Project 3 - District Heating

Computational Heat Transfer, TMMV54

Bharath Kumar Kuna (bhaku277)

Kunal Muralidharan (kunmu664)

Yuvarajendra Anjaneya Reddy (yuvan983)

LINKÖPINGS UNIVERSITET

Linköping university
Division of Applied Thermodynamics and Fluid Mechanics
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1 Introduction

District heating (DH) by definition is referred to as a system that is being used for distributing heat for the commercial structures and the residential buildings or any other human made infrastructures that has the necessity for water heating or space heating through a system of insulated pipes in particular. The technique here is to generate heat energy in a remote place away from the consumers and supply the generated heat through hot water that is supplied by the pipes that are laid beneath the ground. The colder water from the consumers after utilization of the heat is transported back via the pipes to the heat source where it gets heated again and the process repeats.

District heating is considered to be a more sustainable approach of space heating and water heating than having a mobile heating source for each infrastructure making them avoid unnecessary structures and space. Using a District heating system instead of the alternatives is more efficient in terms of energy generation and consumption, as it takes advantage of resources that are considered to be of no potential use.[1] DH systems are the community energy systems which can provide long-term achievements in terms of greenhouse gas emission reductions thereby directly influencing global warming, reliable energy source, local economic development in small scales. Energy efficiency increases and exploitation of renewable energy resources is reduced.[2]

A District heating system comprises of heating source, piping layout and optionally a cooling service (by making use of methods and technologies like combined heat and power plant (CHP)), additional heat pumps, thermal storage units , geothermal and a source of renewable energy (hot geyser springs, biomass heat generators, solar heating panels, etc). [3]

1.1 Drawbacks

There are many problems and bottlenecks associated with the DH systems that hinder the efficiency and the performance in delivering the heat energy. Some of them are the competition from other heating production techniques, limited generation of heat energy from the source, losses from the piping layout and pipe dimensions. These problems can be solved by improvising the current systems or inculcating new alternate heat generating techniques or sources into the system. Using alternative heat generation techniques or Prosumers in the network comes with a limitation of lower operating temperatures, as increasing the operating temperatures would decrease their efficiencies. However, lower operating temperatures in the system would be more prone to the bottle necks like huge pressure drops.[4]

2 Aim

This project focuses on the case study of the influence of the piping layouts, particularly the pattern in which the pipes are laid out for the purpose of space heating of the football stadium. A simplified model of the DH network is considered here that consists of an industry, a football stadium and residential housings with a constant mass flow rate of water in the pipes. The football stadium is modeled in detail, whereas the industry and the residential housings are modeled as the heat sinks with a constant heat demand, though the demand varies every day or based on the certain period of the year. **Three different patterns of the underground heating pipes are studied here**. Stationary study is performed here over the transient study for the purpose of simplification.

3 Method

In this section a brief overview of the study performed on the District Heating system is described. The focus is mainly on to the Swedish district heating networks, from which certain parameters are considered from the experimental studies performed previously. Of all the regions in that use DH networks, European Union, China and Russia accounts to 85 % of the whole.[5]. In Sweden, about 57 % of the entire heat and hot water demand and roughly 90 % of the residential housings are heated by the District heating systems. An average of more than 60% of district heating is produced from the biomass, which has organic waste in it. Other heating resources include heat from the heat pumps and waste heat.[6]

3.1 District Heating system simplifications

The heat demand from the customers of the DH system is closely related to the outdoor ambient temperatures. These requirements vary throughout the year as the seasons change. In this case study the DH system is considered to be operative in Sweden as mentioned earlier. In Sweden, the major necessity for the DH system is in the winter and the least is during the summer especially for the space heating purposes. The inlet temperature of the water that leaves from the source of heat generation is taken to be pf 70 [degC] in summer and 120 [degC] in winter.[7] The simple network of the district heating system here consists of a piping layout for the transport of water, industry, football stadium and residential buildings. The heat generation plant is excluded in the model. The heat demand for the residential buildings are at peaks in the mornings between 7-9 0' clock, in the evenings between 20-22 o' clock and space heating necessities may be high during the winters and early autumn. For the football stadium DH demand for space heating is based on the season which is quite unpredictable from the empirical data. And for the Industry, the heat requirement is pretty much constant throughout the year, considering them to be inoperative in the summers, in the months of June, July and August.[7]

