

CFD Simulation Methodology for Ground-Coupled Ventilation System

A comparison of alternative modeling strategies using
computational fluid dynamics

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Abstract

In the past two decades, a growing interest in alternative energy resources as a replacement to the non-renewable resources used now days. These alternatives include geothermal energy which can be used to generate power and reduce the demands on energy used to heat and cool buildings. Ground-coupled ventilation system is one of the many applications of the geothermal energy that have a lot of attention in the early 80's and 90's but all designs of the system where based on single case situations. On the other hand, computational fluid dynamics tools are used to simulate heat and fluid flow in any real life situation. They start to develop rapidly with the fast development of computers and processors. These tools provide a great opportunity to simulate and predict the outcome of most problems with minimum loss and better way to develop new designs. By using these CFD tools in GCV systems designing procedure, energy can be conserved and designs going to be improved.

The main objective of this study is to find and develop a CFD modeling strategy for GCV systems. To accomplish this objective, a case study must be selected, a proper CFD tool chosen, modeling and meshing method determined, and finally running simulations and analyzing results. All factors that affect the performance of GCV should be taken under consideration in that process such as soil, backfill, and pipes thermal properties. Multiple methods of simulation were proposed and compared to determine the best modeling approach.

Contents

Abstract	ii
Contents.....	iii
List of figures.....	v
List of Tables:	vii
1. Chapter one: Introduction	1
1.1 Background knowledge:.....	1
1.2 Heat transfer fundamentals:.....	2
1.3 Research focus:	4
1.4 Hypothesis:	5
1.5 Research Goal and Objectives:	5
2. Chapter two: Methodology	6
2.1 Experimental:.....	6
2.1.1 Identify an as-built GCV system(s) that would most conveniently support the research objectives:.....	6
2.1.2 Data monitoring equipments installation:	9
2.1.3 Soil sample analysis and determination of thermal properties:	12
2.1.4 Temperature samples selection:.....	13
2.2 CFD simulations:	13
2.2.1 Available CFD tools and their characteristics:	13
2.2.2 Test the chosen CFD software:.....	15
2.2.3 Set a Soil Simulation Model.....	16
2.2.4 Setup a base CFD model for the selected GCV system.....	17
2.3 Data analysis:.....	30

3. Chapter three: Results.....	31
3.1 Experimental site monitoring and comparisons results	31
3.2 CFD tools comparative investigation results.....	33
3.3 CFD software testing results	34
3.4 Soil sample simulation results	34
3.5 GCV system modeling methods simulation results.....	36
3.6 Data analysis results.....	43
3.7 Multiple pipes simulation:.....	43
4. Chapter Four: Conclusions	45
Works Cited.....	46

List of figures

Figure 1-1: Schematic image of GCV system-----	1
Figure 1-2: GCV system environment and design factors -----	2
Figure 1-3: Soil temperature distribution as factor of depth (DOE & Tech, 2004) -----	3
Figure 1-4: Schematic heat flow conditions within a GCV system-----	3
Figure 1-5: Issues to be covered in this research-----	4
Figure 2-1: Solar House CM after it's been constructed in 1981 -----	7
Figure 2-2: Vitrified clay pipes used in the Solar House CM's GCV system and the gravel backfill-----	7
Figure 2-3: Schematic drawing of the Solar House CM ground coupled system -----	8
Figure 2-4: 3D shows pipes numbering and the air flow assigned to each one-----	9
Figure 2-5: Air flow control via fans with dampers -----	10
Figure 2-6: Thermocouple located at the inlet of the pipe (right) and the buried below grade (left)-----	10
Figure 2-7: Datalogger setup at site -----	11
Figure 2-8: Thermocouples locations in pipe number 4-----	11
Figure 2-9: Soil samples taken from the site -----	12
Figure 2-10: The internal flow through parallel plates -----	15
Figure 2-11: Soil model with probe location in the CFD -----	16
Figure 2-12: Single pipe set with dimensions -----	17
Figure 2-13: Four pipes set model with dimensions-----	17
Figure 2-14: Regions and surfaces classified in the problem model-----	18
Figure 2-15: Generated mesh for the problem surface and volume-----	19
Figure 2-16: Inflation layers defined within surface mesh-----	19
Figure 2-17: Soil domain faces locations -----	21
Figure 2-18: Solver software during simulation process -----	29
Figure 2-19: Results visualization in post-process-----	30
Figure 3-1: Relationship between air volume and temperature change -----	31
Figure 3-2: 24 Hours period temperature change (10/08/2007)-----	32

Figure 3-3: 24 Hours period temperature change (01/21/2008)-----	32
Figure 3-4: Final results of both analytical and CFD simulation to the internal flow problem -----	34
Figure 3-5: Relationship between site soil temperature and simulation output temperature -----	36
Figure 3-6: Method no. 1 (air turbulence) -----	37
Figure 3-7: Method no. 2 (air turbulence) -----	37
Figure 3-8: Method no. 3 (pipe wall roughness) -----	38
Figure 3-9: Method no. 4 (pipe wall roughness) -----	38
Figure 3-10: Method no. 5 (Backfill thickness)-----	39
Figure 3-11: Method no. 6 (Backfill thickness)-----	39
Figure 3-12: Method no. 7 (Backfill thickness)-----	40
Figure 3-13: Method no. 8 (boundary condition) -----	40
Figure 3-14: Method no. 9 (boundary condition) -----	41
Figure 3-15: Method no. 10 (boundary condition)-----	41
Figure 3-16: Method no. 11 (boundary condition)-----	42
Figure 3-17: Method no. 12 (mixed) -----	42
Figure 3-18: Data outcome of multiple pipes simulation -----	44

List of Tables:

Table 2-1: Temperature samples chosen for the CFD simulation from the monitored experiment site-----	13
Table 2-2: Parameters of the problem-----	15
Table 2-3: Materials thermal properties-----	20
Table 2-4: Air domain boundary conditions definitions -----	21
Table 2-5: Pipes domain boundary conditions definitions -----	21
Table 2-6: Backfill domain boundary conditions definitions -----	21
Table 2-7: Soil domain boundary conditions definitions-----	21
Table 2-8: List of the 12 simulation methods used in this research and their properties -	22
Table 2-9: Method No. 1 (air turbulence)-----	23
Table 2-10: Method No. 2 (air turbulence) -----	23
Table 2-11: Method No. 3 (pipe wall roughness)-----	24
Table 2-12: Method No. 4 (pipe wall roughness)-----	24
Table 2-13: Method No. 5 (backfill thickness)-----	25
Table 2-14: Method No. 6 (backfill thickness)-----	25
Table 2-15: Method No. 7 (backfill thickness)-----	26
Table 2-16: Method No. 8 (soil boundary condition) -----	26
Table 2-17: Method No. 9 (soil boundary condition) -----	27
Table 2-18: Method No. 10 (soil boundary condition)-----	27
Table 2-19: Method No. 11 (soil boundary condition)-----	28
Table 2-20: Method No. 12 (Mixed) -----	28
Table 3-1: CFD software comparisons-----	33
Table 3-2: Results of stage one in soil simulation (in F°)-----	35
Table 3-3: Results of stage two of soil simulation (F°) -----	35
Table 3-4: Method no. 1 (air turbulence) -----	36
Table 3-5: Method no. 2 (air turbulence) -----	37
Table 3-6: Method no. 3 (pipe wall roughness) -----	38
Table 3-7: Method no. 4 (pipe wall roughness)-----	38

Table 3-8: Method no. 5 (Backfill thickness) -----	39
Table 3-9: Method no. 6 (Backfill thickness) -----	39
Table 3-10: Method no. 7 (Backfill thickness) -----	40
Table 3-11: Method no. 8 (boundary condition) -----	40
Table 3-12: Method no. 9 (boundary condition) -----	41
Table 3-13: Method no. 10 (boundary condition) -----	41
Table 3-14: Method no. 11 (boundary condition) -----	42
Table 3-15: Method no. 12 (mixed) -----	42
Table 3-16: Simulation data statistical comparison results via Fisher's LSD means comparison method -----	43
Table 3-17: Multiple pipes simulation run results -----	44

1. Chapter one: Introduction

1.1 Background knowledge:

Ground coupled ventilation systems a relatively new technology, that can save energy by exchanging heat with the soil via circulating air or coolant through a buried coil before introducing it (or re-introduce it) to the conditioned space. Because the ground temperature is much more stable than the air temperature, by exchanging heat with the earth the fluid temperature can be raised in the winter months and lowered in the summer. By taking advantage of the heat exchange between the fluid and the earth the amount of energy needed for final tempering of the fluid is reduced and energy is conserved. A schematic image of the GCV system is shown in Figure 1-1.

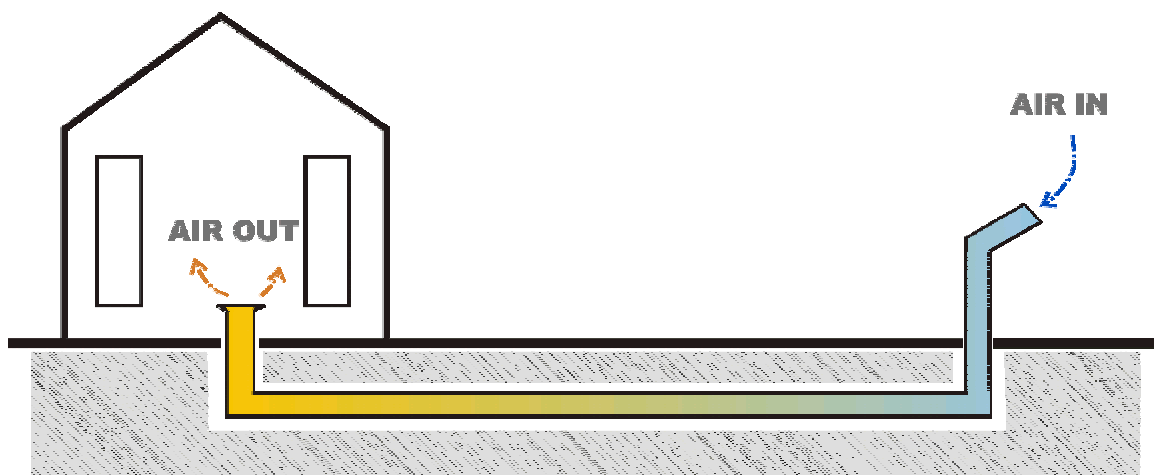


Figure 1-1: Schematic image of GCV system

Although this concept seems rather new indeed the concept was used hundreds of years ago by Thomas Jefferson at Mt. Cello and in the animal kingdom. For example, White ants (termites) build nests with integrated underground tunnels to cool the fresh air before introducing it to the colony's core. As for the residential applications GCV systems were first introduced after WWI and WWII when a group of scientists noticed significant temperature change of the air coming from ventilation tunnels for bunkers built underground. Since then, the system has been undergone several stages of

development which led to the invention of the geothermal heat exchange system that uses water rather than soil as the mediate. Many materials and methods of exchange have been investigated over the past several years but the two most common types are the closed loop system and open loop system. The closed loop circulates air through a heat pump. This system typically has lower efficiency than the open loop system that uses outdoor air directly in the indoor environment directly. Figure 1-2 shows some of the factors that can affect GCV systems efficiency.

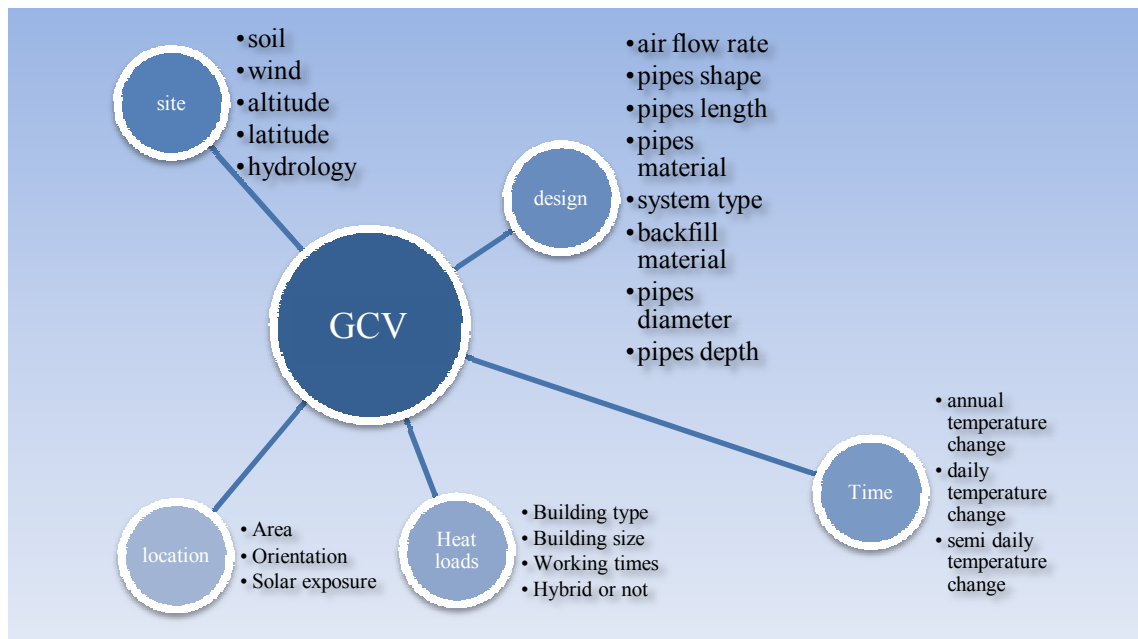


Figure 1-2: GCV system environment and design factors

1.2 Heat transfer fundamentals:

The heat exchange mechanisms associated with this system are fairly well known, convection and conduction, although they are dynamic with time and space. As outdoor ventilation air enters the tube the temperature of the air will be different than that of the soil surrounding the tube, and thus a temperature differential develops across the wall of the tube. As a result of this temperature difference and the flow of air, heat will be exchanged due to convection at the inside surface of the tube. Assuming steady air flow, this heat flow will be dynamic along the length of the tube because: first, the temperature of the air will be changing and second, the temperature of the surrounding soil will be changing. Thus the heat flow situation becomes more complex. As the heat flows by

conduction through the tube wall to the soil and then three-dimensionally through the soil the situation gains complexity. The conduction complexity arises due to: 1) the soil temperature will vary as a function of the depth below grade, 2) the rate of heat exchange from the air to the tube and then to the soil (as will be the case along the length of the tube) and 3) the time-dependent thermal response and time-lag of the soil temperature in response to air temperature and depth as shown in Figure 1-3. The heat flow situation is shown schematically in figure 1-4.

