Proceedings of IOE Graduate Conference, 2017
Volume: 5 ISSN: 2350-8914 (Online), 2350-8906 (Print)

Design and Numerical Analysis of Solar Underfloor Heating System : A Case Study of Resort in Nagarkot, Nepal

Sarika Kumari Mishra [a], Tri Ratna Bajracharya [b], Rabindra Nath Bhattarai [c]

[a, b, c] *Department of Mechanical Engineering, Pulchowk Campus, IOE, TU, Nepal*
[b] *Center for Energy Studies, IOE, TU, Nepal*
Corresponding Email: [a] sarikamishra34@gmail.com,

Abstract

With concerns to energy savings and environmental protection, it is important to consider application of renewable energy to substitute for conventional energy sources. Despite of the huge potential of solar energy as well as successful implementation of solar PV and solar water heaters, solar space heating has not been practiced much in Nepal. In this study, a solar underfloor heating system for a resort in Nagarkot, Nepal is designed and analyzed from thermal perspective. Two different configurations for piping are compared with respect to temperature distribution in the floor cross section and floor surface using academic version of commercial CFD code ANSYS Fluent. From the analysis it is seen that counterflow spiral type layout is best option for it has created uniform temperature distribution in floor surface.

Keywords

Thermal Comfort – Numerical Simulation – Temperature Distribution – underfloor Heating

1. Introduction

All over the globe, people and industry consume massive quantities of energy to power their homes and offices, travel across the world, and operate factories that produce billions of dollars of goods. Buildings account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions [1]. According to ASHRAE[2], thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space.

Comparatively, underfloor heating offers several advantages over conventional radiator heating. With underfloor heating there is a little air circulation and the rooms are evenly heated. It is an energy efficient way to heat up the whole house. The heat comes from the floor and not from above [3].

For the Floor heating system has been efficiently used in order to achieve occupant thermal comfort in building with low energy demand which is increasing everyday. Floor heating system warms objects such as carpet, furniture and even people. Instead of heating air and circulating it throughout the house, underfloor heating systems require less energy to transfer heat directly to comfort zone, rather than entire room filled with heated air like a forced-air furnace [4].

Solar thermal systems (STS) collect energy from the sun and transform it into heat used to raise the temperature of a heat transfer fluid. The heat generated can also be stored in a proper storage tank for use in the hours when the sun is not available. In all cases, thermal energy can be transferred by means of heat-exchanger designed according to the final energy application [5]. Moreover today, it is desired that human activities be more climate positive and energy efficient thus reducing the carbon footprint. To achieve this goal, solar underfloor heating plays a vital role by reducing the energy consumption in building by substituting the conventionally used boiler and also providing hot water in some cases.

The numerical ways of calculating the fluid characteristics in dynamic conditions, has become the most strong way or tool in analyzing the fluid flow and also the heat transfer in a system with symmetrical or non-symmetrical geometry. The numerical approach for solving difficult equations made the researchers and the engineers more dependent on this new way of solving fluid and heat problems in the last decades [6].

To keep uniform heat transfer distribution to the desired condition space, heat must be given to the circulating water, and to distribute hot water to pipes loop underfloor, heat must be released from floor surface since hot air is normally transferred from bottom of the space to the top [7]. Experimental study in energy consumption by floor heating system in building with CFD simulation has been done to investigate the energy loss in rooms with floor and radiant heating systems by [4]. In the study, the required energy to achieve the thermal comfort in a room by floor and radiant heating systems has been calculated by modelling the velocity and temperature fields and compared with each other and with the data calculated by conventional method of heating load calculation. Two dimensional dynamic model for simulation of the floor heating systems has been developed in [8] in which the authors calculated the heat loss value and temperature of a slab on a grade floor with floor heating system. Importance of solar floor heating system in reducing the demand of fossil fuel by studying about applications of floor heating system using solar collector in jordan has been done in [9]. It can be seen from above that with recent trends being application of commercial CFD codes to simulate temperature distribution so that no temperature gradients are formed in heated space, some researches are dedicated for comparative study with other heating system as well.