As the main focus of this report is to study the influence of the piping pattern for the space heating of the football stadium, the heat requirements are set as constant heat fluxes throughout the year, with no variations.The inlet temperature of the water is set to be 120 [degC], implying winter condition. The mass flow rate of the warm and cool water flowing through the entry and return pipes is also considered to be a constant of about 15 [Kg/s]. Prosumers like solar heat plate collector, geothermal energy generation are not modeled as they would add up to the complications in modelling and setting up the boundary conditions.

A typical DH system consists of four independent control systems for the smooth functioning and to have a check on the bottleneck problems. The customer has heat demand control (taps and thermostatic valves) and flow control (substation control valves). The operator has the supply temperature control and the differential pressure control on his end to ensure control over the DH network. These control systems are eliminated from the system here and are set as the flow parameters in the COMSOL Multiphysics 5.5 software where the simulation is set up.

Input Variables	Value	Units
Supply Pipe Diameter	0.75	m
Football field pipe diameter	0.15	m
Depth of Football Field	0.3	m
Humidity	1	
Heat transfer Coefficient of Ground	3000	W/(m^{2}.k)
Heat demand industry	80	KW
Heat demand per house	2	KW
Density of Sand	1742	Kg/m^{3}
Thermal Conductivity Sand	1.5	W/(m*K)
Specific Heat Capacity Sand	1175	J/(kg*K)

Table 1: Geometric Details and Properties [1], [6]

3.2 Geometric model of the simplified District Heating system

There are mainly two different ways in which the district heating system is laid out. They are the indirect connection and the direct connection, represented in **Fig.1** implying the connection between the individual heat sources, sinks and other components as cited in the thesis report based on the DH networks.[4]. The indirect connection has a hydraulic separation between the heat source and the heat consuming components, which is known as the substation that indeed acts as heat exchanger. This has the advantage of regulating the flow rate and the differential pressure thereby possibly avoiding the effects of bottlenecks.

Figure 1: Indirect and Direct connections of the DH network, referred from [4]

However, this indirect connection is expensive compared to the direct system where the components are directly connected to the heat generating source. Also, there can be chances of losing some amount of heat in the heat exchanger or the substation that is unnecessary. Though, the indirect connection is most common in Sweden, here the direct connection is modelled prioritising the football field piping layout. The substation is generally located at the consumer end, which are owned by the consumers.

The geometry of the DH network is built in the COMSOL Multiphysics 5.5 software. The pipes are modelled as one dimensional lines, for the both warm and cool water pipes. The pipes for space heating of the football stadium are also modelled as one dimensional pipes. The industry and the residential buildings are modelled as two dimensional structures, that are U-shaped and unclosed as shown in the **Fig.2**. These are then specified with certain values of heat flux mimicking the heat consumption (heat sinks). The football ground which is of prime importance is modelled as a three-dimensional domain, where the two-dimensional rectangle is extended in either directions enclosing the heating pipes laid out in a particular pattern.

