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Comparison of Hourly Simulation Models for Multi-Vertical Borehole Heat Exchanger Arrays

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ABSTRACT
This paper presents a comparison of hourly simulation models for multi-vertical boreholes heat exchangers (BHE). The comparison is based on three different methods that are Duct Storage model, Eskilson's g-function, and incomplete Bessel Function. The proposed comparison is simulated with TRNSYS and the results plotted with R-Studio. EFT for balanced dominant buildings are within the same range for all B/H ratios where its decreasing with increasing B/H ratios for cooling dominant buildings and increasing with increasing B/H ratios for heating dominant buildings. The average energy consumptions over 20 years are decreasing with increasing B/H ratios. EFT results for both Incomplete Bessel function and DST are matchable, where Eskilsons' results are not with 15% to 18% mismatch at 100kW load and 20 boreholes and 10% mismatch with 500kW load and 100 boreholes. Eskilson's model is more efficient compared to the other models because the energy consumption is less and EFT variation less as well. Finally, the differences between Eskilson's model and the other methods reduces in cooling and balanced dominant buildings with higher loads and higher B/H ratios.

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I. INTRODUCTION

The vertical borehole heat exchanger (BHE) is a pipe that is assembled vertically with a specific radius and depth to exchange heat with earth. Double U-tube is always preferred over single ones because it has the benefit of lowering the thermal resistance of boreholes [1]. There are three methods to simulate vertical boreholes that are Eskilson's g-function, Incomplete Bessel Function, and Duct Storage model.

First, g-function was introduced by Eskilson on 1987. The concept of g-function is to get a dimensionless "thermal response factors" from a particular borehole designs and thermal resistance of ground. There are different B/H curves for every design of boreholes. Cimmino and Bernier [2] introduced different boundary conditions for the g-function. In Eskilson's method, wall temperature of all boreholes is the same and no matter how long the borehole is. However, heat transfer and wall temperature in reality supposed to vary with the length of boreholes [3]. The change of boreholes wall temperature versus heat transfer and time can be calculated by g-function. Superposition method was used by Eskilson to test multiple borehole structures. Second, Incomplete Bessel function that is known also as the leaky well function produces g-functions at different boundary layers efficiently [4]. In this method, g-function is the total of all other boreholes impacts. The third method is the Duct Ground Storage (DST). The main purpose of this method is to maintain the storage temperature as low as possible in order to achieve two things that are decreasing of heat losses and increasing the efficiency of solar collectors by using heat pump [5]. The simulation is based on GHX outlet temperature calculation and the energy of heat pump consumption on time basis either hourly or monthly.

Numerical and g-function are the two methods to model multi vertical borehole heat exchanger arrays. TRNSYS is a program that uses both methods to compute the DST outlet temperature with some assumptions like the borehole orientation. DST model can predict how much of heat moved from boreholes to ground.

The scope in this paper is to construct TRNSYS models of three variant methods for simulation of vertical BHEs. The first method is the Eskilson's g-functions. It is also somewhat of an industry standard model, but Eskilson (1987) developed g-function response factors for prescribed field geometries. The second method is Incomplete Bessel function that Developed by Andrew Chiasson. The third method is the Duct Storage (DST) model. This model is considered to be an "industry standard" model but is limited to rectangular borehole field shapes.

II. LITERATURE REVIEW

Cimmino and Bernier 2013 and 2014 [2&6] used two different methods to generate and determinate thermal response factors (g-functions).

In 2013, they used a method known as finite line source to study the thermal response of boreholes based on the ratio of boreholes depth and length. Their results were very comparable with Eskilson's model even though they have assumed different boundary conditions. Shorter simulation time with smaller borehole configurations provided better match with Eskilson's model where longer simulation time with larger borehole configuration provided more differences and mismatches. On the other hand, on 2014 they reduced the mismatches with Eskilsons from 32% to 5% by dividing the boreholes into parts and assuming that the heat extraction is varying with the boreholes' length and the wall temperature as well.

Chiasson and Elhashmi [3] used incomplete Bessel function to calculate the g-function (thermal response factor) for vertical ground heat exchangers. They have used different borehole configurations and boundary conditions. They have got a matchable results with Eskilson's when small ratio of borehole spacing and depth and uniform heat along the borehole length were assumed. Also, 4% a mismatch with Eskilson's when they assumed constant wall temperature of boreholes. B/H ratio of 0.1 with large configuration of boreholes (10 x10) have better match with Eskilson's than using B/H ratio of 0.05 where the common B/H ratio in US is 0.08.