In this study, a commercial system, a resort is taken into consideration. The resort selected is Avatar Resort in Naldum, Nagarkot. Resort has total land area of 8139.84 m^2 The designed building is oriented towards north consisting three storey with total building area of 218.51 m^2. Ground floor consists of reception, massage, sauna and jacuzzi. Bedrooms and living rooms are in first floor. It is required to design solar underfloor heating for ground floor that has total area of 89.76 m^2 and height 3.27 m with 8 windows.Since different piping layouts are preferred for underfloor heating systems, this study aims to analyze two different piping systems which are commonly practiced.

2. Methodology

The plan of floor to be heated is as shown in Figure 1.

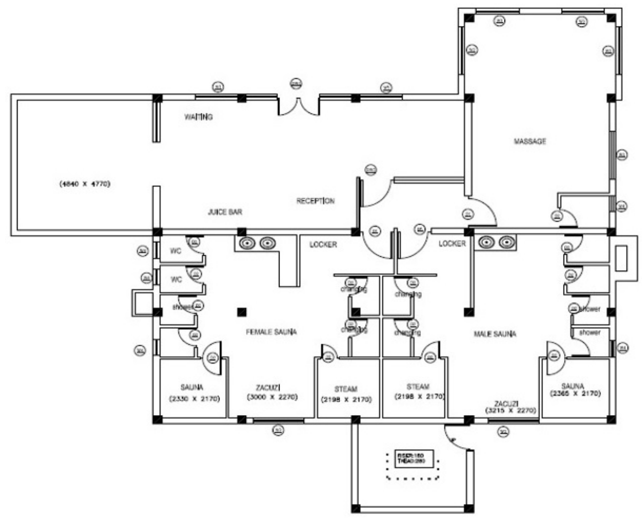

Figure 1: Floor Plan of Selected Site.

For jacuzzi and sauna being hot space themselves, they are excluded as load however, when not in use, heat loss of course occurs from the heated space to these. Hence, heat loss to this area is being considered. It is required to design solar underfloor heating for ground floor in reception and massage room area. Different piping layouts are preferred for underfloor heating systems, this study analyses the temperature distribution in floor surface with various layouts by use of CFD code. CFD simulations were used with steady state formulations to perform investigation on floor temperature with single loop taken as computational domain.

2.1 Design Assumptions

Major design assumptions considered for study can be summarized as:

1. Steady state condition has been considered.
2. Heat gain due to people and lightning have not been considered as it will be in
3. Windows with single glazed have been considered.
4. Sauna and Zacuzi are excluded from underfloor heating.

5. As suggested in ASHRAE 55 Standard, for thermal comfort the indoor design temperature is considered to be $20°C$

6. From NASA Surface meteorology and Solar Energy data, the minimum outdoor temperature for Nagarkot, Nepal was found to be $3°C$. So, the outdoor temperature for system design is choosen to be $3°C$.

To simplify the naming, the reception room is taken as Room 1 and Massage room as Room 2 as shown in Figure 2.

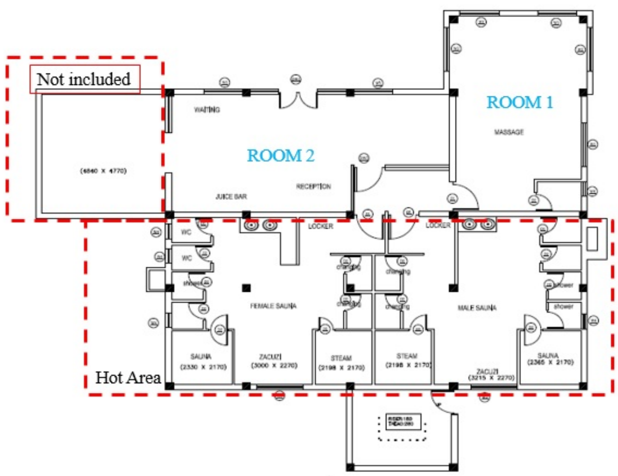

Figure 2: Site Conditions after Design Assumptions

2.2 Heating Load Calculation

2.2.1 Calculation of Overall Heat Transfer Coefficients

The various heat transfer coefficients may be combined into an overall coefficient so that the total heat transfer can be calculated from the terminal temperatures. An overall heat transfer coefficient, U based on the difference between the bulk temperatures $t_1 - t_2$ of the two fluids is defined as follows

$$q = U \times A \times (t_1 - t_2)$$

Where, A is the surface area and U the overall heat transfer coefficient. The U-value for a wall can be determined from the following relationship:

$$U = \frac{1}{R_1 + R_2 + R_3 + R_4 + \ldots\ldots\ldots\ldots\ldots + R_n}$$

Where, R_i is the thermal resistance offered by each componets for passage of heat through it.