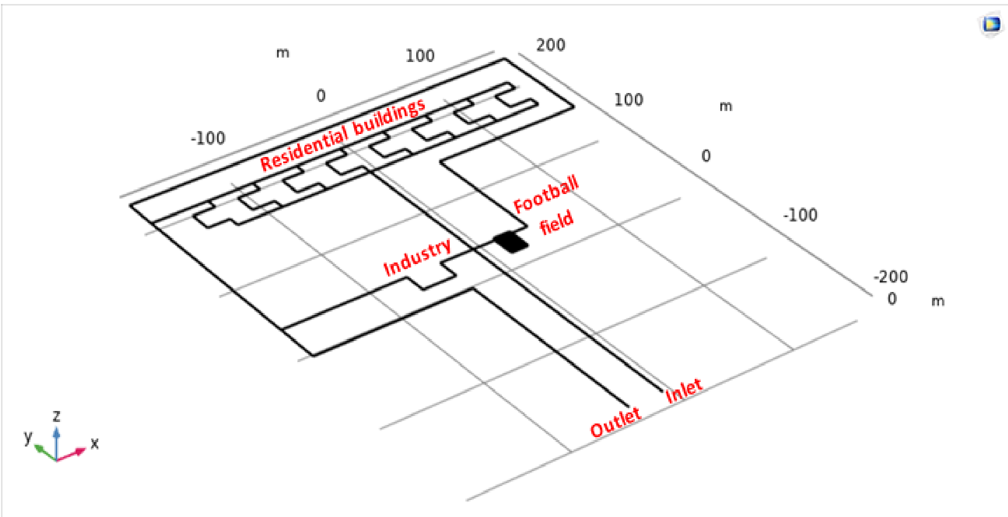


Figure 2: Simplified district heating model

The actual district heating network is operative from several metres to hundreds of kilometers. Here for the purpose of simplification, the whole network is designed within a 400m*200m square grid. Considering the fact that the pipes being modeled as one dimensional entities, replicating the actual size of the district heating network in COMSOL would run effortlessly. But, a lot of time and mesh elements would have been required to model the three different patterns for the football stadium piping layout. The heat consumed by the industry, foot ball ground and the residential houses per annum are defined based on the literature study.[4] The heat power that is transferred from a district heating network to a consumer like the residential building or the industry is calculated using the equation,**Eq.1**

$$P = \dot{m}.C_p.(t_s - t_r) \tag{1}$$

Here, P is the consumed heat power [W], $\dot{m}$ is the mass flow rate in [Kg/s], C_p is the specific heat capacity of the water that carries the heat energy in [J/Kg/K], t_s is the temperature of the hot water or the supply temperature in [degC] and t_r is the temperature of the cooler water or return water temperature in [degC]

The pipes are considered to be laid underground, and also to be insulated, only for the supply pipes. Whereas the pipes used for the ground heating of the football stadium are not insulated but undergo heat transfer in two modes, convection and conduction. The three different orientations of the pipes of the football stadium are presented in **3**. These pipes are at a depth of 0.3 [m] from the ground surface, as these convect the heat through the soil in which they are buried. If the pipes are laid out at a greater depth, then the heat transfer would be less effective as it the volume of soil would increase. If they are laid at a depth close to the soil, then the roots of the grass would be effected, which is not desired. Though the presented orientations were modelled in CATIA V5 as 3D models, in the end they were remodelled in COMSOL as one dimensional entities to be in agreement with the assumptions made.

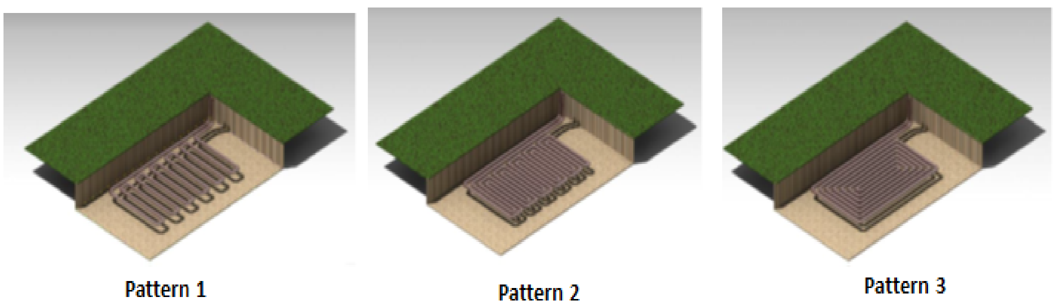
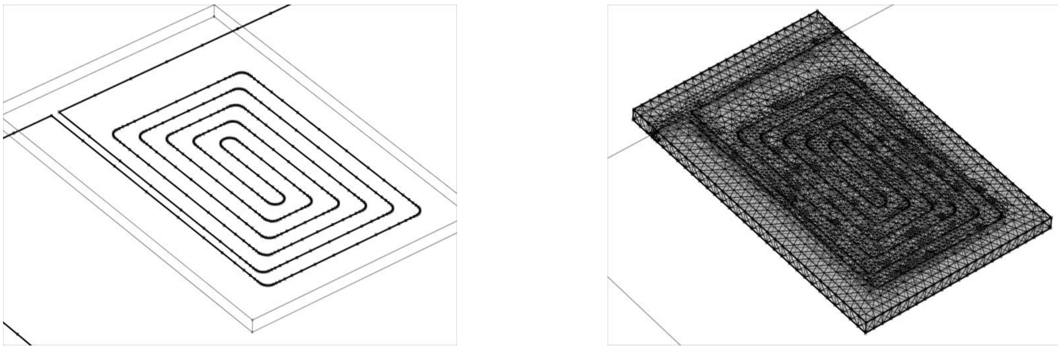