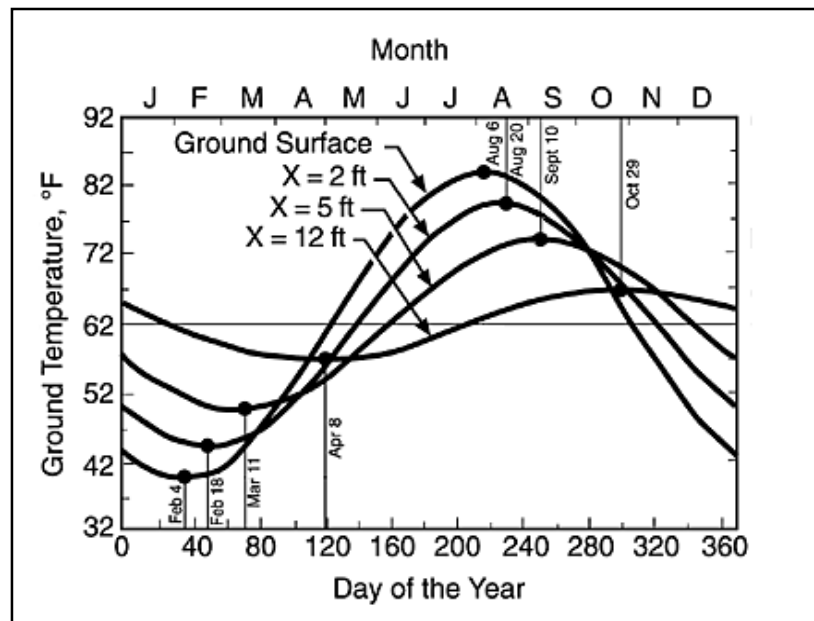


Figure 1-3: Soil temperature distribution as factor of depth (DOE & Tech, 2004)

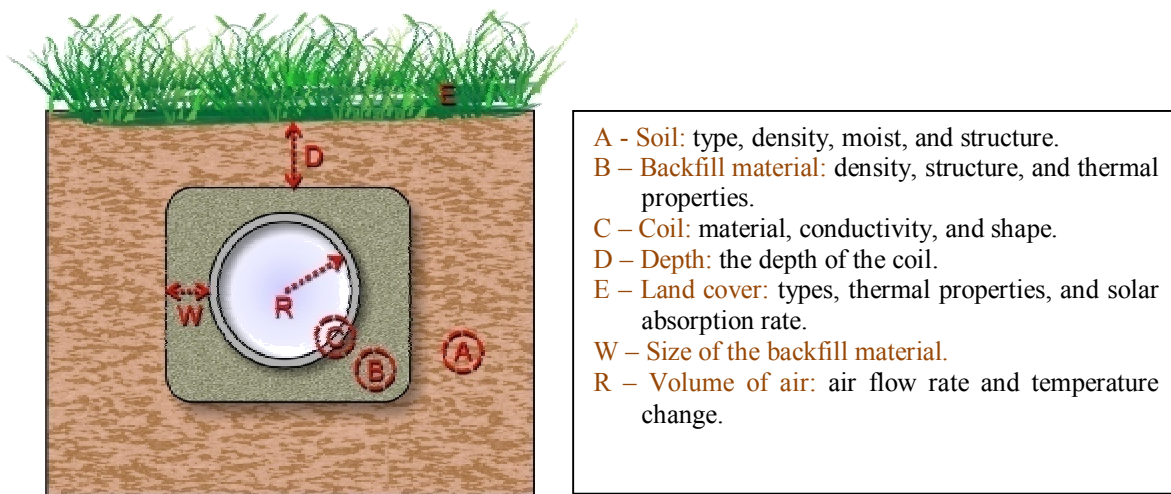


Figure 1-4: Schematic heat flow conditions within a GCV system

1.3 Research focus:

Despite the developments that have occurred for the system components, there have been few studies concerned with the design of the whole system to maximize the efficiency for different types of environmental conditions. None have suggested general guidelines for designing GCV systems. Were the selection of materials, piping method, backfill approach, depth and length of the piping with environment factors. Such variability will affect the overall performance and benefit of the system. While, there have been multiple attempts to apply CFD (Computational Fluid Dynamic) for the design of specific systems there has not been an attempt to use this approach for design guideline development. While CFD might be used to meet this goal it should be applied with careful consideration. This is because what CFD simulators attempt to do is model the behavior of the system in heat transfer and fluid mechanics. A question that then emerges is how well can CFD represent the reality of a GCV system?

There are other issues that could affect GCV system's overall performance such as construction technique, coast limitation, energy demand charges and many more. These factors will not be covered in the focus of this study but are planned to be included in the subsequent work. The main issues are as displayed in Figure 1-5.

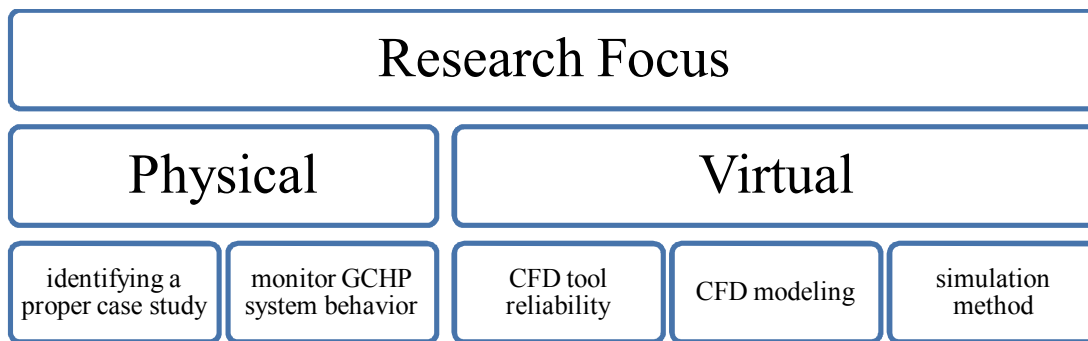


Figure 1-5: Issues to be covered in this research

1.4 Hypothesis:

The performance optimization of GCV systems depends on several location, climate and design variables. CFD maybe a performance evaluation approach to iteratively evaluate the interactions among these variables. This research seeks to test the hypothesis that:

Computational Fluid Dynamics can capture the thermo-physical behavior of GCV systems and a modeling strategy can be developed to accurately simulate an in-site GCV system.

1.5 Research Goal and Objectives:

The purpose of this research is to explore and work with CFD modeling and simulation programs to determine an appropriate approach to modeling. Simulated performance will be compared to measurement data from a full-scale as-built system to determine the accuracy of alternative modeling techniques. The results of this research will be the foundation for a future dissertation to develop design guidelines and rules-of-thumb for estimating the performance of GCV systems over the typical ranges of variables that influence performance. As for this research the goal is to improve our understanding of the thermal behavior of GCV systems.

In order to achieve this goal these tasks were conducted:

1. To explore alternative simulation strategies using CFD and compare the results to field monitored data to determine the “best approach” for modeling a GCV system.
2. To monitor an as-built GCV system, analyze the data for comparison with the simulation results and to better understand the behavior of these systems.

2. Chapter two: Methodology

To test the research hypothesis with a CFD tool there must be a reference point to compare simulation result to it and find the proper method of simulation. This reference could be hypothetical or experimental. Hypothetical reference has the mathematical and physical laws to support it but it may not include all factors affecting the GCV system performance and cause a data bias. On the other hand, experimental monitoring will provide the research with the full spectrum plus it gives an opportunity to study the behavior of the GCV system during the monitoring period.

Research methodology described in this chapter will be under three phases: Experimental, CFD simulations, and data analysis.

2.1 Experimental:

2.1.1 Identify an as-built GCV system(s) that would most conveniently support the research objectives:

The Solar House CM at the Virginia Tech Environmental System Laboratory facility provides an excellent case study for this research. Built in 1980 this building was designed and constructed with a GCV system integrated with the floor and building envelope. The GCV system consists of vitrified clay pipes, gravel backfill and onsite soil. The ground-coupled air circulates through the building envelope without being directly introduced into the space. This GCV system was selected for comparison with the CFD results for the following reasons:

1. It is located on the Virginia Tech Campus and is conveniently accessible.
2. The design and construction of the system is well documented.
3. Because the building is unoccupied the system can be experimentally controlled.

- **System description:**

- **Pipes:** Made of vitrified clay with inner diameter of 7.5 inches and a thickness of 1.5 inch. Each pipe has a total length of 84.4 ft and contains 18 segments. The external ends of the pipes are capped to prevent insects

and pests from entering the pipes. At mid-length there is a joint segment to drain water that may accumulate in the system (see figure 2-3).

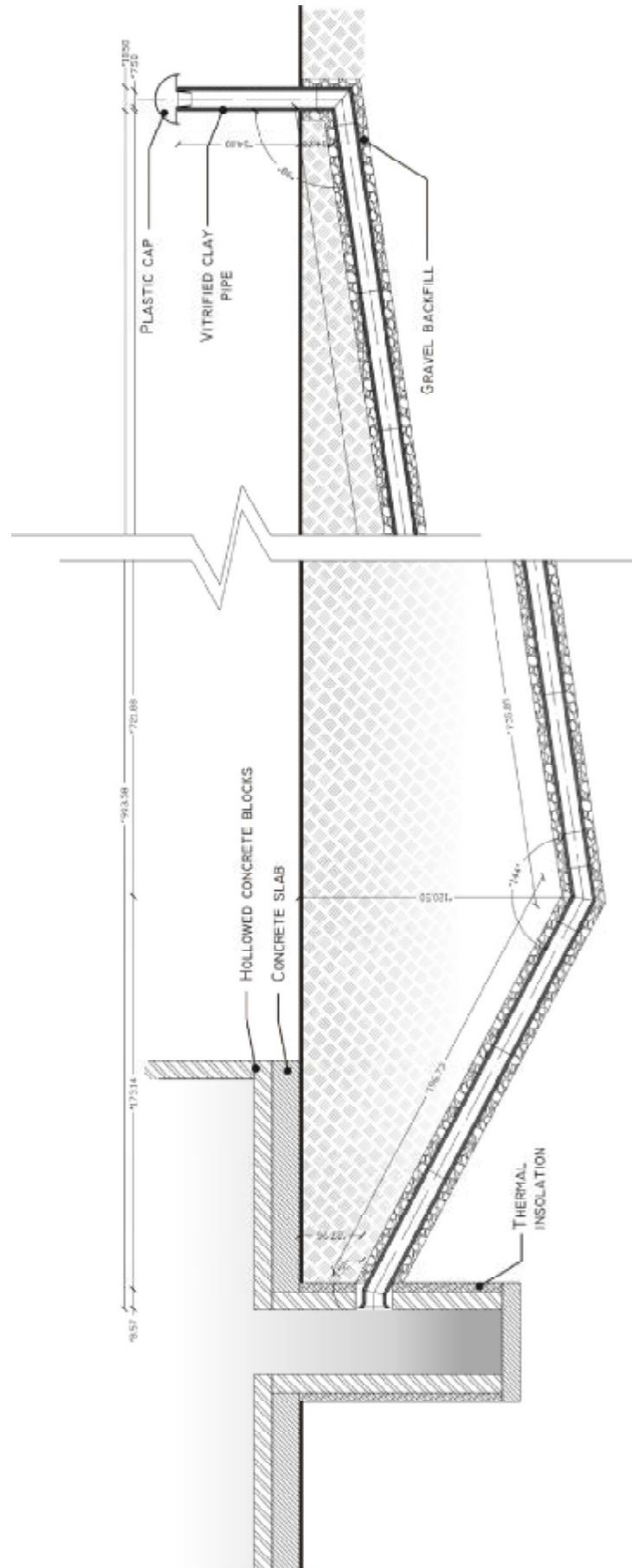
- **Backfill:** Pipes are surrounded with 1 inch average diameter gravel with a thickness between 8 to 12 inches.
- **Soil:** No replacement was made to the onsite soil for this system. Ground cover includes grass and wild weeds.



Figure 2-1: Solar House CM after it's been constructed in 1981 (photo by Robert Schubert, 2007, 1981)



Figure 2-2: Vitrified clay pipes used in the Solar House CM's GCV system and the gravel backfill (photo by Robert Schubert, 2007, 1981)



2.1.2 Data monitoring equipments installation:

One goal of this research was to compare the CFD results to the as-built system for a range of outdoor air temperatures and air flow rates through the system. For this, each of the four ventilation pipes in the as-built system was controlled at a different flow rate. The flow rates were:

- 50 fpm
- 100 fpm
- 150 fpm
- 270 fpm

To experimentally control the flow rate a manifold piping system was installed with flow control dampers. A model 11 Blackhawk variable speed fan was installed and used to control the speed in each pipe. A TSI model 4755 omni-directional air flow transducer connected to a Campbell Scientific model 21x micrologger datalogger was used to monitor air flow rates. A trial-and-error approach was used to set the desired air flow rates in each pipe.

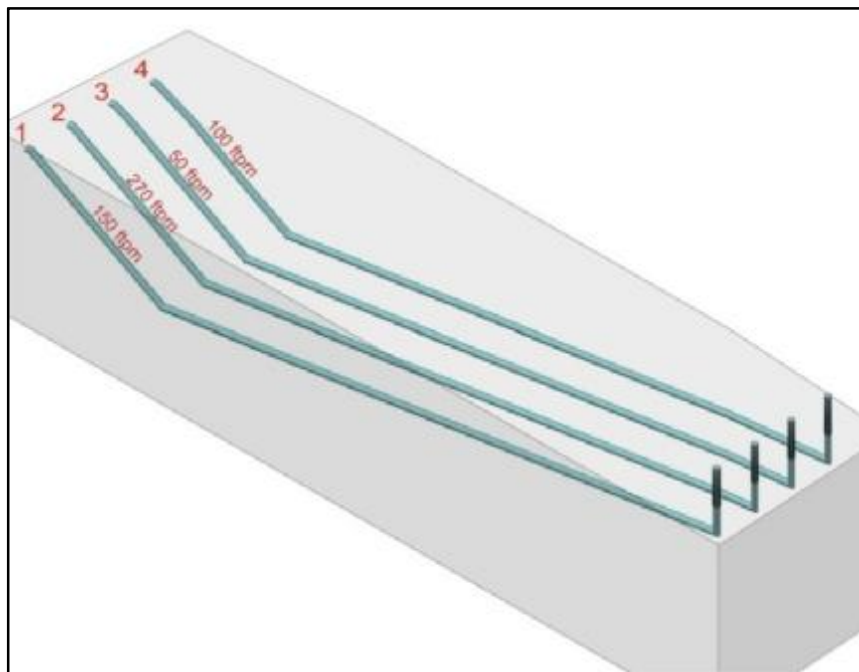


Figure 2-4: 3D shows pipes numbering and the air flow assigned to each one



Figure 2-5: Air flow control via fans with dampers (photo by author, 2008)

Ten copper-constantan thermocouples were selectively located and connected to a Campbell Scientific 21x micrologger datalogger. Eight thermocouples were placed at each end of the four pipes. The other two thermocouples were installed near the middle of the air path in pipe no. 3 and the other was buried 4 feet below grade near mid-length of pipe no.3. Data were gathered for a range of outdoor temperature conditions, at 5 minutes intervals from August 1st 2007 to June 15th 2008. The data were logged and stored in a file for analysis.