Chapuis and Bernier [5] implemented a seasonal borehole thermal energy storage to minimize the heat losses and therefore improve the efficiency of the collectors. They concluded that high solar fraction can be achieved by keeping BTES temperature high. However, the heat loses and collectors efficiency will decrease. On the other hand, reducing collectors' area and increasing the BTES volume by having four pipe boreholes with two separate circuits will reduce thermal loses of boreholes and keep them low. Therefore, heat pump or boilers are needed for direct space heating. The solar fraction and collector efficiencies are 78% and 58% respectively.

Spitler and Bernier [8] emphasized on the importance of having correct size of GHE and that will guarantee the durability of the system and maintain the minimum and maximum temperature of fluid entering the heat pump (EFT) within the acceptable range. Heat extraction and rejection over time is affecting the sizing of GHE that is why predicting the load is very important. Sizing of boreholes is also affected by thermal properties and thermal resistance of ground and boreholes and heat pump's properties as well. Minimizing the size of GHE is what researchers looking for to enhance the model.

Malayappan and Spitler [7] stated that assuming uniform boreholes wall temperature in computing g-function rather than uniform heat flux will result in a smaller sizing of GHE. Based on the configuration of the boreholes, a wall temperature is given by g-function assuming the heat input is constant. G-function is used to analyze ground's heat transfer.

III. METHODOLOGY

A model was developed by Andrew Chiasson to simulate arbitrary borehole field configurations on hourly level. This model was built to be compared to different benchmarking models by using TRNSYS. TRNSYS were used to generate different synthetics building loads. The three loads generated were for cooling, heating, and balanced dominant buildings using type 686. Various building loads were simulated using different borehole field geometries. The ratio of borehole to borehole spacing to the borehole length (B/H) were 0.05, 0.1, and 0.15. These ratios were used for two cases. The first case is without thermal resistance and small borehole diameter such as 1in (25.4mm). In this case, the comparison was made between Incomplete Bessel Function and Duct Storage Model (DST). The second case is with steady state thermal resistance of 0.1 m-k/W and borehole diameter of 6in (152.4mm). The comparison in this case were made among the three methods which are Eskilson's, Bessel Functions, and DST. The simulation was made hourly for 20 years with cooling and heating peak loads of 100 kW. The borehole configuration is 4x5 (20 boreholes) for both cases. Moreover, the above two cases were repeated for bigger boreholes configuration of 10 x 10 with 500 kW peak loads. The ratio for the heating and cooling dominated buildings are 5:1 and 1:1 for the balanced dominated building case. For the cooling dominated buildings, it was assumed that the cooling period is from Mid-March to the end of the year. On the other hand, the heating period is all year long except June, July and Mid-August. The ratios are 80 to 20 percent. However, for the balanced dominated building case. March to September and September to March are the cooling and heating periods.

IV. RESULTS AND DISCUSSIONS

The first comparison was made for two models only that are incomplete Bessel function and DST. In this comparison, some assumptions were made such as no thermal resistance, small borehole diameter of 1in (25.4mm), load of 100kW, 20 boreholes, and three B/H ratios for three different building dominants. The entering fluid temperature for balanced dominant building is within the same range for different B/H ratios (table1 & figures1-3), where in cooling dominant building is decreasing with increasing the B/H ratios (table1 & figures 3-6), where it is increasing with increasing the B/H ratios for the heating dominant building (table1 & figures 7-9). The EFT results for both models are matchable for all cases. The effect of B/H ratios on HP energy is clear in table2, the higher the ratio is, the lower energy consumption.

Balanced Dominant Building 100kW	EFT "Bessel g-function"		EFT DST	
W/O Thermal R, 25.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	11.82	17.90	11.74	17.84
B/H = 0.10	11.54	17.83	11.65	17.71
B/H = 0.15	11.52	17.72	11.57	17.69
Cooling Dominant Building 100kW	EFT "Bessel g-function"		EFT DST	
W/O Thermal R, 25.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	22.06	28.30	22.03	28.32
B/H = 0.10	17.61	24.04	18.18	24.47
B/H = 0.15	16.02	22.39	16.62	22.94
Heating Dominant Building 100kW	EFT "Bessel g-function"		EFT DST	
W/O Thermal R, 25.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	1.06	7.51	0.99	7.47
B/H = 0.10	5.15	11.76	4.73	11.19
B/H = 0.15	6.75	13.29	6.23	12.71

Table1: Entering Fluid Temperature for Incomplete Bessel Function vs. Duct Storage model without thermal resistance