Figure 3: Pipe orientations for the football ground heating

3.3 Meshing

The simplified model of the District heating network is further discretised into much smaller elements and this process is called meshing. The piping layout, both the supply pipes and the heating pipes in the football stadium, which are modelled as one dimensional entities are meshed with 'edge' type meshing option present under the mesh toolbar in COMSOL Multiphysics 5.5 as shown in **Fig.4 (a)**. The meshed elements are the hexahedral elements that are generally used for cleaner geometries, where there are no complexities. Using hexahedral mesh elements also reduces the mesh elements count when compared to the tetrahedral meshes, there by reducing the computational cost. Even though there are bends in the pipes, particularly in the heating pipes, considering the fact that they are one dimensional, hexahedral elements were preferred over the tetrahedral elements.



(a) (b)

Figure 4: Generated meshes of pipes and football stadium ground respectively

The stadium ground which is modelled as the three dimensional model, by extruding the two dimensional rectangle (corresponding to the dimensions of the football ground) in either directions to a depth of 0.3 [m], is generated as free tetrahedral mesh. This option is preferred over the swept mesh which would generate the hexahedral elements because of the reason that, the domain encloses the heating pipes within it, which needs more element density around the pipes as the convection of heat occurs there and it is an important aspect. Since the prism layers or boundary layers are applicable only for the boundary, to add more elements around the pipes in the soil domain, the 'refine' option is used. From **Fig.4(b)** the generated mesh for the soil domain can be easily visualised.

Fig.5 shows the overall generated mesh for the simplified district heating system. The quadrilateral elements dominate over the hexahedral elements, increasing the computational cost, but are effective in capturing the physics in complicated areas.

3.4 Mesh independency

Mesh independence provides an insight into the influence of mesh on the results. As we decrease the mesh element size, the mesh density increases, which is one of the factor for increasing the accuracy of the solution. But just increasing the number of mesh elements does not necessarily increase the accuracy of the solution. The parameters or the results stop varying at a certain size of mesh, where increasing the mesh elements had no effect on the results. Henceforth, a mesh independence