Figure 2-6: Thermocouple located at the inlet of the pipe (right) and the buried below grade (left) (photo by author, 2008)



Figure 2-7: Datalogger setup at site (photo by author, 2008)

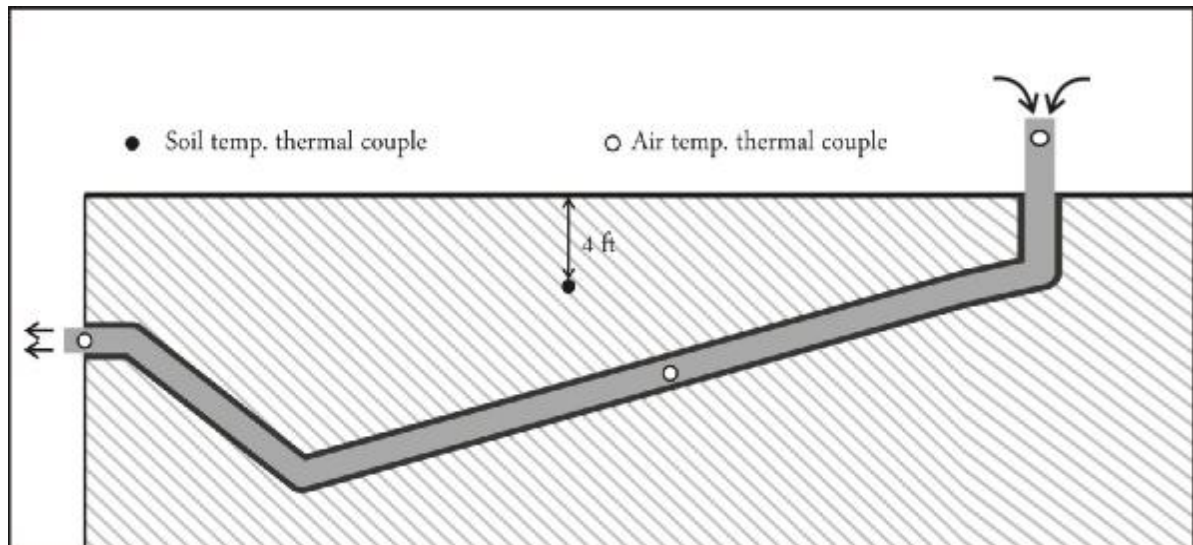


Figure 2-8: Thermocouples locations in pipe number 4

2.1.3 Soil sample analysis and determination of thermal properties:

The thermal properties of the soil can significantly influence the CFD results. The soil thermal properties used in this study are as follows:

- **Type:** Heavy damped with organic components
- **Soil taxonomy:** Ultisols
- **Density** = 150 lb/ft³
- **Thermal conductivity** = 0.75 Btu/ft.F°
- **Specific heat capacity** = 0.75 Btu/lb.F°
- **Thermal diffusivity** = 0.025 ft²/Hr

These values were based on published information from the:

- 1- Virginia Department of Mines, Minerals, and Energy
- 2- The U.S. Department of Energy's, State Energy program
- 3- Virginia Polytechnic Institute and State University

These publications are part of a joint program to promote geothermal and GCHP systems to educational spaces throughout Virginia. The soil type used in this study is classified as “southern Appalachian ridges and valleys soil”. This is mainly a farming and forest soil type.



Figure 2-9: Soil samples taken from the site (photo by author, 2008)

2.1.4 Temperature samples selection:

In order to determine the most accurate method of simulation, 14 samples were selected from the monitored experiment site and fed to the CFD as the initial state of the problem. These selected samples include soil temperature, inlet air temperature, and the outlet temperature (for comparisons). Table 2-1 shows these samples with time and dates.

No.	Year	Day	Time	Surface temp.	Probe temp.	CFD soil temp. at 13.5'
1	07	207	1815	75.5	66.94	53.81
2	07	220	1600	100.7	69.92	54.6
3	07	240	1715	88.7	71.1	55.32
4	07	260	1615	98.89	86.54	65.73
5	07	345	1345	75.6	49.58	76.4
6	07	352	1700	41.8	49.45	85.15
7	08	2	1415	19.51	45.64	89.88
8	08	20	745	9.06	43.05	93.4
9	08	26	1530	40.33	41.49	82.07
10	08	62	1400	65.06	41.51	38.6
11	08	67	1445	35.58	42.39	77.12
12	08	84	1730	53	44.82	43.5
13	08	99	1600	73.1	47.08	44
14	08	109	1445	60.6	49.37	45.8

Table 2-1: Temperature samples chosen for the CFD simulation from the monitored experiment site

2.2 CFD simulations:

2.2.1 Available CFD tools and their characteristics:

In order to select the most appropriate CFD tool for the task, a general comparative investigation was conducted. With the wide variety of CFD software available, choosing the right tool was a task on its own. The criteria used to compare and select the most appropriate software was as follows:

- **Application:** For what application the software intended to serve? What range of applications does it support?
- **Modeling:** How easy is it to create the problem model in the software? Does the software have a user-friendly modeling tool included?
- **Meshing:** Does the software support creating volume meshes for a given problem? What kind of meshing methods does it support and what are the limits?
- **Customizable:** Is the software customizable or not. Can it accept new codes or allow for modifying existing algorithms?
- **Boundary conditions:** Does the software include all essential models of turbulence, radiation, and heat transfer?
- **Processing:** What are the minimum hardware and companion software requirements? What are the CFD tool limitations in processing and solving a problem?
- **Post-simulation:** How does the software present the results of a simulation and in what format? Is there a post-simulation analysis capability included and what can it provide?
- **Supportive elements:** Does the software include libraries for fluids and materials? Can it import and export files in different formats? Are there tutorials included or sold separately? Does it have a user-friendly interface? What kind of licenses the developer offer? Does it have trouble-shooting and support in case of problems?

These were the criteria by which the CFD tools were evaluated. The CFD tools that were considered for this study were:

- Flomerics Flovent™
- Ansys CFX™
- Fluent™
- CFdesign™
- AcuSolve™

These are among most common tools used for fluid flow analysis.

2.2.2 Test the chosen CFD software:

For any CFD tool there must be a sanity check to test the creditability of the simulator. A simple parallel plates problem of 2D internal flow was created (figure 2-10) then solved by both the CFD tool and mathematically with the results compared of both ways.

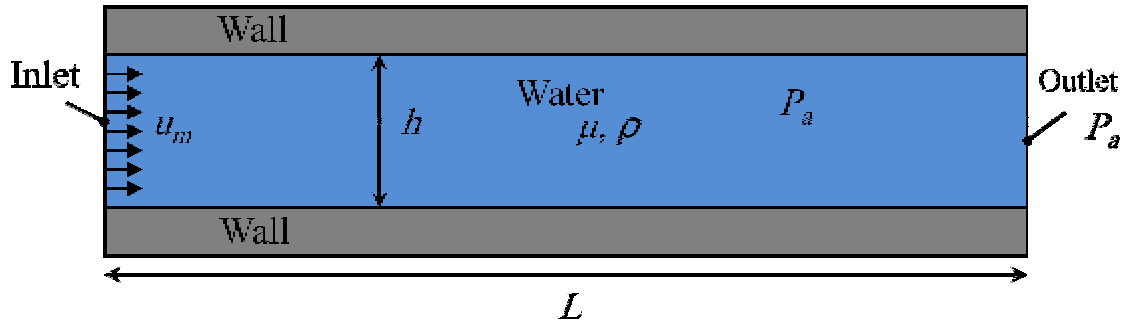


Figure 2-10: The internal flow through parallel plates

Parameter	Symbol	Value
Height	h	10 mm
Length	L	50 mm
Mean velocity	u_m	5 mm/s
Viscosity	μ	8.899E-4 kg/m-s
Density	ρ	997 kg/m ³
Atmospheric pressure	P_a	1 atm

Table 2-2: Parameters of the problem

For this simple problem, the mathematical solution can be achieved by the following equation:

$$u(y) = 6 u_m \left[\left(\frac{y}{h} \right) - \left(\frac{y}{h} \right)^2 \right]$$

2.2.3 Set a Soil Simulation Model

This step was made to insure that the soil simulation process of the CFD soft-ware is accurate according to the data from site. A 3D geometry was created in CAD then imported into CFD software for simulation (see Figure 2-10). After running the simulation with the chosen data from site as initial conditions, a probe was placed to measure temperature at the same location and depth as the site. Comparisons were made between data from site and simulation results and based on that results, a further process will take place to predict temperature of the deep soil layers. Such process will assist the GCV system simulation later.

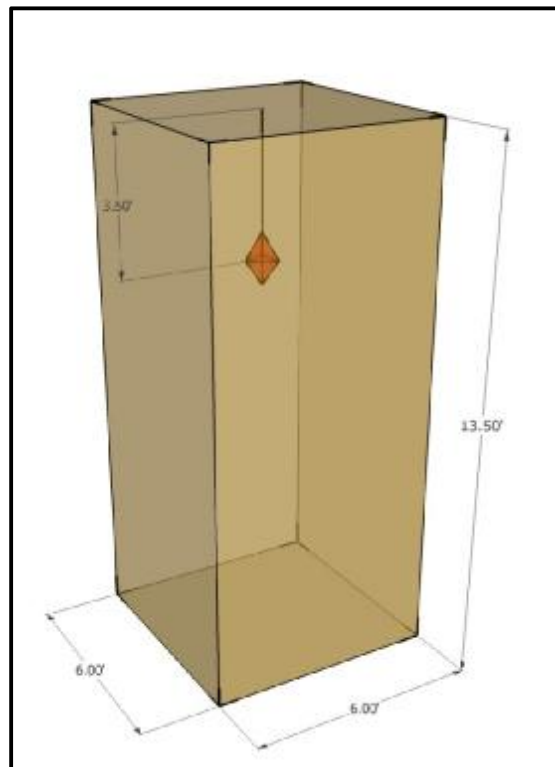


Figure 2-11: Soil model with probe location in the CFD

2.2.4 Setup a base CFD model for the selected GCV system

Setting a model for the selected GCHP system must go through the following procedures:

2.2.4.1. Modeling: By creating the geometry of the problem in CAD software then export it in a 3D format (ACIS Solid Model or SAT) supported by CFD tool used for this purpose. The created geometry includes a single pipe set (Figure 2-11) and a 4 pipes set (Figure 2-12). The reason behind creating the two geometries is to discover whether the heat transferred from soil to air is affected by the function of the other pipes.

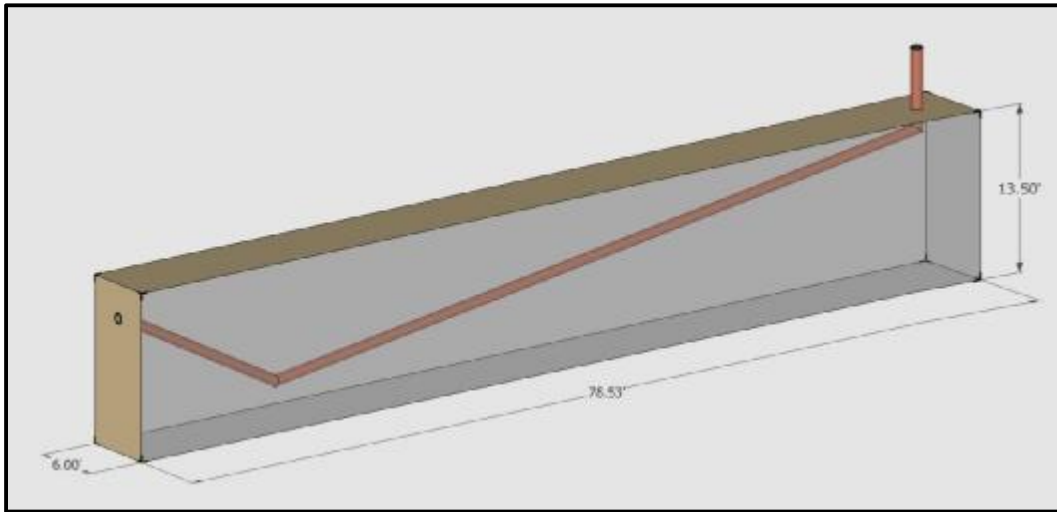


Figure 2-12: Single pipe set with dimensions

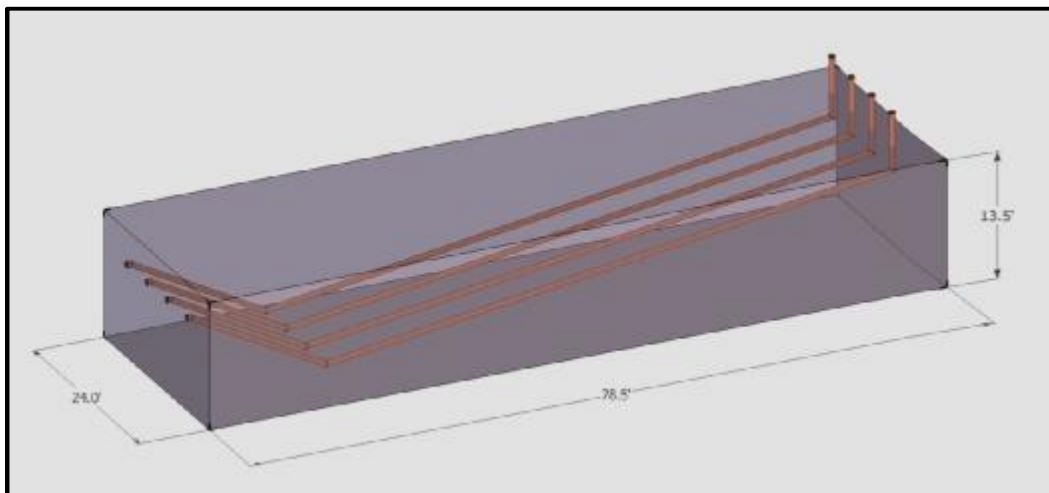


Figure 2-13: Four pipes set model with dimensions

2.2.4.2. Meshing: This step is to define volume mesh of the imported geometries.

This task was performed in the following order:

- a. Import geometry into the CFD file
- b. classify surfaces and regions of the problem (Figure 2-13)
- c. Set the mesh type, size, spacing and inflation¹ layers (Figure 2-14 and Figure 2-15)
 - i. Mesh type: Tetrahedron
 - ii. Face spacing type: Angular resolution at 30°
 - iii. Maximum face spacing length: 10"
 - iv. Minimum face spacing length: 1.5"
 - v. Inflation levels: 5
 - vi. Inflation expansion factor: 1.2
- d. Generate surface and volume mesh
- e. Export mesh file for the next step

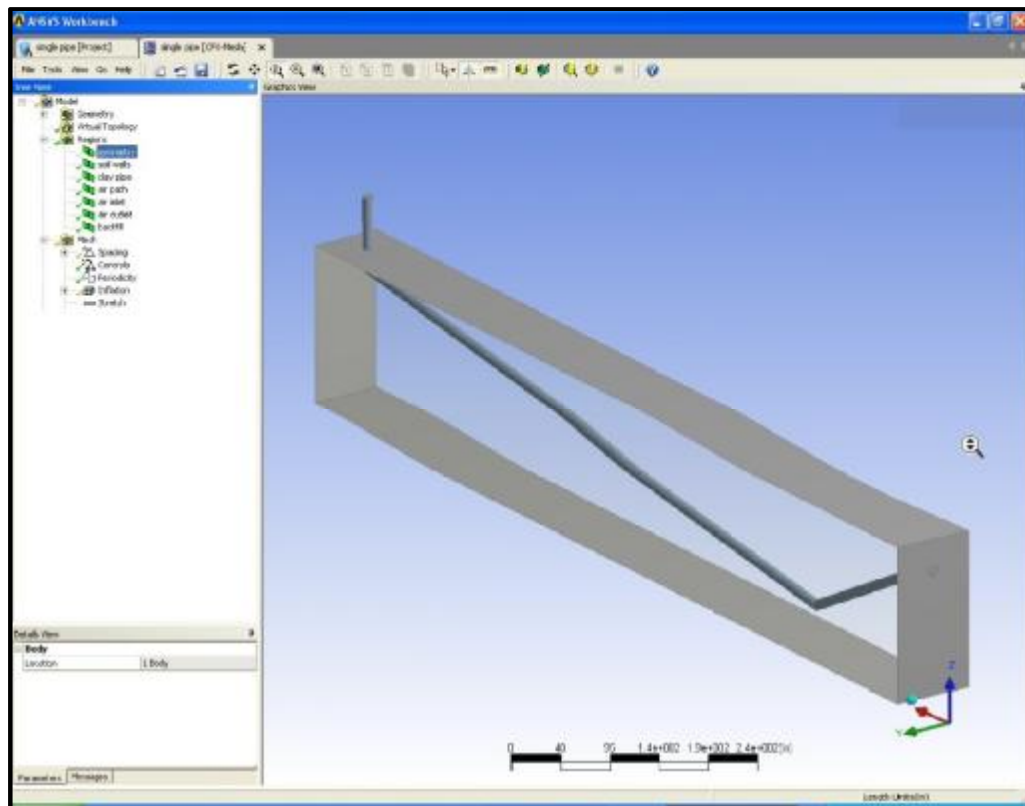


Figure 2-14: Regions and surfaces classified in the problem model

¹ Inflation: a near-wall region mesh. Usually finer, structured and constructed in multiple 2D rectangular levels to simulate better near-surface reactions.

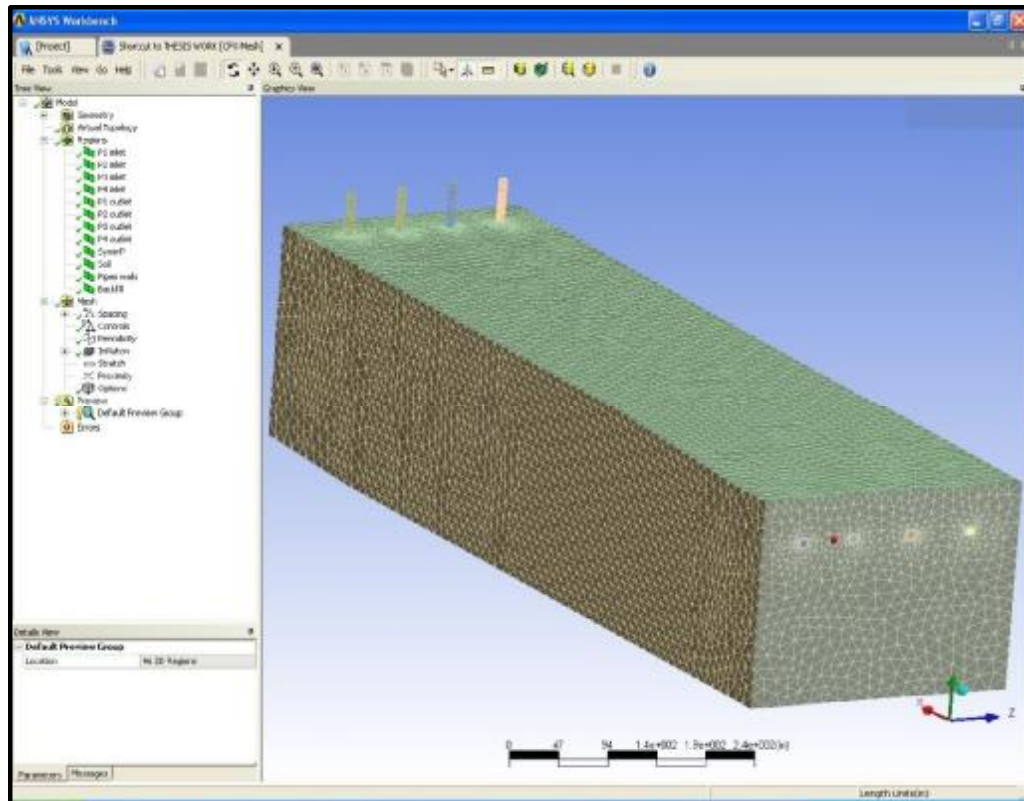


Figure 2-15: Generated mesh for the problem surface and volume

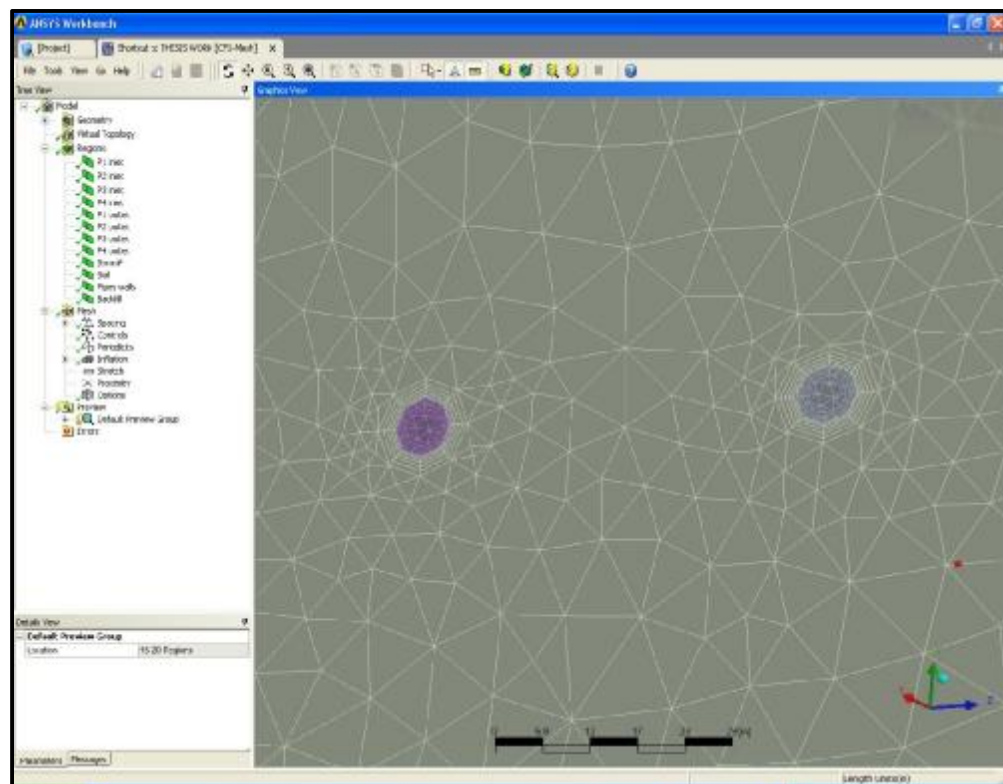


Figure 2-16: Inflation layers defined within surface mesh

2.2.4.3. Problem definition: problem definition is the step where elements of the given geometry are fed into the CFD. These elements such as domains identified, materials assigned, thermal properties defined, and finally inlets and outlets locations are located. The values of the defined elements as follows:

- a. Domains: Soil (solid), pipe (solid), backfill (solid), and air (fluid)
- b. Materials defined: Soil, vitrified clay, gravel, air
- c. Materials thermal properties: see table 2-3

material	Density	Thickness	Thermal conductivity	Thermal diffusivity	specific heat capacity
Soil	150 lb/ft ³	---	0.75 Btu/Ft.F°	0.025 Ft ² /Hr	0.23 Btu/lb.F°
Vitrified clay	2000kg/m ³	1.5"	1.2 W/m*K	0.023 Ft ² /Hr	0.215 Btu/lb.F°
Air (at 25° c)	Default	---	Default	Default	Default
Gravel	2629 kg/m ³	3" – 5" (1")	4.8 W/m*K	---	0.79 kJ/(kg K)

Table 2-3: Materials thermal properties

2.2.4.4. Boundary conditions: boundary conditions and initial state are set to insure proper thermal behavior that matches the existed GCV system (Figure 2-15). Furthermore, these conditions are the main variables in this research and by tuning them the results will vary. The process of defining the initial boundary conditions includes:

- a. Air domain boundary conditions (see table 2-4)
- b. Pipe domain boundary conditions (see table 2-5)
- c. Backfill domain boundary conditions (see table 2-6)
- d. Soil domain boundary conditions (see figure 2-17 and table 2-7)
- e. Linking all domains together
- f. Write the solver file for simulator to process next step

Full name	Air domain	turbulence	Heat transfer	Thermal radiation	Inlet temp.	Inlet pressure	Inlet velocity	Outlet momentum	outlet pressure
Code name	A-	Tu	Ht	TR	InT	InP	InV	OM	OP

Table 2-4: Air domain boundary conditions definitions

Full name	Pipe domain	Initial temp.	Heat transfer	Thermal radiation
Code name	P-	IT	Ht	TR

Table 2-5: Pipes domain boundary conditions definitions

Full name	Backfill domain	Initial temp.	Heat transfer	Thermal radiation
Code name	B-	IT	Ht	TR

Table 2-6: Backfill domain boundary conditions definitions

Full name	Soil domain	Initial temp.	Heat transfer	Thermal radiation	face A heat transfer	face B heat transfer	face C heat transfer	face D heat transfer	face E heat transfer
Code name	S-	IT	Ht	TR	fA	fB	fC	fD	fE

Table 2-7: Soil domain boundary conditions definitions

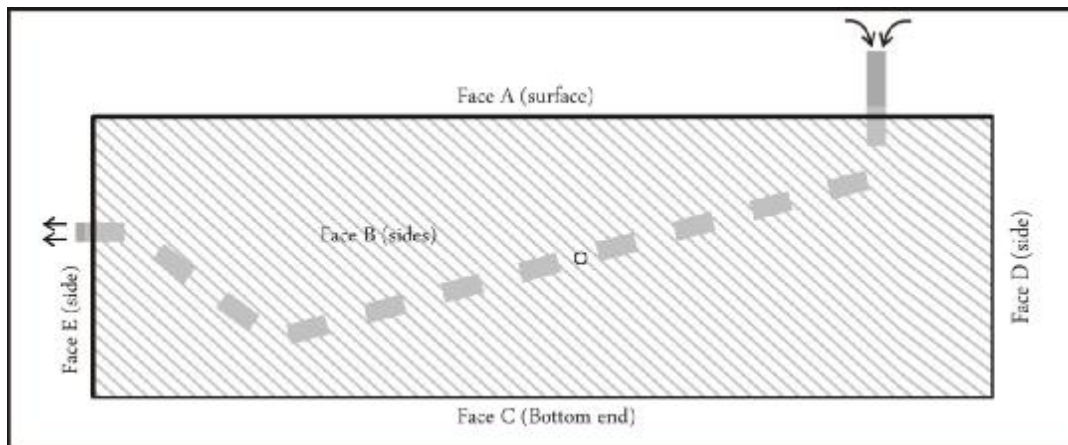


Figure 2-17: Soil domain faces locations

Once the boundary conditions of the problem were identified, multiple simulation methods were created by combining and adjusting these boundary conditions of the four domains. 12 methods were created with 12 different boundaries conditions combinations to determine the most accurate method of simulation. The combinations of these methods are as follows:

Method No.	Subject of interest	Elements under investigation	Number of trials	Table no.
1	Air domain	turbulence model	14	2-9
2	Air domain	turbulence model	14	2-10
3	Pipe domain	walls roughness	14	2-11
4	Pipe domain	walls roughness	14	2-12
5	Backfill domain	thickness	14	2-13
6	Backfill domain	thickness	14	2-14
7	Backfill domain	thickness	14	2-15
8	Soil domain	walls Ht	14	2-16
9	Soil domain	walls Ht	14	2-17
10	Soil domain	walls Ht	14	2-18
11	Soil domain	walls Ht	14	2-19
12	Mixed	mixed	14	2-20