Thermal resistance for each wall materials is calculated by following formulae:

$$R = \frac{\text{Material Thickness (t)}}{\text{Thermal conductivity coefficient (k)}}$$

And for each fluid adjacent to boundary by:

$$R = \frac{1}{\text{Convection Coefficient (h)}}$$

Where, t is available from design drawings and numeric values of k and h are adopted from ASHRAE Fundamentals Handbook. [10]

2.2.2 Calculation of Heat Loss

Total heat loss is calculated by summation of heat loss through various heat loss mechanisms. In this case, transmission heat loss and infiltration heat loss will be calculated and summed up to get total heat loss which will thus be our heating load.

Transmission heat loss through each building components can be calculated after calculation of overall heat transfer coefficient for each component by using following equation

$$q = U \times A \times (t_i - t_o)$$

Where, t_i is indoor temperature and t_o is the outdoor temperature.Substituting all known values, q the heat transfer through exposed surface can be calculated.

Infiltration heat loss is heat lost by air leakage through joints in the construction and cracks around windows and doors.In general, ASHRAE recommends using low infiltration rates for small buildings ($<$ 0.5 air changes per hour, ACH) to use. The equation to estimate infiltration losses is

$$Q = \frac{\text{ACH} \times \text{V}}{\text{C}}$$

Where, Q is infiltration rate, V the gross space volume and C a constant whose value is 3600 for SI.

Having estimated Q, the infiltration heat loss given by q is calculated from following equation:

$$q = \frac{\text{Q} \times (c_p) \times (t_i - t_o)}{v_o}$$

With reference to [10], 0.2 ACH has been adopted in this case.

2.3 System Sizing

The tube spacing and total tube required varies due to the required floor output and the size of the tubing being used. From data book as supplied by manufacturers, we can select the tube size and spacing which then leads us to selection of the appropriate spacing factor. Total tube required can be found by multiplication of the tube coverage area by the spacing factor [11].Two types of layouts are generally used in underfloor heating system.

1. Serpentine
2. counterflow

The two loops used in the study are as shown in figure 3. The solid boundary represents the boundary of concrete while the dotted line represents the piping.

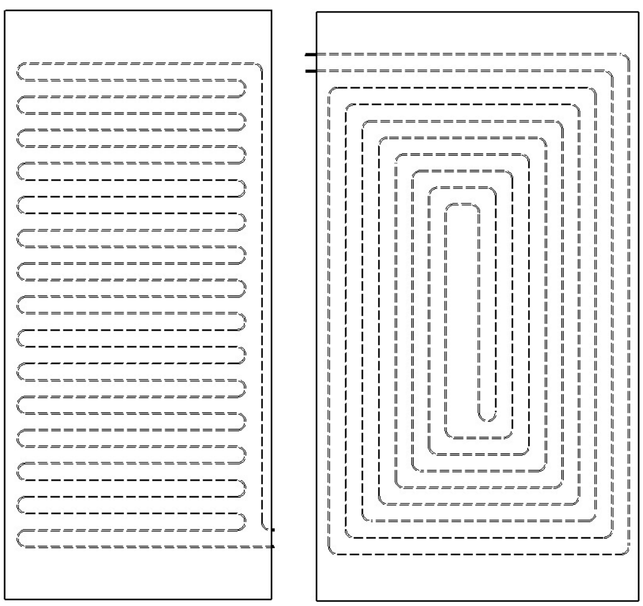

Figure 3: Piping Layouts

Storage volume depends upon the temperature difference, physical and thermal properties of storage material. In this research, water has been selected as the storage material because of its high specific heat capacity and economic advantage.

Collector choice significantly affects the overall performance of the floor heating unit. The prime measure of appropriateness of a collector is its relative ability to convert solar energy into thermal energy. As shown in [12] for their high efficiency in required range of solar underfloor heating i.e. 40°C to 50°C, flat plate collector is chosen.

