USE OF MUNICIPALITY WATER SYSTEM FOR BUILDING COOLING AS AN ALTERNATIVE TO CONVENTIONAL GROUND SOURCE HEAT PUMP

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Abstract

This paper investigates the usage of municipality water supply system for cooling a residential building. The study in this paper proposes that by using municipality water supply system, it is possible to reduce the cost of space cooling for residential units. Additionally, this system would have a lower initial investment cost in comparison to the conventional ground source heat pumps where specially designed piping system placed a few meters beneath the ground allows the usage of earth's stored heat. For a regular municipality water delivery system, the carried water circulates through kilometers of piping already located underground which allows the water to exchange heat with the earth. Thus it is possible to replace conventional heat pump systems and use regular tap water as a coolant for a residential unit. In order to achieve cooling, pipes can be installed on the walls and the ceiling of a house. The tap water could be circulated within these pipes. Study represented here shows that 5.48 kW of building cooling load could be handled with only 50 W of pump power for water circulation through the pipes located inside the walls and the ceiling of a proposed typical house.

1. Introduction

Panel heating and cooling systems are becoming more widespread. Today, in South Korea 95 percent of the buildings use panel heating systems (Karabay et al., 2013) [1]. In such a panel heating and cooling system, a refrigerant such as water is circulated inside the pipes which are installed inside floor, walls or ceiling. Because the circulating fluid has lower temperature with respect to other heating systems or higher temperature with respect to other cooling systems, its efficiency is higher and renewable energy sources may also be used in such systems. In addition to this, the waste energy sources may be used in cooling or heating in panel systems.

The panel cooling differs from the conventional cooling systems, because there is not only heat transfer by convection, but also heat transfer by radiation. Cooling by radiation helps to achieve higher total human comfort level, because in radiant cooling systems, it is possible to have more uniform indoor temperature and to control the mean radiant temperature of the cooling panels. Furthermore in these systems, produced noise is relatively lower than other conventional cooling systems such as fan-coil (ASHRAE, 2008) [2].

Typically, air source heat pumps (i.e split air conditioners) are used for space cooling purposes. However, they use significant amount of energy. In addition due to non-uniform cooling of the conditioned space and because of excessive air circulation these systems cause some health problems.

Alternatively, ground source heat pumps systems are used for space cooling. The ground which is only a few meters deep stays at a fairly constant temperature throughout the year. In typical ground source heat pump systems, pipes which are buried a few meters under the soil extract heat from the ground. This heat is used to cool or heat a residential building. In ground source heat pump systems, a mixture of water and antifreeze, or a refrigerant fluid circulate inside the buried pipes. Heat from the ground is transferred to this circulating fluid. This heat is later used in a heat pump.

In ground source heat pumps, there is a risk of the refrigerant running through the pipes to leak to the ground and to cause contamination of ground water sources. In the proposed cooling system, regular tap water from the municipality is used. This water is pumped through the pipes which are installed inside the walls and the ceiling of a building for cooling purposes. This water is then given back to the municipality water circulation system. There is no water wasted for this system, just cooling capacity of the tap water is utilized.

If pipes are installed inside to the walls and the ceiling, and municipality water is circulated through the pipes, a higher temperature cooling fluid could be used. With the same system, heating can also be accomplished. Because of more uniform cooling higher total human comfort level can be achieved. Also, it does not cause high speed air circulation. In addition, maintenance cost could be kept low (De Swardt et al., 2001) [3].

Cooling a house using municipality water running through the pipes inside the walls a new technique and seems to be a promising one. In this paper relevant calculations and analysis have been made, and the study of using tap water as a cooling fluid is presented. In the first part of the paper, a case problem is introduced. In the second part, heat gain of the hypothetical house is calculated. After that, heat transfer from tap water to the house is evaluated. Then, the pressure drop is estimated and according to the obtained values, the pump work is assessed. The results show that this system has several advantages over other cooling systems in term of economical and ecological considerations.

2. Case Problem and Assumptions

In this section, a hypothetical house is conceived to study the concept of using municipality water for cooling purposes and all the major assumptions are presented.