Table 2-8: List of the 12 simulation methods used in this research and their properties

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-9: Method No. 1 (air turbulence)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	k-ε
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-10: Method No. 2 (air turbulence)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Rough → 1mm depth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-11: Method No. 3 (pipe wall roughness)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-12: Method No. 4 (pipe wall roughness)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	8"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-13: Method No. 5 (backfill thickness)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-14: Method No. 6 (backfill thickness)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	12"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-15: Method No. 7 (backfill thickness)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Symmetric
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-16: Method No. 8 (soil boundary condition)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Temperature = from site data (surface temperature)
		fB	Adiabatic
		fC	Adiabatic
		fD	Adiabatic
		fE	Adiabatic

Table 2-17: Method No. 9 (soil boundary condition)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Adiabatic
		fB	Adiabatic
		fC	Temperature = 13.5' depth soil temperature (CFD simulation)
		fD	Adiabatic
		fE	Adiabatic

Table 2-18: Method No. 10 (soil boundary condition)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Temperature = from site data (surface temperature)
		fB	Symmetric
		fC	Temperature = 13.5' depth soil temperature (CFD simulation)
		fD	Adiabatic
		fE	Adiabatic

Table 2-19: Method No. 11 (soil boundary condition)

Boundary conditions	Domain	Elements	Variables
	Air	Tu	Laminar (none)
		Ht	Total energy
		TR	None
		InT	From site data (inlet)
		InP	1 Pa
		InV	100 fpm
		OM	Average static pressure
		OP	Average over whole outlet
	Pipe	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Roughness	Smooth
	Backfill	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		Thickness	10"
	Soil	IT	From site data (soil probe)
		Ht	Thermal energy
		TR	None
		fA	Temperature = from site data (surface temperature)
		fB	Adiabatic
		fC	Temperature = 13.5' depth soil temperature (CFD simulation)
		fD	Adiabatic
		fE	Adiabatic

Table 2-20: Method No. 12 (Mixed)

2.2.4.5. Simulation: This step occurs in the solver program based on the solver file created by previous step. During simulation process the following actions take place:

- Convergence History
 - A graphical progress of root-mean square (RMS) or maximum convergence at each iteration for pressure (P-Mass), momentum (U-Mom, V-Mom, W-Mom), and energy (H-Energy).
- Text Output
 - Numerical summary of convergence at each iteration
 - Simulation parameters summary, final summary of the run
 - Output to text file (*.out)

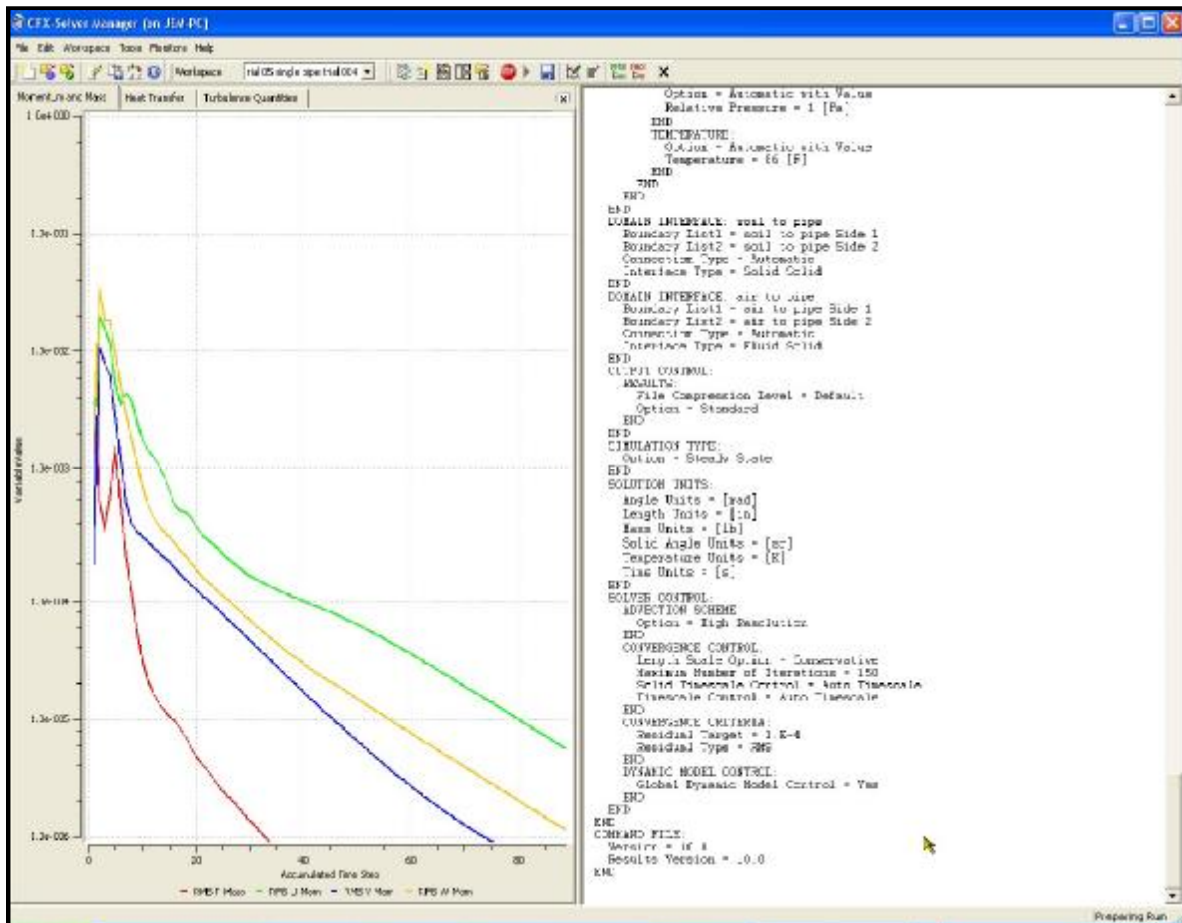


Figure 2-18: Solver software during simulation process

2.2.4.6. View and analyze results: Post-simulation process involves viewing simulation results graphically and numerically (figure 2-19)

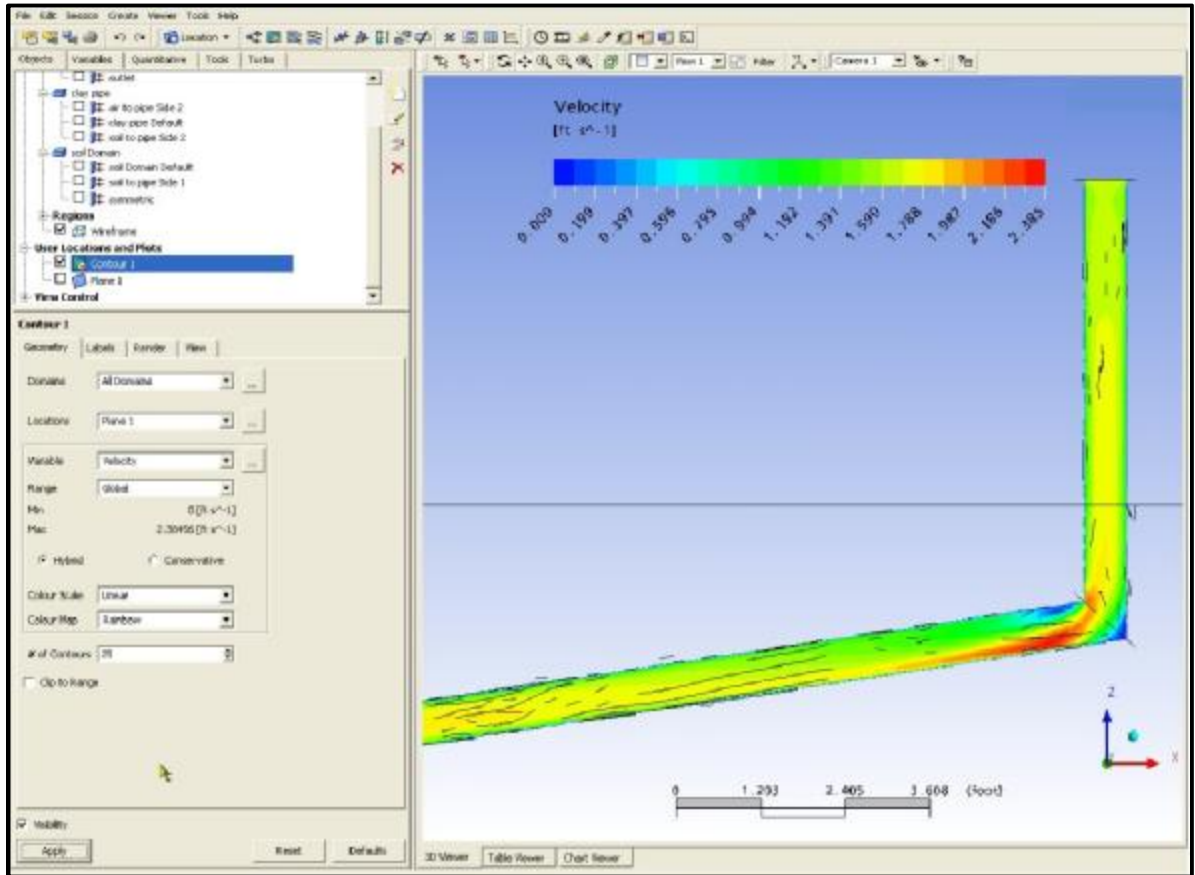


Figure 2-19: Results visualization in post-process

2.3 Data analysis:

Both simulation results and the experiment site data were compared based on statistical multiple means comparison (Fisher's LSD method). With a confidence level of 95% the test was conducted as follows:

Comparison hypothesis: Reject method if

$$|\bar{y}_i - \bar{y}_j| > t_{n-t, \alpha/2} \sqrt{s_w^2 \left(\frac{1}{n_i} + \frac{1}{n_j} \right)}$$

3. Chapter three: Results

This chapter will summarize the outcome of this research under five categories:

1. Experimental site monitoring and comparisons results
2. CFD tools comparative investigation results
3. CFD software testing results
4. Soil sample simulation results
5. GCV system modeling methods simulation results

3.1 Experimental site monitoring and comparisons results

The Solar House CM monitoring results was plotted to confirm the relationship between air volume and temperature change since the linear relationship was in doubt. The reason behind performing these analyses is to have a base ground for the CFD simulation initial states and simulation results calibration. The following graphs states clearly a nonlinear relationship between air volume and temperature change due to time factor, as fast the air passes within the pipes the less time given to exchange heat with the pipe walls. Figure 3-1 shows the temperature deference in the four pipes outlets of a four selected temperatures.

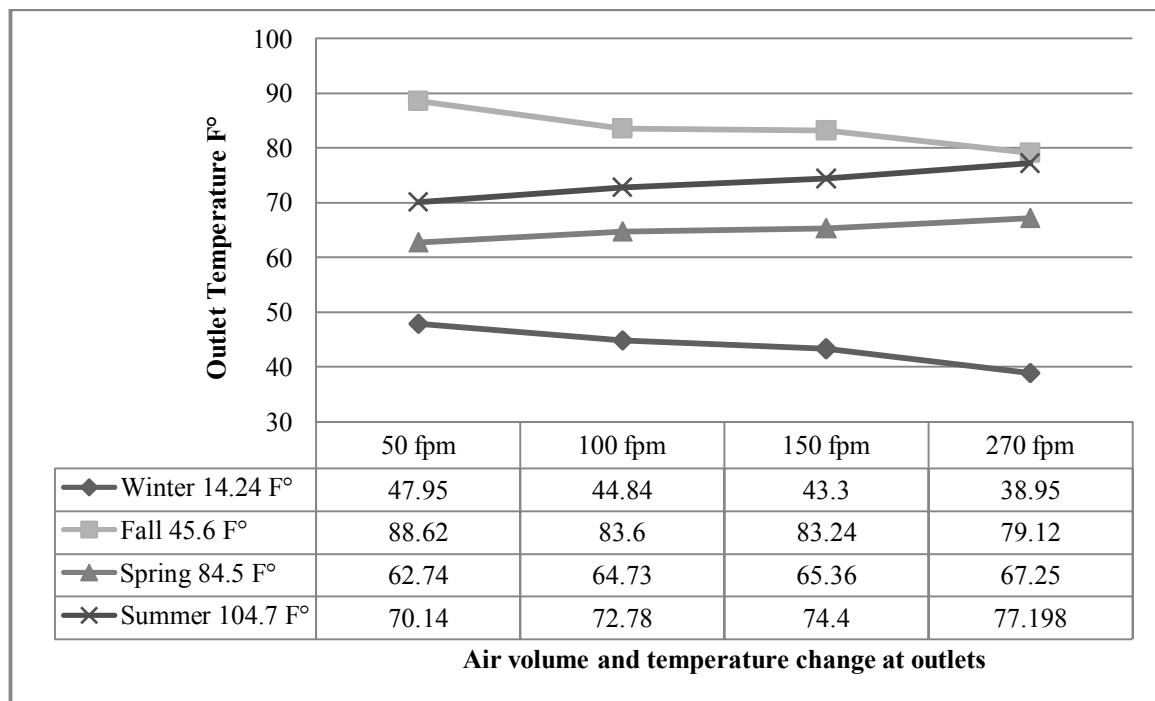


Figure 3-1: Relationship between air volume and temperature change

Figures 3-2 and 3-3 shows temperature change over 24 hour period compared to the inlet temperature and the four outlets of different air volumes of the system.