Collector solar heat gain is given by

$$Q_c = I \times A_c \times \eta_c$$

Where, I = Average solar insolation over surface tilted at β (kWh/m^2 day), A_c = Total Collector area (m^2) and η_c = Collector efficiency. η_c should be calculated for ambient temperature with performance curve supplied from manufacturer. A typical performance curve is shown in Figure 4.

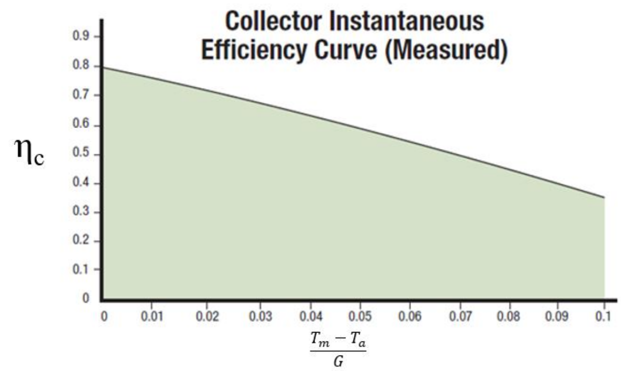

Figure 4: Typical Collector Efficiency Curve

where, T_m is mean water temperature in collector calculated as average of inlet and outlet temperature of water, T_a the ambient temperature and G the radiation at which the collector was tested.

Energy required for floor heating is given by

$$E = Q_l \times t$$

Where, t is system running time.

Energy required by floor heating must be supplied from solar collector. Mass of water flowing through collector is calculated from:

$$Q_c = m \times C_p \times \Delta t$$

Where, C_p the specific heat of water at corresponding temperature and the temperature difference of collector inlet and outlet is given by Δt.

2.4 Numerical Setup

Generally, the heat transfer study of an underfloor heating system can be divided into two major parts:

- The floor of the room, which includes the pipes, the carrying fluid (hot-water), and the middle cover or the space between the pipes and the surface of the floor (concrete).
- The internal space, The space in the room which includes the walls around the room and the air within the room. [6]

The air properties in internal space is directly dependent upon the floor of the room. So, in this study, we limit to thermal analysis of the floor of the room only with understanding that uniform temperature distribution in floor will generate uniform air temperature.

In this study, two different piping arrangements, serpentine and counterflow arrangement were with same pipe diameter of 13 mm of PEX were used with constant mass flow rate of hot fluid. The simulations were conducted using Academic release of ANSYS Fluent 16.2, a software package for CFD analysis. It uses Finite Volume Method for numerically solving the PDEs. The governing equations are Navier-Stokes equation, conservation of mass, momentum and energy. The calculations were performed using second order upwind discretization scheme using SIMPLE algorithm. The convergence criteria was set to 10^{-4}.

The turbulence model used was the RNG k-ε model. The k-ε model is a two equation model: k is the transport equation for the turbulent kinetic energy and ε is the eddy dissipation [13]. Energy equation was also solved for modeling the thermal energy exchange between the fluid flow and solid domain.

2.5 Boundary Conditions

The domain considered was concrete with water flow pipes fitted inside it. The design used were according to the review of past researches done in relevant field and set as per calculated values. For boundary conditions of the solid domain, i.e. the concrete study of past researches done in the field was considered. With Haruo Hanibuchi having studied the functioning of underfloor heating, in [14] he presents that the internal surfaces of the room become warm by receiving radiation from the floor, and then the convection mechanism causes the transfer of the heat between the air and the internal surfaces of the room. Radiation mechanism doesn't have any direct impact on the air in the room so the floor top was defined with convection boundary conditions and bottom was set insulated.