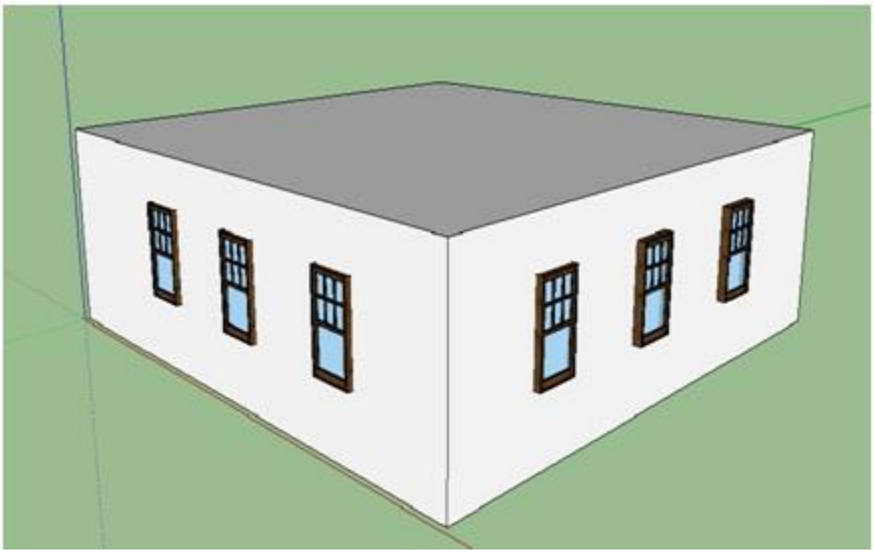

Fig.1. The hypothetical house with municipality water cooling system.

2.1. The hypothetical house

In order to make an analysis of the proposed concept a hypothetical house which is depicted in Fig. 1 is studied. The hypothetical house is assumed to be located in Istanbul, Turkey and positioned in north-south direction. It is assumed that four people reside in this hypothetical house and that it has 100 m^2 (10 m x 10 m) floor area. Thus the side walls have a total of 40 meters length. The walls are assumed to be 3 meters in height.

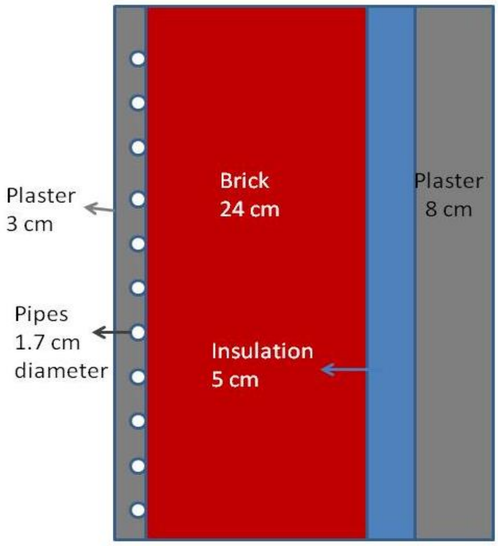

Fig. 2. Depiction of heat transfer from the walls

The side walls are assumed to consist of 8 cm outer plaster, 5 cm insulation material, 24 cm brick and 3 cm inner plaster layers. The layers of the walls are shown in Fig. 2. The ceiling is assumed consist of 12 cm insulation material, 12 cm concrete and 3 cm inner plaster layers. The layers of the ceiling are shown in Fig. 3. It is assumed that the hypothetical house has 3.75 m^2 window area on each side wall, resulting in a total window area of 15 m^2. Therefore the total wall area is 105 m^2, the total ceiling area is 100 m^2.

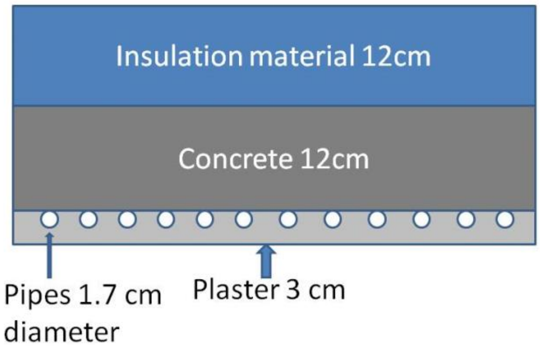

Fig. 3. Depiction of heat transfer from the ceiling

2.2. Assumptions

Istanbul's dry thermometer temperature is taken to be 33°C for summer cooling load calculations (Karakoc, 2001) [4]. The targeted inside temperature is taken to be 26°C which is the maximum desired value for summer room temperature (Olesen, 2004) [5]. It is assumed that the available tap water has a temperature of 20°C for August in Istanbul. Also it is assumed that the inside and outside temperature values are not changing in time. Heat transfer from floor is not included in the analysis, because the temperature of the floor is assumed to be at the target room temperature.