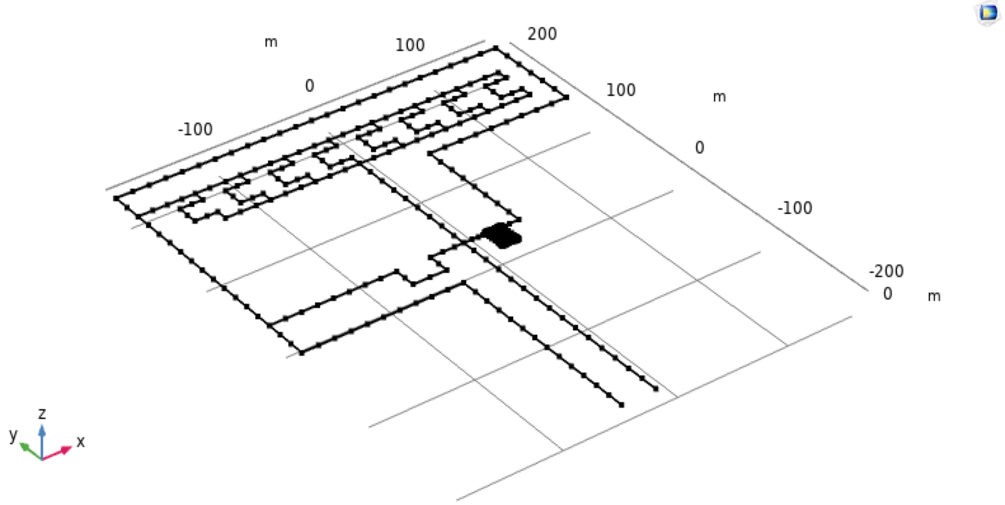


Figure 5: Simplified District heating system mesh a a whole

study is much necessary to find out the optimum size of the mesh where we get reliable results for the smallest possible mesh. Here the mesh independence study was performed by measuring the temperature at two probes. Probe 1 is the maximum temperature of the ground (Foot ball field) and Probe 2 is the average temperature of the Football field.

Table 2: Mesh independency study statistics

Mesh Independence study results						
	Elements number	Element quality	Probe 1 [degC]	%Error Probe 1	Probe 2 [degC]	Error Probe 2 [degC]
Normal Mesh	3156	0.25	104.28	-	10.935	-
Fine Mesh	3863	0.34	107.55	3.14%	10.692	-0.023%
Finer Mesh	7643	0.49	107.67	0.112%	10.045	-6.051%
Extremely fine	22064	0.58	107.79	0.112%	9.98	-0.647%
Super fine	86079	0.61	107.65	-0.001%	9.70	-2.81%

From **Table.2** it can be seen that as the number of mesh elements roughly increase by two fold, the temperature values starts to decrease by smaller quantities. The % Error column indicates the cumulative error between the two successive mesh sizes. It can be seen that the error percentage decreases significantly between the probe temperatures as and when the mesh is finer and the element quality increases. But the difference between the extremely fine mesh and the super fine mesh is considerably very small. Considering the results, the fine mesh with approximately 7K elements was chosen as the optimum size for the simulations, as the error is really low compared to the normal and coarse meshes. Employing finer and extremely fine meshes are not necessary as the the results vary by third or fourth decimal and these would increase the computational cost by a large margin.

3.5 Solver settings

The simulation is set up as the steady state for the detailed analysis of the heat transfer in the District heating network. Transient case is not considered here, as there is lack of enough information regarding heat consumption and variations in the heat demand, which varies day to day or weekly. Since the football field is the domain of interest in this project, the heat transfers occurring in this volume is to be carefully analysed and understood. 'Heat transfer in solids' physics is employed for the conduction of heat from heating pipes that are laid below the surface of the football ground at a depth of 0.3[m]. And, 'Non-isothermal heat transfer' option is used for convective mode of heat transfer in the pipes. The football ground is exposed to the outer atmosphere at ground level, covered by grass. The ambient temperature of air above the surface of the football field is taken as -5[degC] or precisely 268.15[K]. Henceforth, there is a need to model the convection phenomena in this simulation. The heat flux is specified as 'Convective heat flux', with the user defined heat transfer coefficient of 3000[W/m^{2}K]. [8] The supply pipes are considered to be insulated, where there are no losses due to convection during the transfer as they are buried in the soil. The industry and residential housings are associated with a specific value of heat rate 800 [kW] and 2 [kW] per house [6], indicating the heat sinks where the heat energy is used up.

The heating pipes in the football stadium are made up of copper as the copper material has relatively high thermal conductivities 386 [W/m/K] thereby aiding in large amount of heat transfer to the soil around it. The material is set from the built in library of the COMSOL software, hence the thermal conductivity varies according to the temperature that is defined. The diameter of the heating pipes is set to be 0.15[m], obtained from the literature survey. [8] Operating pressure was set to 101325[Pa] with an inlet temperature of 120[degC] specified at the inlet of the supply pipes. Also, the mass flow rate of the water flowing through the supply pipes is kept as a constant of about 15[Kg/s].

The boundary condition for the soil can initially specified in two different ways. One method is to specify general inward heat flux in [W/m^2], when the heat consumption is by conduction mechanism. And the other way is to specify as the heat rate in terms of [W] or heat transfer coefficient[W/m^{2}K]. Considering the fact, that colder air above the surface of the football ground takes away heat from the surface of ground by convection phenomena.