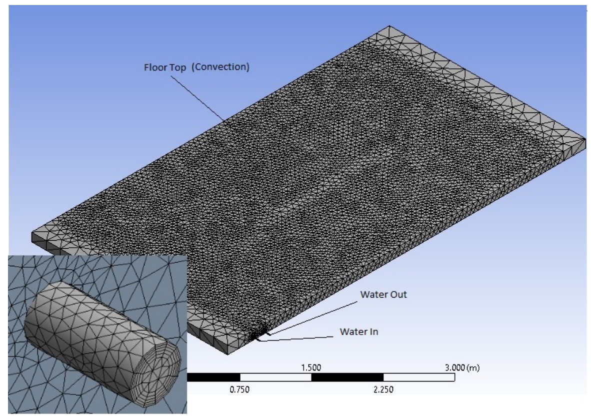

Figure 5: Boundary Conditions

For fluid flow domain, the input was defined as mass flow inlet and outlet as pressure outlet for hot water entering and exiting the system. The inflow water temperature was taken to be 323 K which is the output temperature of collector panel. Coupled wall was used to define interaction between the fluid-flow domain and concrete. The boundary conditions are summarized in Figure 5. For better modeling the fluid flow, 5 inflation layers were used in fluid flow domain. In order to reduce the size of the domain, which directly effects the computational time, one should be considering the usage of the symmetry boundary conditions. The rest of the boundary were taken as insulated due to symmetry conditions.

Thus the system in which hot water flows in the pipes placed under the concrete floor thereby transferring heat to the room has been modeled.

3. Results and Discussion

3.1 U Value Calculation

Overall heat transfer coefficient value calculated for different components are presented in Table 1.

Table 1: U Value of Building Components

S.N.	Component	U Value (W/m^2K)
1	Outside Wall	2.15
2	Ceiling	2.02
3	Floor	5.56
4	Partition	2.39
5	Door	0.63
6	Window	5.94

3.2 Heating Load Calculation

With U value calculated and heat loss area taken from design drawings, transmission heat loss from building components in room 1 was calculated as presented in Table 2.

Table 2: Transmission Heat Loss from Room 1

S.N.	Component	Area (m^2)	Heat Loss (W)
1	Outside Wall	41.89	1532.43
2	Ceiling	38.4	1324.31
3	Partition	15.72	639.93
4	Window	9.72	980.86
	Total Loss , W		4477.55

Similarly, the infiltration heat loss for room 1 was calculated as presented in Table 3.

Table 3: Infiltration Heat Loss from Room 1

S.N.	Items	Values (In SI)
1	Hourly Air Change Rate (ACH)	0.2
2	Density	1.2
3	Specific Heat (Isobaric)	1.005
4	Space Volume	125.79
	Total Loss , W	143.88

Transmission heat loss from room 2 is calculated as shown in Table 4

Table 4: Transmission Heat Loss from Room 2

S.N.	Component	Area (m^2)	Heat Loss (W)
1	North Door	3.37	123.4
2	South Door	5.4	219.75
3	East Door	3.66	39.7
4	East Wall	12.06	441.12
5	North Wall	19.97	730.50
6	Window	11.7	1181.49
7	Partition	29.65	1206.76
8	Ceiling	51.36	1771.27
	Total Loss , W		5714.05

Similarly, the infiltration heat loss for room 2 was calculated as presented in Table 5.

Table 5: Infiltration Heat Loss from Room 2

S.N.	Items	Values (In SI)
1	Hourly Air Change Rate (ACH)	0.2
2	Density	1.205
3	Specific Heat (Isobaric)	1.005
4	Space Volume	168.25
	Total Loss , W	192.44

Thus, the total heat loss from the building is 10.52 kW which was calculated by summing up the total losses as indicated from Table 2 to Table 5. The overall picture is as shown in Figure 6.

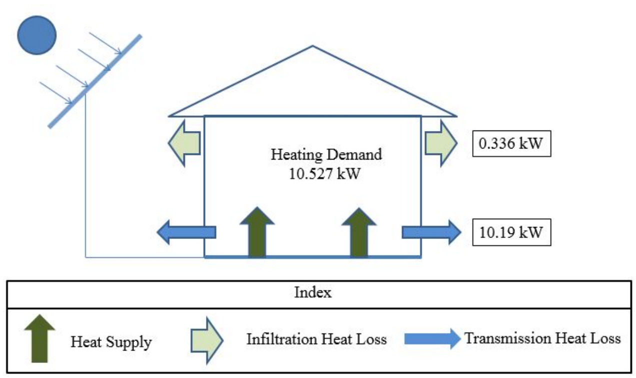

Figure 6: Overall Heating Load

3.3 Sizing the System

With average tilted solar insolation of 6.25 $kWh/m^2/day$, and system running for 12 hours in a day, the daily requirement 126.33 kWh, the total area of collector required is 33.13. Calculating the total heat to be stored by the tank, the total volume of storage tank is calculated to be 6.4 m^3.