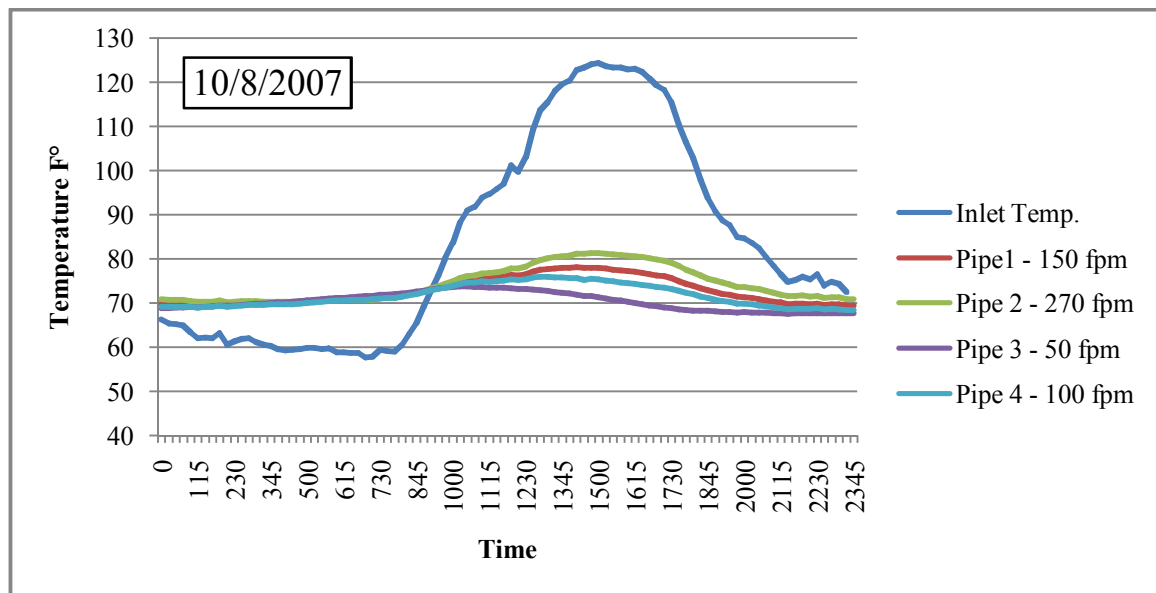


Figure 3-2: 24 Hours period temperature change (10/08/2007)

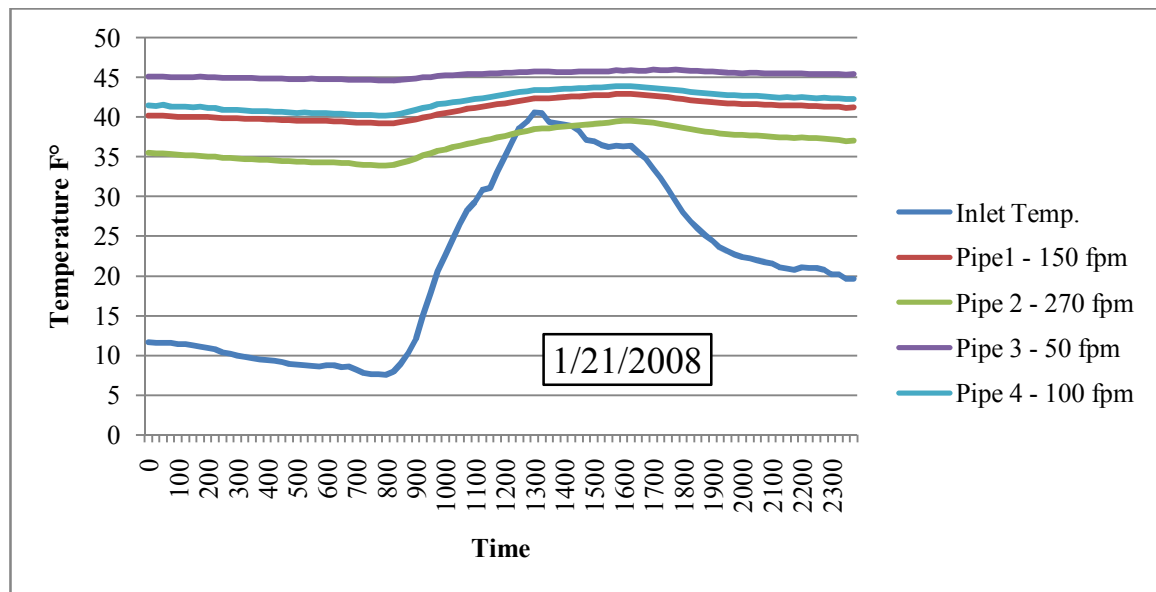


Figure 3-3: 24 Hours period temperature change (01/21/2008)

3.2 CFD tools comparative investigation results

CFD tools that been under investigation for the purpose of this research were compared based on the specifications published by their developers. Table 3-1 shows the compared software and the factors involved in this comparison.














































































		Flomerics Flovent	Ansys CFX	Fluent	CFdesign	ACUSIM AcuSolve
Applications	General					
	Mechanical					
	Chemical					
	Aerospace					
	Architectural					
	Other					
Modeling	Software included					
	Separate bundle					
Meshing method	2D Meshes					
	3D Meshes					
Custom	Add new codes					
	Adjust current codes					
Boundary conditions	Heat transfer					
	Flux					
	Radiation					
	Turbulence					
	Convection					
Misc.	Import/export files formats					
	Library					
	Tutorials					
	Special hardware requirements					

Table 3-1: CFD software comparisons

3.3 CFD software testing results

The results of the CFD software testing were drafted in the figure 3-2 to compare the analytical solution to the CFD final result solved by Ansys CFX.

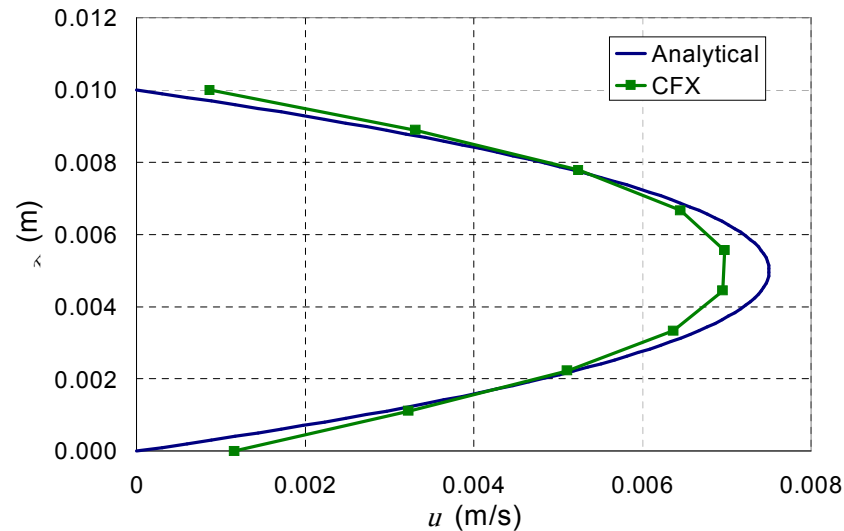


Figure 3-4: Final results of both analytical and CFD simulation to the internal flow problem

3.4 Soil sample simulation results

The simulation of 6' x 6' x 13.5' soil sample was done in two stages, first was in summer time when surface temperature is higher than the body of the soil. Second stage was the prediction stage, when soil body temperature is higher than the surface temperature. The results of the simulation were very close to the readings from site, which confirms the soil thermal properties were given to the simulator to be correct. Furthermore, results of the soil simulation have developed a better understanding of CFD simulation process, soil body thermal behavior and boundary conditions for soil. Tables 3-2 and 3-3 show both stages: successful trials and results.

Trial No.	Year	Day	Time	Soil surface temp.	Soil probe temp.	Boundary conditions				Simulation probe temp.
						Sides Ht	IT	Ht	TR	
1	07	220	1600	100.7	68.69	Adiabatic	61.3	Thermal	None	68.55
2	07	225	1445	94.2	69.92	Adiabatic	61.3	Thermal	None	69.2
3	07	227	1200	85.2	70.2	Adiabatic	62.2	Thermal	None	69.86
4	07	238	1600	93.9	70.8	Adiabatic	66.08	Thermal	None	70.01
5	07	240	1715	88.7	71.1	Adiabatic	66.12	Thermal	None	70.78
6	07	242	1515	90.4	71.3	Adiabatic	66.25	Thermal	None	71
7	07	250	1415	109.86	77.16	Adiabatic	66.71	Thermal	None	75.88
8	07	260	1615	98.89	86.54	Adiabatic	78.08	Thermal	None	85.32
9	07	265	1245	104	89.6	Adiabatic	79.89	Thermal	None	87.6
10	07	288	1530	79.8	66.69	Adiabatic	62.85	Thermal	None	66.04
11	07	293	1600	71.4	65.56	Adiabatic	62.26	Thermal	None	65.82
12	07	294	1530	79.3	65.5	Adiabatic	62.01	Thermal	None	65.91
13	07	308	1500	62.32	61.21	Adiabatic	58.92	Thermal	None	60.89
14	07	309	1600	66.13	60.7	Adiabatic	59.64	Thermal	None	61.3

Table 3-2: Results of stage one in soil simulation (in F°)

No.	Year	Day	Time	Surface temp.	Probe temp.	CFD soil temp. at 13.5'
1	07	207	1815	75.5	66.94	53.81
2	07	220	1600	100.7	69.92	54.6
3	07	240	1715	88.7	71.1	55.32
4	07	260	1615	98.89	86.54	65.73
5	07	345	1345	75.6	49.58	76.4
6	07	352	1700	41.8	49.45	85.15
7	08	2	1415	19.51	45.64	89.88
8	08	20	745	9.06	43.05	93.4
9	08	26	1530	40.33	41.49	82.07
10	08	62	1400	65.06	41.51	38.6
11	08	67	1445	35.58	42.39	77.12
12	08	84	1730	53	44.82	43.5
13	08	99	1600	73.1	47.08	44
14	08	109	1445	60.6	49.37	45.8

Table 3-3: Results of stage two of soil simulation (F°)

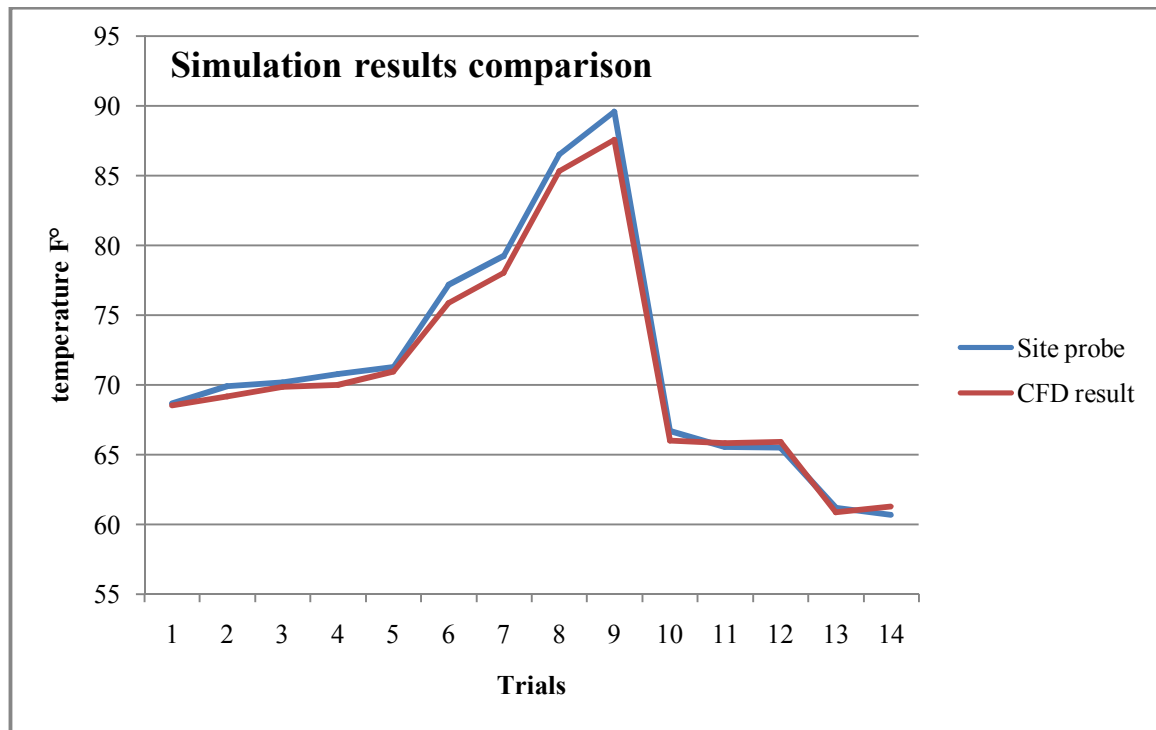


Figure 3-5: Relationship between site soil temperature and simulation output temperature

3.5 GCV system modeling methods simulation results

The results of simulating the GCV system by Ansys CFX were organized, compared and plotted according to the method used for the simulation. Furthermore, all results were based on the same settings used in the soil simulation test previously. The following tables and figures showing the final results from the CFD simulation compared to the data readings from site.