3. Heat Transfer Analysis

In this section, the heat transfer analysis of the hypothetical house is presented. First, the cooling load of the hypothetical house is determined. Then, the heat transfer to water by convection and radiation are calculated and the total heat loss from the pipes is evaluated. Later average water temperature through the pipes is determined and the required pipe length is calculated.

3.1. Cooling load calculations

In this part, the cooling load for the hypothetical house is evaluated. There are heat transfer gains by conduction from walls, windows and roof. Also there are radiation heat gain from the sun and heat gain from the inhabitants of the house, household devices and ventilation through the windows. In order to calculate the heat gain from walls, the equivalence increase in surface temperature is added, because of solar heating of the walls and roof. The accepted values are shown in Table 1 (Ozkol, 1988) [6]. Then the layer characteristics of walls are specified. These values are tabulated in Table 2 (Karakoc, 2001) [4]. It is also assumed that the walls have medium dark color and the ceiling has dark color.

Table 1. Equivalence increase in surface temperature because of sun (Ozkol, 1988) [6]

Surface type	**Wall Side**			**Flat Roof**
	East	**South**	**West**	
Dark Color	5	3	5	11
Medium Dark Color	4	3	4	9
Light Color	3	2	3	5

Table 2. Heat gain from walls

Wall materials	**Thickness [m]**	**Thermal conductivity [W/mK]**	**Thermal resistance [m^2K/W]**
R_I	-	-	0.13
Plaster	0.03	1	0.03
Brick	0.24	0.5	0.48
Insulation material	0.05	0.035	1.429
Plaster	0.08	0.35	0.023
R_e	-	-	0.04
Total thermal resistance = 2.132 m^2K/W Thermal conductivity = 0.471 W/m^2K			

By multiplying thermal conductivity of the wall with total area of the wall, total heat gain per degree can be calculated as 49.46 W/K. Then by multiplying this value with the temperature difference, the total heat gain from the walls can be calculated as 482.19 W.

After that, the heat gain from the windows are calculated. For double glass windows, heat loss per degree Kelvin is 36 W/K and total window area is 15 m^2. Therefore the heat gain from windows by conduction is found to be 36 x 7 = 252 W. Then the heat gain from roof is calculated as presented in Table 3.

Table 3. Heat gain from roof

Roof materials	Thickmess [m]	Thermal conductivity [W/mK]	Thermal resistance [m^2K/W]
R_l	-	-	0.13
Plaster	0.02	1	0.02
Concrete	0.12	2.5	0.048
Insulation material	0.12	0.04	3
R_e	-	-	0.04
Total thermal resistance = 3.278 m^2K/W, Thermal conductivity = 0.305 W/ m^2K			

By multiplying the thermal conductivity of the roof with the total roof area, the total heat gain per degree can be calculated as 30.5 W/K. Then by multiplying this value with temperature difference, total heat gain from roof can be calculated as 549 W. Later, the heat gain from solar radiation is obtained from (ISISAN, 2001) [7] as presented in Table 4.

Table 4. Heat gain from solar radiation in W/m^2 at 40º north latitude at various times

	08:00	12:00	16:00
West	50	50	500
East	500	50	50
South	50	200	50
North	50	50	50

In order to calculate the heat gain from radiation, first the window areas and the directions are specified. The hypothetical house has windows of 3.75 m^2 on each wall. Using the values solar radiation values presented in Table 4 for west, east, south and north directions, it is found that the radiation heat gain from windows is Q=3.75x500 + 3.75x50x3 =2,437.5 W.

However windows have shadow factor which decreases the heat gain from radiation. Shadow factor for double glass window is assumed to be 0.9. Then the net heat gain from radiation is 2,437.5x0.9=2,193.75 W.