With 13 mm PEX pipe selected, and 6.6 as tubing spacing factor, the total tube required is 549.52 m. Thus, we decide to use 7 circuits with length of circuit not more than 78.5 m and pipe placed with 150 mm gap. The flow rate for each zone is 3.59 US gpm.

For better thermal comfort, temperature distribution in the floor should be uniform rather than having a gradient. To analyze this, CFD tool, ANSYS Fluent is used. A single circuit of each type of layout has been analyzed.

3.4 Thermal Analysis

As our desire is to generate isothermal temperature in the floor, our parameter of interest in thermal analysis will be the temperature distribution in region of interest i.e. floor top surface.

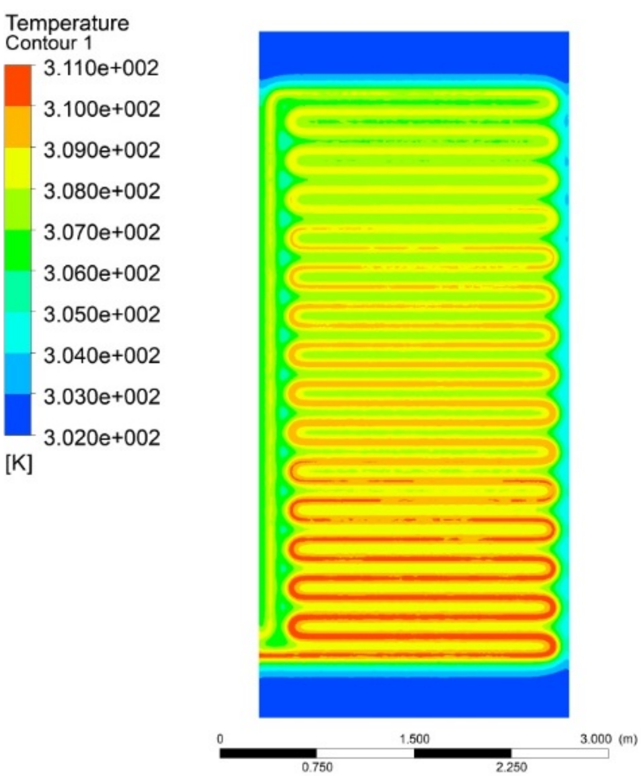

Figure 7: Analysis of Serpentine Loop

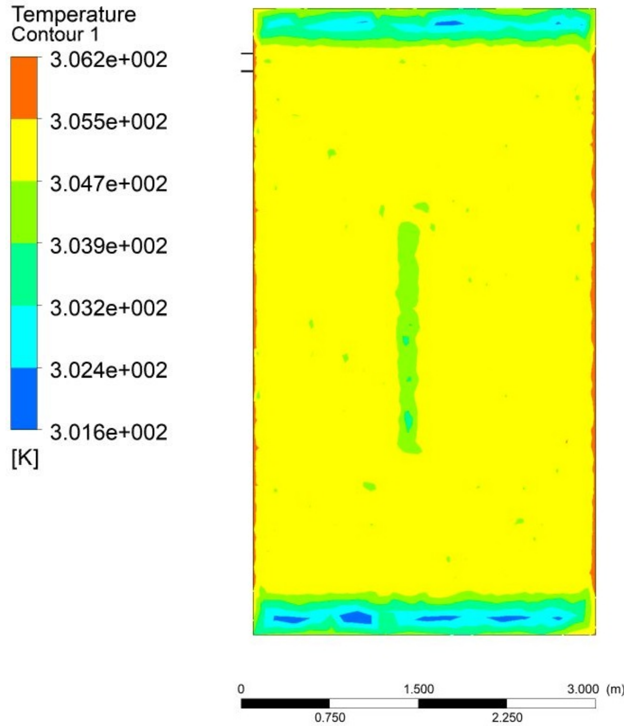

Figure 8: Analysis of counterflow spiral Loop

The simulations discussed herein were performed under the assumption of steady state conditions. Figure 7 and 8 show the predicted temperature for two different heating systems.