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+ 2	- 6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-4: Method no. 1 (air turbulence)

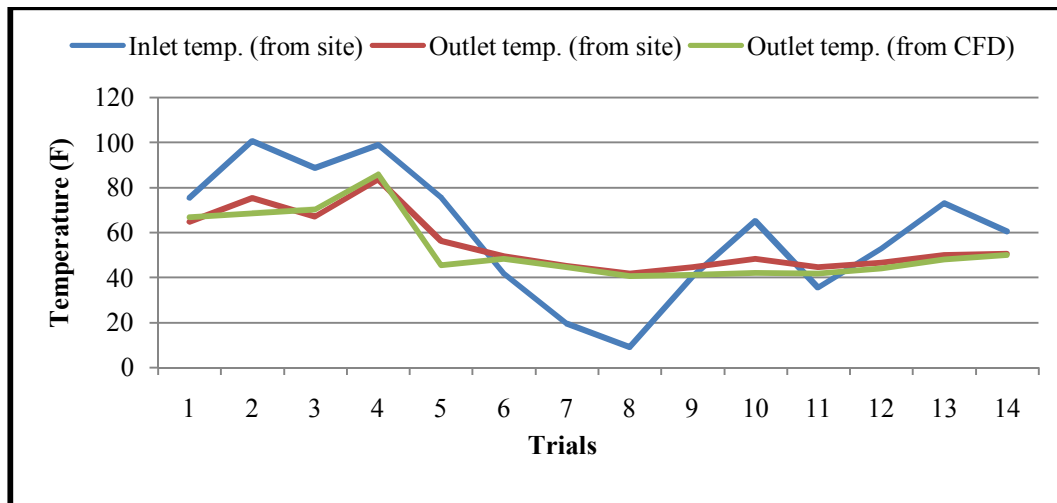


Figure 3-6: Method no. 1 (air turbulence)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+ 2	- 6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-5: Method no. 2 (air turbulence)

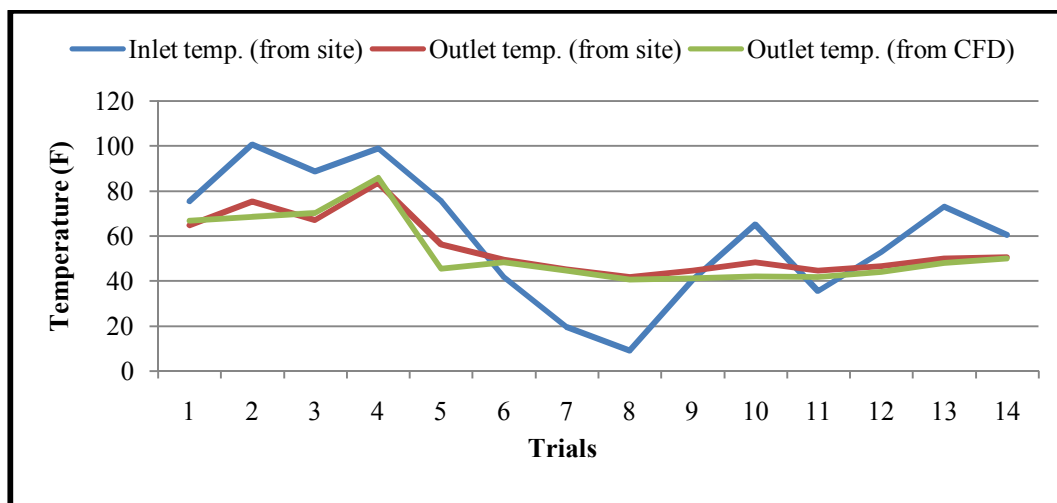


Figure 3-7: Method no. 2 (air turbulence)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+ 2	- 6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-6: Method no. 3 (pipe wall roughness)

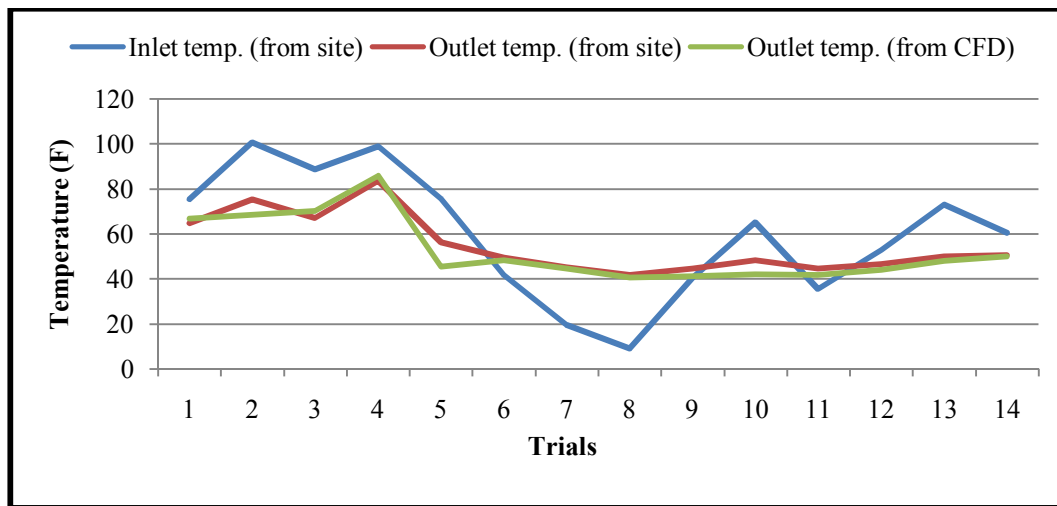


Figure 3-8: Method no. 3 (pipe wall roughness)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+ 2	- 6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-7: Method no. 4 (pipe wall roughness)

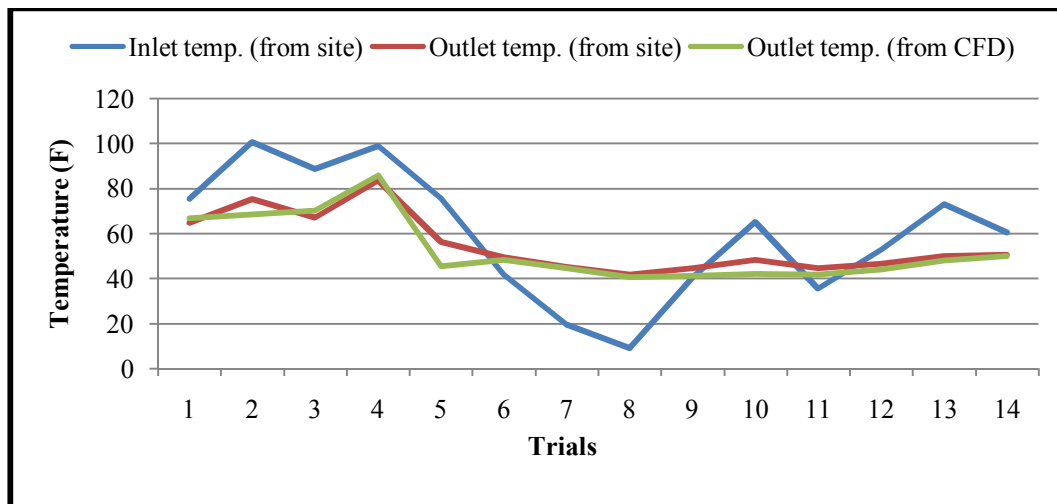


Figure 3-9: Method no. 4 (pipe wall roughness)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.8	70.4	86.1	45.7	48.5	44.6	40.7	41.4	42.2	41.9	44.2	48.2	50.2
Difference	+2	-6.5	+3.2	+2.6	-10.7	-0.9	-0.7	-1.2	-3.2	-6.3	-2.8	-2.6	-2	-0.4

Table 3-8: Method no. 5 (Backfill thickness)

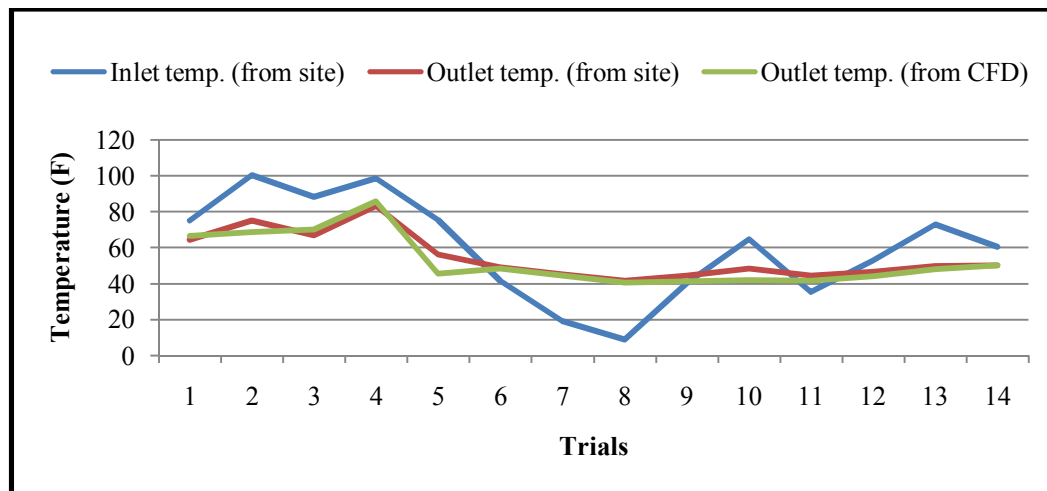


Figure 3-10: Method no. 5 (Backfill thickness)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+ 2	- 6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-9: Method no. 6 (Backfill thickness)

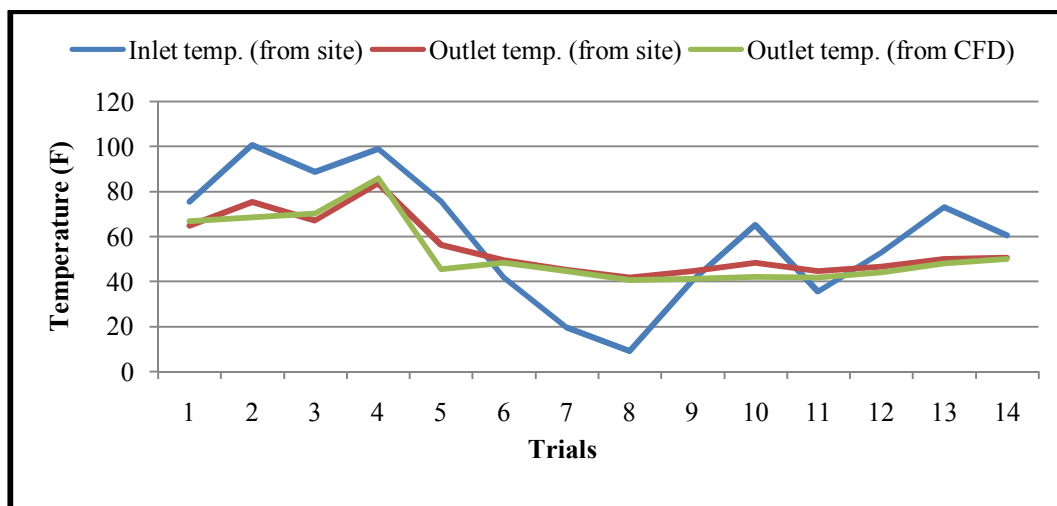


Figure 3-11: Method no. 6 (Backfill thickness)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.8	68.7	70.3	85.9	45.6	48.5	44.6	40.7	41.4	42.1	41.9	44.2	48	50.2
Difference	+2	-6.6	+3.1	+2.4	-10.8	-0.9	-0.7	-1.2	-3.2	-6.4	-2.8	-2.6	-2.2	-0.4

Table 3-10: Method no. 7 (Backfill thickness)

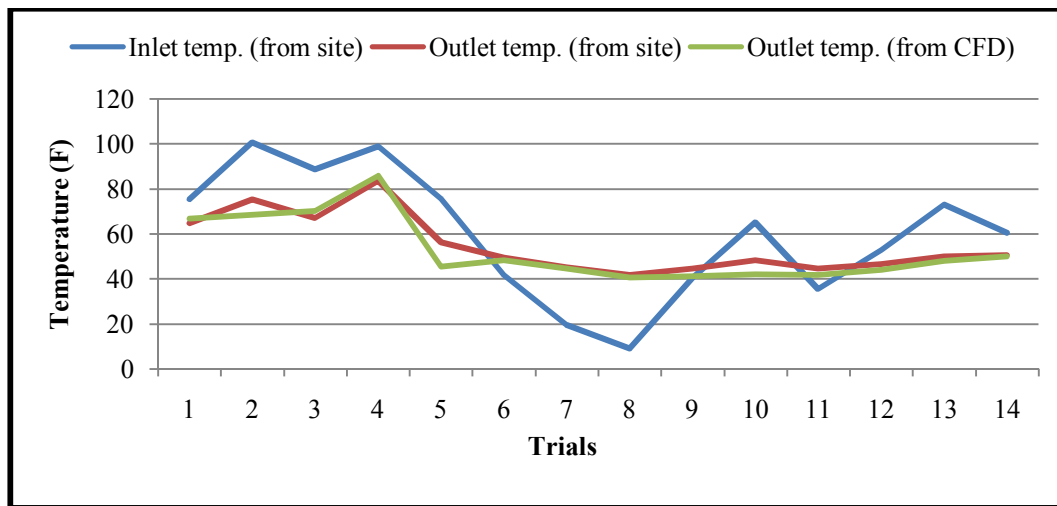


Figure 3-12: Method no. 7 (Backfill thickness)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.7	69.6	73	87.3	50.1	49.4	45.2	40.6	41.3	42.4	41.8	45.3	48.1	50.3
Difference	+1.9	-5.7	+5.8	+3.8	-6.3	0	-0.1	-1	-3.3	-6.1	-2.4	-1.5	-2.1	-0.3

Table 3-11: Method no. 8 (boundary condition)

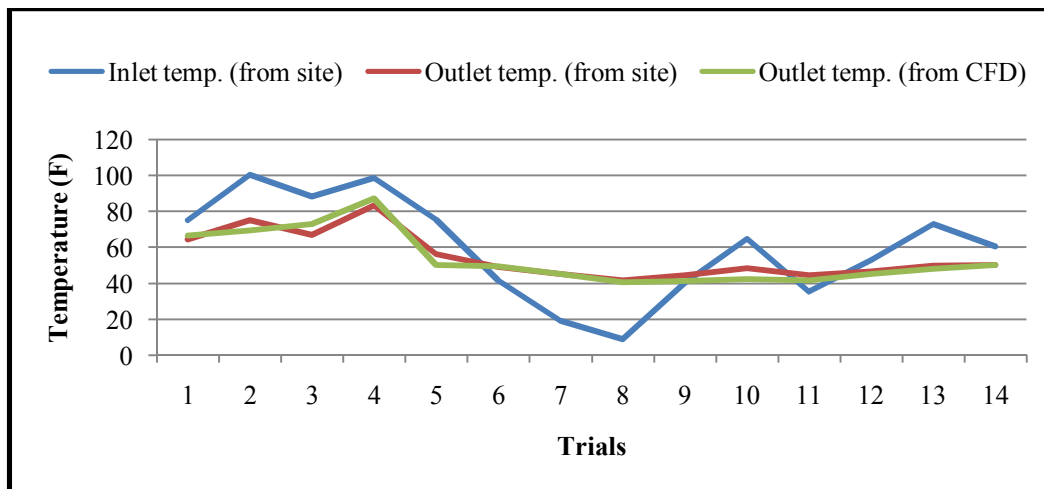


Figure 3-13: Method no. 8 (boundary condition)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	70.7	79.4	78	90.8	56.6	43.5	40.1	31.2	41.1	48.1	41.6	47.2	56.3	52.1
Difference	+5.9	+4.1	+10.8	+7.3	+0.2	-5.9	-5.2	-10.7	-3.5	-0.4	-3.1	+0.4	+6.1	+1.5

Table 3-12: Method no. 9 (boundary condition)