A stationary study is added to the simulations to run the steady state case. A relative tolerance of 1e-8 is set as per general rule of thumb for any CFD problem. However, there was no convergence studies done to find an optimum value for iterative convergence. The residuals for the first pattern of pipe orientations are presented in **Fig.6**. Default settings in the steady state stationary solver, expect for the maximum number of iterations. The max. number of iterations are reset to 500 though it was not necessary.

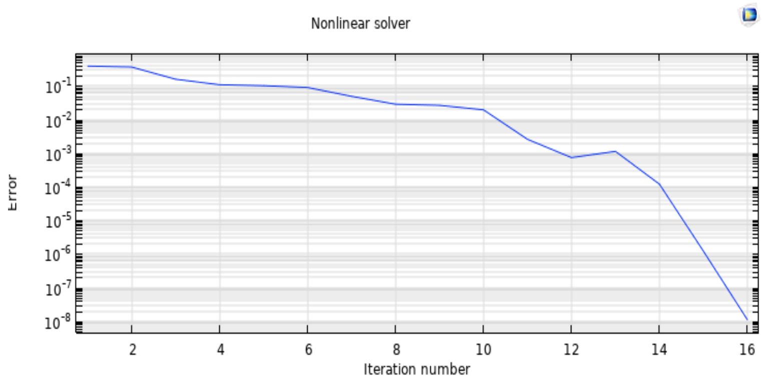


Figure 6: Residuals convergence for the piping pattern 1 in the football field ground

4 Results

Fig.7 shows the temperature variation along the supply pipes of diameter 0.75[m]. The water is fed from the heat source through the inlet of the domain, which is 120[degC] indicated by red colour. When the heat is gradually lost, on passing through the heat sinks, the colour changes to blue, indicating that the water is getting cooled. The temperature at the outlet is close to 90[degC], which is returned to the heat source for reheating.

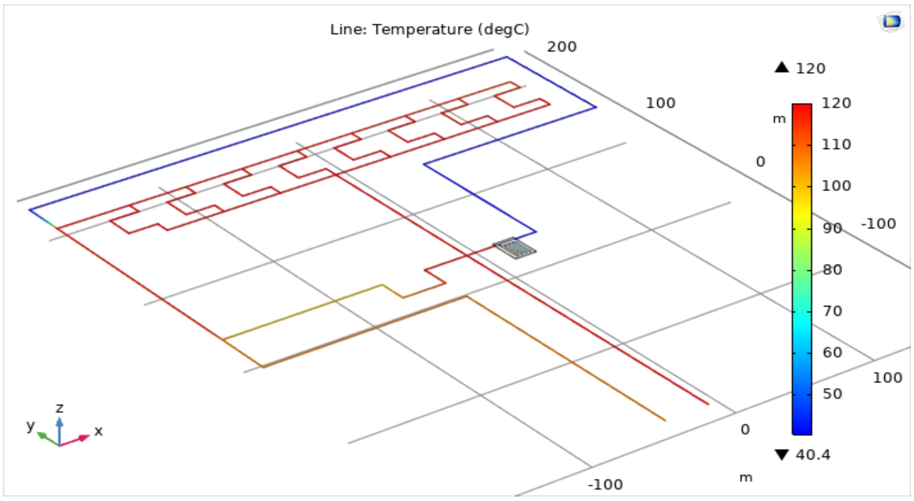
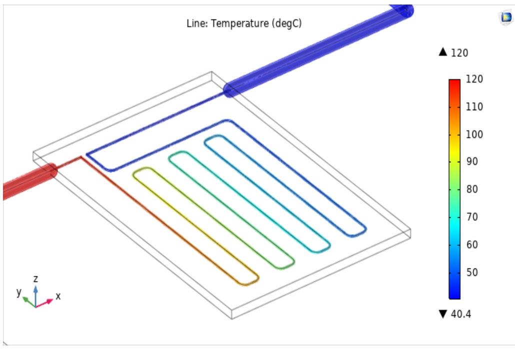