Balanced Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy DST
W/O Thermal R, 25.4mm Dia.	avg. of 20 year	avg. of 20 year
B/H = 0.05	49432.74	49612.19
B/H = 0.10	50019.47	49774.23
B/H = 0.15	49848.44	49876.21
Cooling Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy DST
W/O Thermal R, 25.4mm Dia.	avg. of 20 year	avg. of 20 year
B/H = 0.05	51924.19	52067.54
B/H = 0.10	48986.59	49147.13
B/H = 0.15	47763.39	48159.65
Heating Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy DST
W/O Thermal R, 25.4mm Dia.	avg. of 20 year	avg. of 20 year
B/H = 0.05	57326.36	57447.89
B/H = 0.10	55801.22	55871.02
B/H = 0.15	55066.90	55317.03

Table2: Average HP Energy for Incomplete Bessel Function vs. Duct Storage model without thermal resistance:

The comparison of the three models together are under the same assumptions and conditions above, but bigger diameter (6in or 152.4mm) and with thermal resistance of 0.1 m-k/W (tables 3&4). The EFT and HP energy results are the same as explained above. However, Eskilson's model is way off comparing to the other models with 15% to 18% mismatch. The percentage difference is increasing with increasing the B/H ratios (figures 10-17). The maximum average EFT for Eskilson's is always less compared to the other models. Also, the variation between minimum and maximum EFT is less with Eskilson's model. Moreover, the energy consumption is with Eskilson's model is always less compared to the other models.

Balanced Dominant Building 100kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	11.86	17.86	13.03	16.57	11.42	18.16
B/H = 0.10	11.57	17.82	12.98	16.38	11.33	18.03
B/H = 0.15	11.58	17.68	12.93	16.33	11.26	18.01
Cooling Dominant Building 100kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	22.03	28.23	21.31	24.88	21.88	28.81
B/H = 0.10	17.55	23.98	17.77	21.17	18.01	24.93
B/H = 0.15	15.97	22.31	16.34	19.77	16.44	23.39
Heating Dominant Building 100kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.05	1.16	7.56	12.02	14.61	0.52	7.65
B/H = 0.10	5.23	11.81	8.06	11.49	4.27	11.39
B/H = 0.15	6.85	13.32	9.40	12.85	5.77	12.91

Table3: Entering Fluid Temperature for the three models with thermal resistance

Balanced Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.05	49349.94	47969.80	49796.29
B/H = 0.10	50059.73	47870.37	49957.75
B/H = 0.15	49737.54	47934.94	50061.09
Cooling Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.05	51862.70	48939.99	52364.95
B/H = 0.10	49016.59	46415.31	49390.00
B/H = 0.15	47692.23	45628.20	48386.75
Heating Dominant Building 100kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.05	57269.54	51009.35	57644.51
B/H = 0.10	55820.68	53802.88	56052.98
B/H = 0.15	55003.82	53327.47	55495.42

Table4: Average HP Energy for the three models with thermal resistance

The load increased five times and the number of boreholes as well to 500kW and 100 boreholes respectively and the comparison was repeated. For the case of without thermal resistance and small diameter (1in or 25.4mm), the comparison was done only with the B/H ratio of 0.15 (table5 &6 and figures18-20). The average energy prediction over 20 years for Incomplete Bessel function is less on all building types compared to DST model and on both configurations (small and large number of boreholes). Also, the EFT results for both models are matching. On the other hand, for the thermal resistance case and large borehole diameter (6in or 152.4mm), the comparison was made for the same ratio for all building dominants and for all models and the three ratios for the balanced dominant buildings (table7 & 8 and figures 21-23). The difference between Eskilson's and the other two models is less than 10% for balanced and cooling dominant buildings and very high in heating dominant building. Thus, with higher loads and number of boreholes, the mismatch between

Eskilson's and the other methods were reduced in balanced and cooling dominant buildings.

W/O Thermal R, 25.4mm Dia.	EFT "Bessel g-function"		EFT DST	
B/H = 0.15 @ 500 kW	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
Balanced Dominant Building	11.50	17.70	11.54	17.66
Cooling Dominant Building	16.38	22.74	17.44	23.77
Heating Dominant Building	6.32	12.86	5.29	11.78

Table5: Entering Fluid Temperature for Incomplete Bessel Function vs. Duct Storage model without thermal resistance

W/O Thermal R, 25.4mm Dia.	HP Energy "Bessel g-function	HP Energy DST
B/H = 0.15 @ 500 kW	avg. of 20 year	avg. of 20 year
Balanced Dominant Building	249219.41	249356.00
Cooling Dominant Building	239970.87	243664.88
Heating Dominant Building	276176.74	278491.99