Figure 8 shows that a isothermal condition is generated by counterflow spiral loop and a thermal gradient is formed by use of serpentine loop as shown in Figure 7. It shows that at the inlet side of the serpentine loop, higher temperature region is created.

Hot air expands thus has low density and rises up to ceiling. Thus, use of serpentine loop will heat air in one side much more thus creating a periodic cycle if air flow in the domain. In contrast, counterflow spiral has created a uniform temperature distribution, which is further expected to generate a low air velocity field and provide comfort temperature.

4. Conclusion

Avatar resort in Nagarkot was selected as suitable site being cooler place nearby valley populated with commercial systems like hotel and resorts. Total heating load was estimated to be 10.527 kW, which is supplied by solar system. To meet this heating load 33.13 m2 collector area was calculated.

CFD simulation of temperature distribution over the floor surface was studied for different pipe loop arrangements and varying pipe spacing for best-found loop. Serpentine arrangement of pipe creates temperature gradient while uniform temperature distribution was created by the counterflow spiral piping which provides better thermal comfort. It was seen that temperature gradient of about 5 K was formed in use of serpentine loop of 80 m PEX pipe with pipe spacing of 150 mm employed to heat area of 11.89 m2. Further analysis was done by varying piping gap in counterflow loop as recommended by manufacturer. With variation of piping gap to 170 mm, a slightly low temperature region was formed in corners of piping. Further, it was seen that with further increments in pipe gap, chilled zones were formed in between pipes with effect being more severe on the bends. With piping gap set to 230 mm, the temperature in the corner was 2 K less than that above the piping. This formed temperature gradient would not only effect the thermal comfort but also cause thermal fatigue in floor as result of which cracks might be developed on the floor. So, it would be recommended to go with low value of pipe spacing given on design guidelines as provided by manufacturer for pipes for underfloor heating. Further, as the region in between pipe bends was found to be critical, larger radius of bends would be recommended during installation.

Acknowledgments

The authors would like to acknowledge Avatar Resort, Nagarkot for providing necessary helps in times required.

References

[1] Liu Yang, Haiyan Yan, and Joseph C. Lam. Thermal comfort and building energy consumption implications – a review. *Applied Energy*, 115:164–173, 2014.

[2] ASHRAE. *ASHRAE STANDARD*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2010.

[3] Heating and Plumbing Warehouse Limited. How does underfloor heating work?, 2017.

[4] V. Golkarfard, M. Salmanzadeh, and P. Talebizadeh. Energy consumption of floor heating system in buildings. In *Proceedings of the Second International Conference on Heating, Ventilation and Air-Conditioning*, 2010.

[5] IEA-ETSAP and IRENA. Solar heating and cooling for residential applications, 2015.

[6] Mohammad Javad Izadi and Kamyar Makaremi. Cfd simulation of temperature distribution in a room with various under floor heating system models. In *Proceedings of the ASME 2009 Fluids Engineering Division Summer Meeting*, 2009.

[7] Kunping Lina, Yinping Zhanga, Xu Xua, Hongfa Dia, Rui Yangb, and Penghua Quina. Experimental study of underfloor electric heating system with shape - stabilized pcm plates. *Energy and Buildings*, 37:215–230, 2005.

[8] P. Weitzmann, J. Kragh, P. Roots, and S. Svendsen. Modelling floor heating system using a validated two dimensional ground coupled numerical model. *Building Environment*, 2:153–163, 2005.

[9] Faisel Al Ghathin and Tareq Al Azab. Under floor heating with solar collectors in jordan. In *International Conference on Sustainable Mobility Applications, Renwables and Technology (SMART)*, 2015.

[10] ASHRAE. *The Fundamentals Handbook*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2017.

[11] INFLOOR. *RESIDENTIAL HEATING DESIGN & INSTALLATION GUIDE*. INFLOOR Heating Systems, 2016.

[12] EEM Energy & Environment Media GmbH. Basic knowledge — solar collectors, 2017.

[13] ANSYS. *ANSYS Fluent 16.2 Theory Guide*. ANSYS, 2016.

[14] Haruo Hanibuchi. Basic study of radiative and convective heat exchange in a room with floor heating. In *ASHRAE Transactions*, 1998.