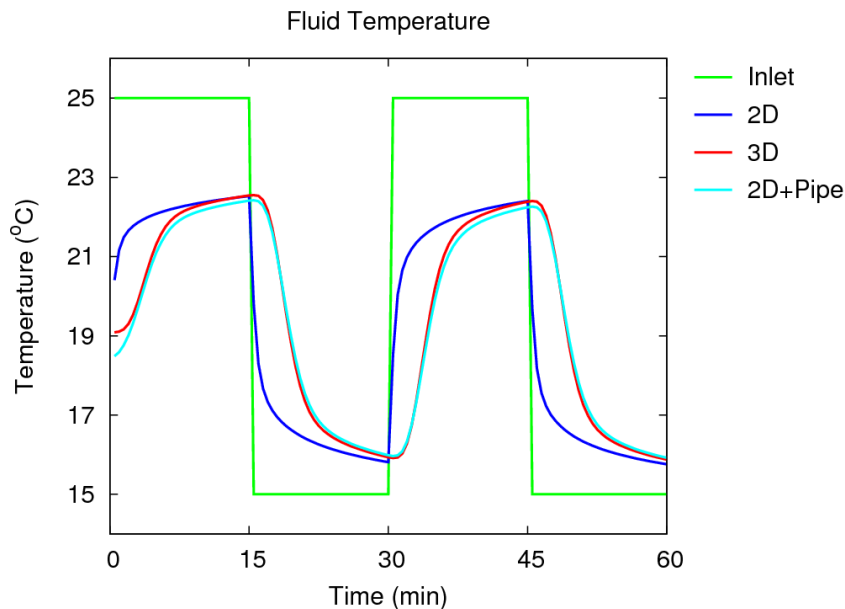
#### 4.2 Simulation Results

Applying a step change in inlet temperature, the changes of the outlet temperature in short time scale can be examined in terms of outlet temperature response,  $A^*$  (Equation 2). As expected, the simulation results are dependent on the number of cells divided along the length of the pipe. The results of the number of cells equal to 1, 2, 12, and 46 are shown in Figure 9, while comparing with the results by the two-dimensional and three-dimensional models. The results by the improved two-dimensional model show significant improvement when compared to the two-dimensional model, even when the whole pipe is considering as only one cell. As the number of cells increases, the simulation result gets closer to the three-dimensional model, but the difference becomes smaller. When the number gets higher than 12, the difference is hardly noticeable, for example, the simulation results of 12 cells and 46 cells.



**Figure 9 Outlet temperature response by the improved 2D model, comparing with the 2D and 3D models.**

Another way to evaluate the improved two-dimensional model is to apply periodic step changes in inlet temperature, and to compare the outlet temperature with those of the two-dimensional and three-dimensional models. Figure 10 shows the outlet temperature of improved two-dimensional model with 12 cells, comparing with the outlet temperatures by the two-dimensional and three-dimensional models. The improved two-dimensional model shows a significant improvement of the two-dimensional model, and the outlet temperature predicted by the improved two-dimensional model closely matches the outlet temperature predicted by the three-dimensional model.



**Figure 10 Comparison of outlet temperatures by the 2D, 3D and improved 2D models of periodic step changes.**

## 5. Conclusions and Future Work

A dynamic three-dimensional numerical BHE model has been developed to simulate the fluid transport along the pipe loop as well as the heat transfer with the ground. The model applies the finite volume method to solve the partial differential heat transfer equation on three-dimensional boundary fitted mesh, which enables the method to be applied to complex geometries of BHEs. The dynamic responses of a BHE have been investigated in detail using the three-dimensional model, and the results have been compared to those by the two-dimensional model, in order to highlight the differences between them. It is shown that delayed response associated with the transit of fluid along the pipe loop, is of some significance at short time scales (10 minutes) but much longer than the transition time of the fluid along the pipe loop (200 seconds). This effect, both in terms of response, control operation and effective heat transfer rate, maybe significant where there is on/off control or where peak loads of buildings are important.

Study of BHE characteristics using this dynamic three-dimensional model gives insights into the different behaviours of the three-dimensional and two-dimensional models, as well as the limitations of two-dimensional models. Though the three-dimensional model can simulate more realistic dynamic responses of a BHE, it is still not practical for system annual simulation due to the computation power it requires. Therefore, an improved two-dimensional model has been developed, which includes a pipe model to simulate the fluid

transport along the pipe loop. This model can also capture the dynamic responses of a BHE, and they match closely to those responses by the three-dimensional model.

It is the intention that this improved two-dimensional model will be used to carry out investigation of borehole fields and thermal interaction between the boreholes.

### Acknowledgements

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