There is also heat gain from ventilation through the windows, because the outside air temperature is higher than the inside air temperature. For 1 person, 20 m^3/h fresh air is needed (ISISAN, 2001) [7]. Thus the total ventilation cooling load can be calculated: Q_v= 7 x n(person) x $\dot{V}$ (fresh air)[watt] (ISISAN, 2001) [7], plugging in the assumed values: Q_v=7 x 4 x 20 = 560 W. Here $\dot{V}$ is the fresh air volume flow rate.
Then the heat gain due to the presence of inhabitants is calculated, since the dwellers are heat source for the hypothetical house. It is assumed that for one person, there is 110 W heat gain. Therefore heat gain of hypothetical house from people is 4x110 = 440 W (ISISAN, 2001) [7].

Also it is assumed that there is no lighting load because the sunlight is sufficient for the considered times of the day. A heat gain of 1,000 W is assumed from household devices such as refrigerator, television and computer (ISISAN, 2001) [7]. After adding all these heat gains, the total heat gain of the hypothetical house is found to be 5.48 kW.

3.2. Panel cooling calculations

In order to cool the hypothetical house, the pipes are assumed to be installed inside the walls and ceiling as shown in Figure 4. Tap water which is taken from the municipality water system will be circulated in these pipes and be given back to the municipality water system. To understand whether the cooling capacity of the tap water is sufficient, heat transfer to the walls has been calculated. First heat transfer by convection and radiation is analyzed. Then heat resistance of the panel has been evaluated. After that average water temperature is found and necessary pipe length has been determined. By knowing the pipe length and pipe properties, the pressure drop is calculated and the required pump work is assessed.

Fig. 4. Sample wall cooling system (Yensis) [8]

3.2.1 Heat transfer to the water by convection and radiation

In order to calculate the heat transfer from the room to the wall, mean radiant temperature (MRT) method has been used. By using this method, the radiant heat flux is calculated using the following equation (ASHRAE, 2008) [2]:

$$q_r = 5 \times 10^{-8} \left[\left(T_p + 273.15 \right)^4 - \left(T_{AUST} + 273.15 \right)^4 \right] \tag{1}$$

Where, T_p is the effective panel surface temperature in ^oC, T_{AUST} is the area-weighted temperature of all indoor surfaces of walls, ceiling, floor, windows, doors, etc. In the hypothetical house T_p is assumed to be 23 ^oC and T_{AUST} is assumed to be 26 ^oC. By substituting the values into the equation q_r is found to be -15.82 W/m^2.

After that, cooling by convection is calculated. Natural convection heat flux between cooled ceiling surface and indoor air is calculated using the formula (ASHRAE, 2008) [2]:

$$q_{c-ceiling} = 2.42 \times \frac{|T_p - T_a|^{0.31}(T_p - T_a)}{De^{0.08}} \quad (2)$$

Natural convection heat flux between cooled wall panel surface and indoor air is calculated using the formula (ASHRAE, 2008) [2]:

$$q_{c-wall} = 1.87 \times \frac{|T_p - T_a|^{0.32}(T_p - T_a)}{H^{0.05}} \quad (3)$$

where, T_p is 23 ^oC, T_a which is designated dry-bulb indoor air temperature is 26 ^oC, D_e which is the equivalent diameter of the panel (4 x area/perimeter) is 10 meters and H which is the height of wall panel is 2.7 meters. By using these values $q_{c\text{-}ceiling}$ is found to be -8.48 W/m^2 and $q_{c\text{-}wall}$ is found to be -7.58 W/m^2.

3.2.2 Thermal resistance of panel

In order to calculate the average water temperature, thermal resistance of active panel surface should be calculated. Thermal resistance of panel affects the heat transfer to the pipes. Lower the thermal resistance higher the heat transfer. To calculate the thermal resistance of panel the following equation is used (ASHRAE, 2008) [2]:

$$r_u = r_t M + r_s M + r_p + r_c \quad (4)$$

where M is the spacing between adjacent tubes, r_t is the thermal resistance of the tube wall per unit tube spacing in a hydronic system, r_s is the thermal resistance between tube and panel body per unit spacing between adjacent tubes, r_p is the thermal resistance of the panel body, r_c is the thermal resistance of active panel surface covers, r_u is the characteristic (combined) panel thermal resistance.

In the hypothetical house, the tubes are embedded in the plaster. When the tubes are embedded in the plaster, r_s may be neglected. Also in the sample house there is only painting on the surface, therefore thermal resistance of painting may be neglected.

The r_p of the panel may be calculated by using the following formula (ASHRAE, 2008) [2]:

$$r_p = \frac{x_p - \frac{D_o}{2}}{k_p} \quad (5)$$

where D_o is the outer diameter of the pipe, x_p is the distance between the center of the pipe and the inside surface of the wall and k_p is the thermal conductivity of the plaster.