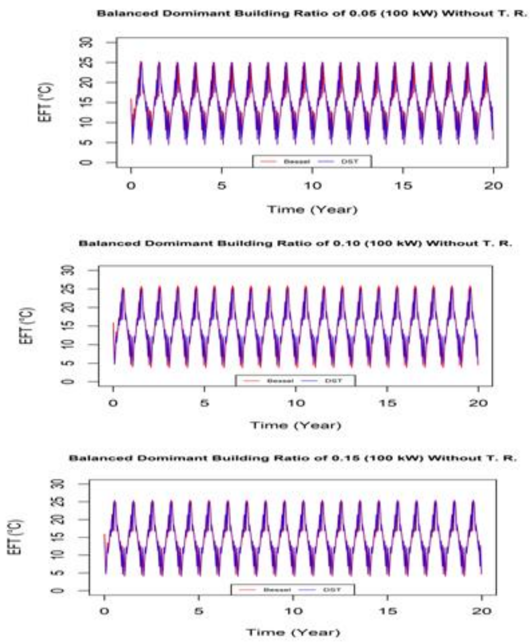
Table6: Average HP Energy for Incomplete Bessel Function vs. Duct Storage model without thermal resistance:

Balanced Dominant Building 500kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min.	Max.	Min. Avg.	Max. Avg.
B/H = 0.05	12.04	18.05	13.18	16.78	11.47	18.19
B/H = 0.10	11.54	17.84	13.01	16.42	11.31	18.01
B/H = 0.15	11.55	17.66	12.92	16.32	11.23	17.98
Cooling Dominant Building 500kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.15	16.34	22.66	17.17	20.61	17.27	24.23
Heating Dominant Building 500kW	EFT "Bessel g-function"		EFT "Eskilson's g-function"		EFT DST	
W/ Thermal R, 152.4mm Dia.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.	Min. Avg.	Max. Avg.
B/H = 0.15	11.82	17.90	8.52	11.98	11.74	17.84

Table7: Entering Fluid Temperature for the three models with thermal resistance

Balanced Dominant Building 500kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.05	246085.97	239883.00	248373.00
B/H = 0.10	250620.56	239577.19	249685.11
B/H = 0.15	248615.84	239813.47	250280.15
Cooling Dominant Building 500kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.15	239586.48	230714.91	244843.41
Heating Dominant Building 500kW	HP Energy "Bessel g-function	HP Energy "Eskilson's g-function	HP Energy DST
W/ Thermal R, 152.4mm Dia.	avg. of 20 year	avg. of 20 year	avg. of 20 year
B/H = 0.15	275841.18	268397.55	279396.97

Table8: Average HP Energy for the three models with thermal resistance



Figures 1-3: Balanced Dominant Building without thermal resistance, with B/H ratios of 0.05, 0.10, and 0.15, and peak load of 100kW

Figures 4-6: Cooling Dominant Building without thermal resistance, with B/H ratios of 0.05, 0.10, and 0.15, and peak load of 100kW
Figures 7-9: Heating Dominant Building without thermal resistance, with B/H ratios of 0.05, 0.10, and 0.15, and peak load of 100kW

Figures 10-12: Balanced Dominant Building with thermal resistance and B/H ratios of 0.05, 0.10, and 0.15, and peak load of 100kW
Figures 13-15: Cooling Dominant Building with thermal resistance and B/H ratios of 0.05, 0.10, and 0.15 and peak load of 100kW
Figures 16-17: Heating Dominant Building with thermal resistance and with B/H ratios of 0.10, and 0.15, and peak load of 100kW
Figures 18-20: Three different building dominant types without thermal resistance, B/H ratio 0.15 and peak load of 500kW

Figures 21-23: Three different building dominant types with thermal resistance, B/H ratio 0.15 and peak load of 500kW

Conclusion

In this article, we proposed a comparison among three models that are Incomplete Bessel Function, DST, and Eskilsons' g-function in an hourly basis over 20 year. TRNSYS and R-Studios were used to simulate and plot the results. EFT versus B/H ratios are different for each building type. It has opposite relationship in cooling dominant buildings and linear relationship in heating dominant buildings, where it is within the same range in balanced dominant building. The average energy consumptions over 20 years are decreasing with increasing B/H ratios.

EFT results for both Incomplete Bessel function and DST are almost the same, where Eskilsons' results are not with 15% to 18% mismatch at 100kW load and 20 boreholes. Also, it is 10% off with 500kW load and 100 boreholes. The differences between Eskilson's model and the other methods reduces in cooling and balanced dominant building with higher loads and B/H ratios. Eskilson's model is more efficient compared to the other models because the average energy consumption over 20 years and EFT variation are less as well.

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