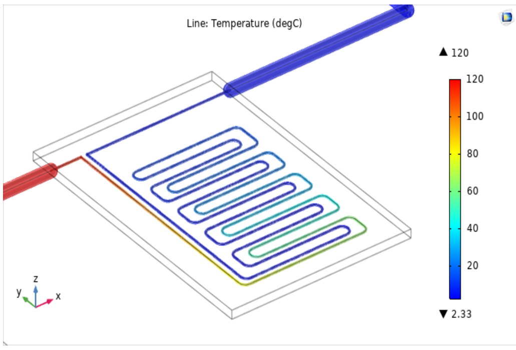
Figure 7: Temperature variations along the supply pipes as the heat is transferred by the moving water

Fig.8, shows the temperature distribution in the piping patterns that are laid out inside the football field. The supply pipes are of diameter 0.75[m] and the heating pipes in the field are of diameter 0.15[m], which can be clearly differentiated in these plots.

Fig.9, shows the temperature distribution of the football field surfaces. It can be seen that the heating pipes conduct the heat to the soil around it, thereby raising the overall temperature of the field volume. Piping pattern 3, in **Fig.9 (c)** shows a



(a)



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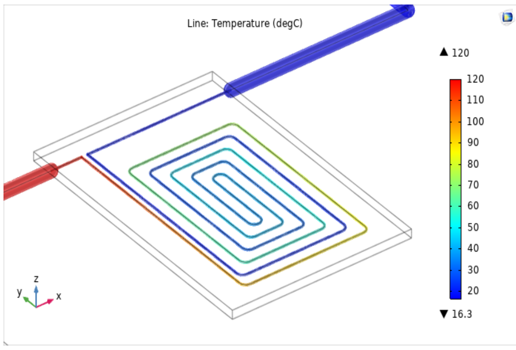
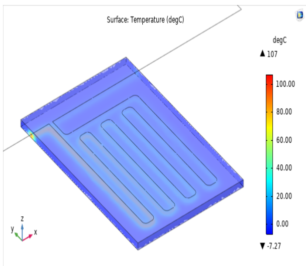


(c)

Figure 8: Temperature contours variation and Iso-surfaces for constant temperatures of the steady state case of the antenna

better heat spreading or even distribution of heat compared to the other two patterns.



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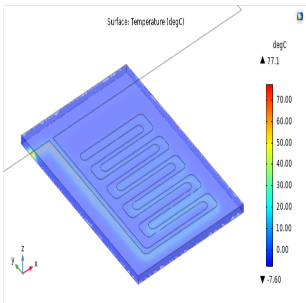

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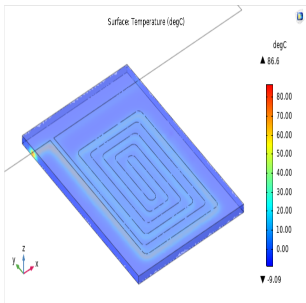

(c)

Figure 9: Surface temperatures of the football field for different orientations of heating pipes beneath the surface

Table.3 presents the probe temperature readings for the three different pipe patterns laid in the football field. First column is the maximum temperatures recorded in the ground. Ground refers to the volume that contains soil and the heating pipes of the football stadium. Second column is the minimum temperature of the ground. And the last column is the average temperatures of the foot ball field ground. This gives a better estimate of the heating of the football field by the copper pipes that are laid at a depth of 0.3[m].

Pattern	Max Temp(degC)	Min Temp(degC)	Average Temp(degC)
1	107.19	-10.402	10.025
2	80.739	-9.754	1.6997
3	89.321	-4.974	6.6192

Table 3: Quantification of ground temperature for different temperature

5 Discussion

The heating in the district system is a basic requirement that a country or a region needs if they are situated in the colder parts of the world. An efficient district heating system is a better step towards the sustainable use of the energy resources that are at our disposal. To make a system perform at its optimal conditions several researches and sufficient effort has to be put in solving the common problems that pop up. The research question chosen for this project is in developing a efficient piping pattern for the football ground heating.