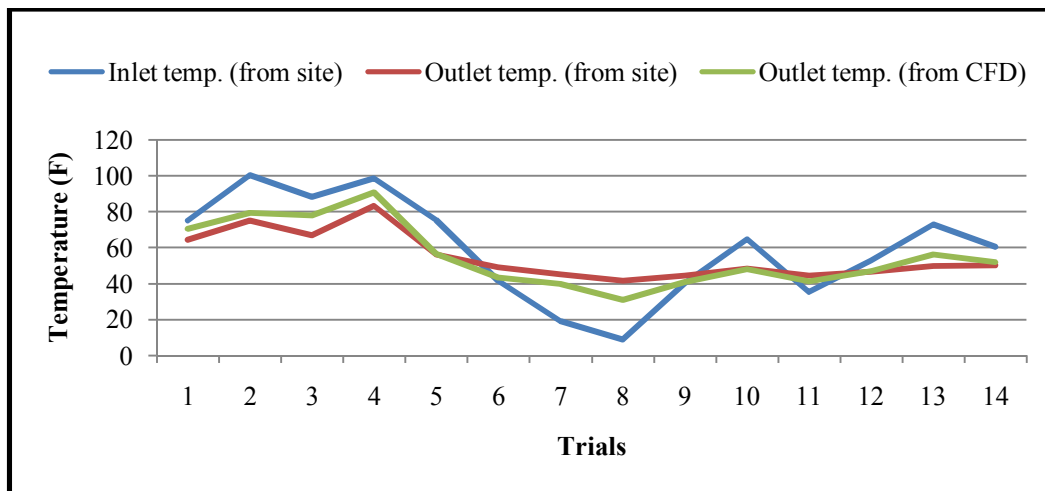


Figure 3-14: Method no. 9 (boundary condition)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	64.5	68.6	62.7	80.8	63.9	59.7	69	68.3	50	40.2	46.5	44.1	45.9	49
Difference	-0.3	-6.7	-4.5	-2.7	+7.5	+10.3	+18.7	+26.4	+5.4	-8.3	+1.8	-2.7	-4.3	-1.6

Table 3-13: Method no. 10 (boundary condition)

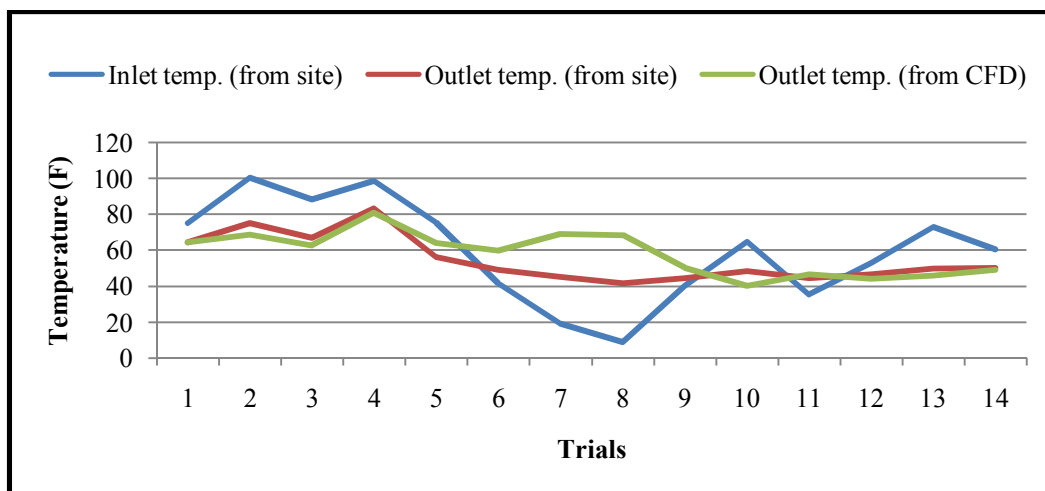


Figure 3-15: Method no. 10 (boundary condition)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	66.7	69.6	73	87.3	50.1	49.4	45.2	40.6	41.3	42.4	41.8	45.3	48.1	50.3
Difference	+1.9	-5.7	+5.8	+3.8	-6.3	0	-0.1	-1	-3.3	-6.1	-2.4	-1.5	-2.1	-0.3

Table 3-14: Method no. 11 (boundary condition)

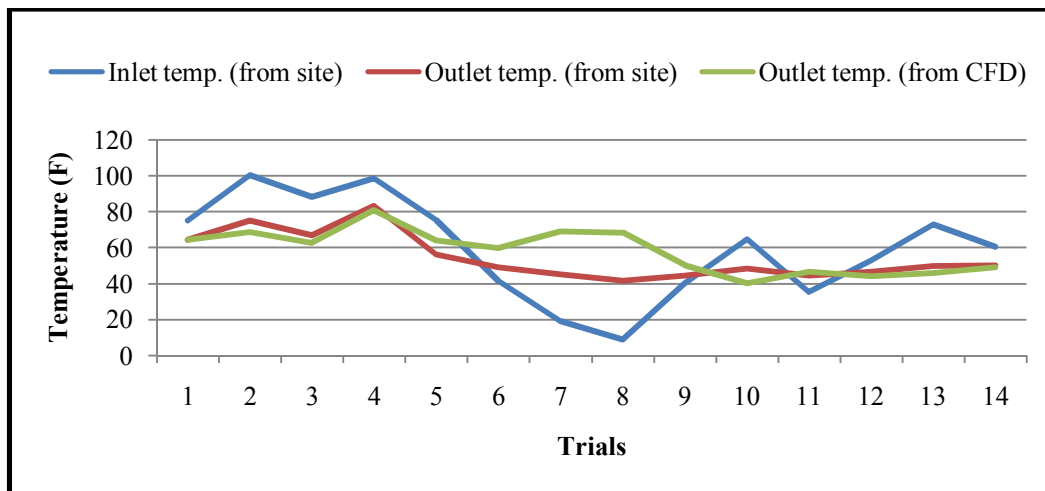


Figure 3-16: Method no. 11 (boundary condition)

Samples >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Inlet temp. (from site)	75.5	100.7	88.7	98.89	75.6	41.8	19.5	9.06	40.3	65.06	35.6	53	73.1	60.6
Outlet temp. (from site)	64.8	75.3	67.2	83.5	56.4	49.4	45.3	41.9	44.6	48.5	44.7	46.8	50.2	50.6
Outlet temp. (from CFD)	65.2	76.1	68.3	83.7	57.6	49.2	46.1	42	44.7	49.4	44.9	47.2	51.1	51.1
Difference	+0.4	+0.8	+1.1	+0.2	+1.2	+0.2	+0.8	+0.1	+0.1	+0.9	+0.2	+0.4	+0.9	+0.5

Table 3-15: Method no. 12 (mixed)

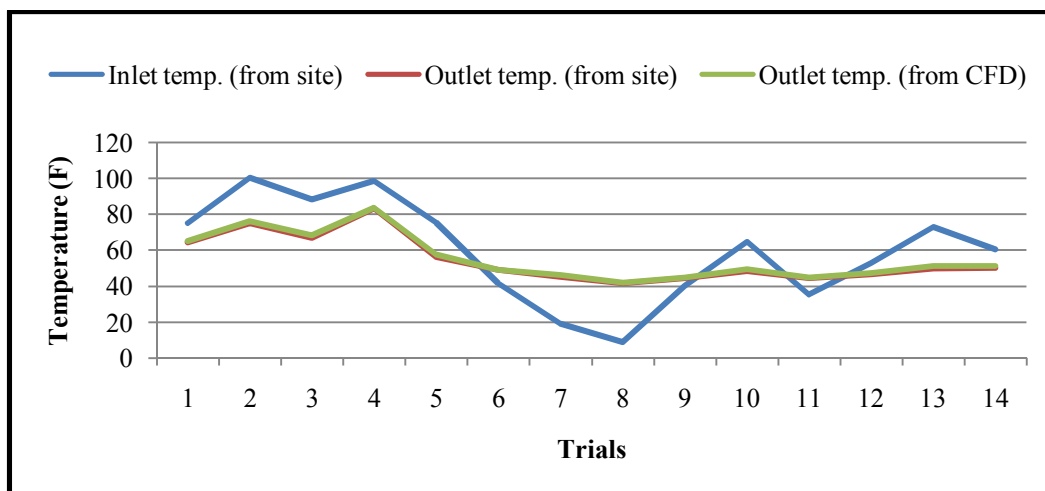


Figure 3-17: Method no. 12 (mixed)

3.6 Data analysis results

In order to determine the best approach in simulation using one of the previous methods a statistical test was made. Based on Fisher's LSD means comparison method the following table shows the results were concluded:

Method	Mean	Hypothesis test result ($ y_i - 55.993 > 1.805$)
1	52.778	Rejected
2	52.778	Rejected
3	52.778	Rejected
4	52.778	Rejected
5	52.835	Rejected
6	52.778	Rejected
7	52.778	Rejected
8	53.65	Rejected
9	55.478	Rejected
10	58.085	Rejected
11	58.085	Rejected
12	55.471	Accepted

Table 3-16: Simulation data statistical comparison results via Fisher's LSD means comparison method

3.7 Multiple pipes simulation:

The purpose of this simulation is to find out if there a significant effect on GCV performance when operating multiple pipes at the same time and the same area. So far, the CFD simulation shows no effect on the performance and/or outcome of these GCV systems on the steady state runs. Table 3-17 shows a comparison between all four pipes simulation results based on the 12th method approach.

Sample no.	Inlet temp.	Pipe 1 (150 fpm)			Pipe 2 (270 fpm)			Pipe 3 (50 fpm)			Pipe 4 (100 fpm)		
		Outlet temp. (from site)	Outlet temp. (from CFD)	Difference	Outlet temp. (from site)	Outlet temp. (from CFD)	Difference	Outlet temp. (from site)	Outlet temp. (from CFD)	Difference	Outlet temp. (from site)	Outlet temp. (from CFD)	Difference
1	75.5	63.9	64.4	+0.5	64.5	65.1	+0.6	64.2	64.6	+0.4	64.8	65.2	+0.4
3	88.7	68.5	69.6	+1.1	70.6	71.9	+1.3	64.9	65.9	+1.0	67.2	68.3	+1.1
6	41.8	48.7	49	+0.3	46.2	46.7	+0.5	51.1	51.3	+0.2	49.4	49.2	+0.2
8	9.06	40.7	40.8	+0.1	36.1	36.3	+0.2	45.4	45.4	0	41.9	42	+0.1
11	35.6	44.2	44.5	+0.3	43	43.4	+0.4	44.9	45.1	+0.2	44.7	44.9	+0.2

Table 3-17: Multiple pipes simulation run results

The table indicates no significant change on the outcome of pipe no. 3 even after the model has been simulated with other pipes operating simultaneously. Furthermore, the difference between the outcomes of all four pipes and the data gathered from site prove the simulation method success with different air velocity fed to the inlet.

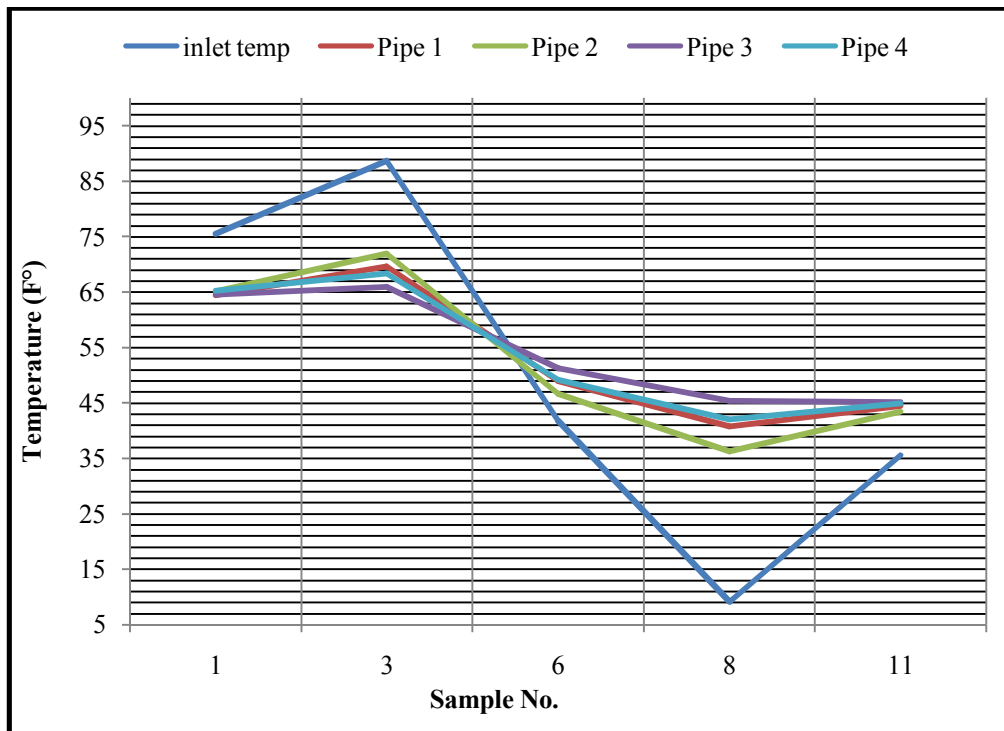


Figure 3-18: Data outcome of multiple pipes simulation

4. Chapter Four: Conclusions

This research was conducted to develop the best approach of simulation for GCV systems through CFD tools. All contributing factors to the GCV system performance were taken under consideration in the modeling and solving phases. The main model of CFD simulation was digital imitation to the GCV system of Virginia Tech Solar House CM (1981) Blacksburg, VA. From the results of each step performed in this research, the following can be concluded:

- **Solar house monitoring:** results confirm that the relationship between heat transfer and air velocity is a non-linear relationship. Furthermore, the slower air passes through the system pipes the higher temperature change occur.
- **CFD tools investigation:** for available CFD tools in the market, basic and through comparison suggest using Ansys CFX as primary candidate for this research purposes. This software has all needed components to perform all required elements in this research.
- **Soil sample simulation:** first phase of soil simulation run proved the accuracy of soil thermal properties claimed by the U.S Department Of Energy. Next phase was made to predict the soil body temperature based on data from the Solar House. These predictions are essential for the main GCV simulation later.
- **Single pipe simulation:** the results of simulating 14 samples by twelve different methods provide a clear evidence of the delicacy of soil domain temperature initial setting and how it affects the results. The 12th method was proved to be the best approach to simulate the GCV system and that is the main objective of this research. This method includes non-turbulent air flow at 100 fpm, smooth pipe surface, a 4" backfill thickness, soil surface temperature taken from site and finally, soil temperature at 13.5' taken from soil sample simulation.
- **Multiple pipes simulation:** the effect of simulating multiple pipes per model in a steady-state method shows no effect on the outcome of each pipe simulated in this model.

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