5.1 Pipe orientations

There are two aspects to consider in case of choosing the best piping layout for the football field heating. One is the heat loss from the pipe depicted in **Fig 8** and the other one is the heat distribution at surface, depicted in **Fig9**. The surface temperatures provide an estimation of the average ground temperature that is exposed to the outer atmosphere that consists of air at -5 [degC]. The air moves naturally above the grass layer, convecting away heat from the soil. The soil is initially at an higher temperature than the surrounding air, creating a temperature gradient. Within the scope of the project, heat transfer through conduction and convection are modeled in the simulations. The walls of the pipe laid out under the ground conduct heat to the soil, which can be clearly seen from the surface temperature plots.

However, the thermal conductivity of the soil is less, which hinders the heat transfer process. And there are other parameters like the humidity of soil, presence of gravel, roots of the grass ,etc (all these parameters are not included in the simulations for the purpose of simplification), that can also affect the surface and average temperatures of the football field. From the average surface temperature plots in **Fig9**, pattern 1 has the higher average temperature of 10.025 [degC], thereby increasing the temperature by almost 15 [degC] from an initial temperature of -5 [degC].

By analysing the line temperatures (as the pipes are modeled as one dimensional mesh elements) from **Fig 8**, maximum heat loss is observed in pattern 2 and minimum in pattern 1. As stated earlier, from the **Table.3** it can be seen that the average temperature of the ground for pattern 1 is comparatively higher than pattern 3 and 2 by large margin. But when we look at the line temperatures for pattern 1, it can be seen that the left side of the field gets more heated up, than the right side of the field. Whereas, for pattern 3 there is even heating of the field or uniform heat spreading. This pattern seems more efficient in temperature distribution, which serves the purpose very well compared to pattern 1 and pattern 2. Since the objective is to have good heat distribution (highest average surface temperature) along with minimum heat loss (lowest heat loss in line temperature) pattern 3 stands out as a good combination on considering both these factors. Pattern 3 has an average temperature of 6.6 [degC], indicating that the overall temperature of the field rises by approximately 11. [degC], which is acceptable.

5.2 Verification

Verification of the model is a process of finding the accuracy of the results. Mesh density and convergence level are two parameters that that contribute to achieving accurate results. Meshing is a basic process which enables one to understand the flow condition at that nodal region and hence forth form a cumulative image of the flow. Mesh Independency is when the solution gets independent of the mesh density. Not checking this can either result in having erroneous results or increase in the computational time. The finer the mesh, it is capturing more details and hence more heat is absorbed into the ground and lesser is the pipe temperature. This explains the decrease in the probe2 values in the table 2. Residuals are the most important measures of the iterative solution's convergence and signifies the local imbalances of any conserved field variable in a individual control volumes. Therefore, the lower the residual value, more accurate the solution is. Once the residuals converge, further iterations can be avoided as the result with least error margin will be obtained. The Residual monitor in figure 6 shows that it the solution converges after 16 iterations and no convergence study was performed as it took just iteration for residuals to reduce from $e^{-}4$ to $e^{-}6$.

5.3 Validation

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. A simulation is considered to be validated if the difference between experimental data and CFD model results is smaller than the validation uncertainty[9]. Although some the values in the CFD model are taken from the validated literature data, it is difficult to completely validate this model because of the simplifications and approximations made in modelling and unavailability of the experimental data which replicates the exact model and boundary conditions. Hence, in this case the outlet temperature of the pipeline is a reasonable parameter to compare against the real world data. These values are found to be close the literature data.

6 Conclusion

A steady state analysis of a simple district heating system is performed. The residential houses, industry and football stadium were considered as heat sinks in the system. The approximations and simplifications had to be made for modelling for some of the parameters because of the lack of literature and experimental data. The subsequent impact was on the accuracy of the validation. The inlet temperature of the water supplied to the main supply pipes from the heat generation plant is 120 [degC] and the outlet temperature of the water flowing into the heat generating source for reheating purpose is around 90 [degC], thereby losing a temperature of 30 [degC]. The focus was to understand the difference in heat transfer when three different patterns of piping system was considered for heating the football ground. The best pattern was determined based on the heat transferred, the distribution of heat over the field and the overall average temperature of the ground. Pattern 3 turns out to be more efficient and effective based on the above mentioned criteria.

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