For the hypothetical house, x_p is 0.0305 m, D_o is 0.021 m, k_p is 1.00 W/mK. Therefore, r_p is calculated as 0.009 m^{2}K/W. To calculate r_t for circular tubes the following formula is used (ASHRAE, 2008) [2]:

$$r_t = \frac{\ln(D_o \div D_i)}{2\pi k_t} \quad (6)$$

where D_i is the inner diameter of the pipe and k_t is the thermal conductivity of the pipe. For the hypothetical house D_o is 0.021 m, D_i is 0.017 m and k_t for pipe made of PEX is 0.38 W/mK. Therefore r_t=0.088 m^{2}K/W. As a result r_u=r_tM + r_p = 0.022 mK/W for M=0.15.

3.2.3 Panel design

The average skin temperature of the tubing and the average circulating water temperature are the determining factors of the system. Panel surface temperature is determined to be 23 ^oC and for this temperature value the needed average water temperature should be calculated. Average water temperature depends on the thermal resistance of the panel, spacing between adjacent tubes, indoor design temperature, and panel surface temperature.

In order to find the average skin temperature of the tubing the following equation is used (ASHRAE, 2008) [2]:

$$T_d \approx T_a + \frac{(T_p - T_a)M}{2W\eta} + q\left(r_p + r_c + r_s M\right) \tag{7}$$

where T_d is the average skin temperature of the tubing, q is the combined heat flux ($q = q_c + q_r$) on panel surface, T_a, the air temperature may be replaced by T_{AUST}, 2W is the net spacing between tubing, and η is the fin efficiency. In order to calculate fin efficiency the following equations are used (ASHRAE, 2008) [2]:

$$\eta = \frac{\tanh(fW)}{fW} \tag{8}$$

$$\eta \approx 1 \div fW \; for \; fW > 2 \tag{9}$$

where, f is calculated using the following formula (ASHRAE, 2008) [2]:

$$f \approx \left[\frac{q}{m(T_p - T_a)\sum_{i=1}^{n} k_i x_i}\right]^{0.5} \tag{10}$$

where, $m = 2 + r_c/2r_p$, n is the total number of different material layers including panel and surface covers, x_i is the characteristic thickness of each material layer, k_i is the thermal conductivity of each layer.

In the hypothetical house q is found to be -23.85 W/m^2 using the q_r and q_c values obtained in section Heat transfer to the water by convection and radiation, $\sum_{i=1}^{n} k_i x_i$ is obtained to be 0.00976 W/m, m is 2, f is 20.18 and W is 0.0645 m. With these, η is found to be 0.662 and T_d is found to be 21.15 ^oC. After, in order to find the average water temperature circulating through the pipes the following formula is used (ASHRAE, 2008) [2]:

$$T_w = (q + q_b)M r_t + T_d \tag{11}$$

where q_b is the back and perimeter heat losses. For the hypothetical house $q+q_b$= -26.71 W/m^2, then T_w= 20.80 ^oC which means in order to meet the cooling need of the hypothetical house, average water temperature circulating through the pipes should be 20.80 ^oC.

T_w value can also be determined using the design graph presented in Figure 5 provided the thermal resistance of the panel, the heat flux of the hypothetical house, and the appropriate geometrical pipe parameters.

3.3 Heat transferred to water

In order to determine the length of a pipe section, to be installed inside the walls and the ceiling, that satisfies the average circulating water temperature found in the previous section, first the heat transferred to water is calculated using the following equation (ASHRAE, 2008) [2]:

$$q_w = 1000\dot{m}c_p\Delta T \qquad (12)$$

where q_w is the heat transfer rate to water, $\dot{m}$ is the mass flow rate of the circulating water, c_p is the specific heat of water, and ΔT is the water temperature increase across one pipe section.

In the hypothetical house, it is assumed that municipality water temperature is 20 ^oC and the exit temperature of municipality water is 21.60 ^oC because average water temperature is 20.80 ^oC. Therefore ΔT is equal to 1.60 ^oC.

Also it is assumed that the velocity of the water inside the pipes is 0.5 m/s to prevent noise and it is known that inside diameter of pipe is 0.017 m. Therefore the mass flow rate $\dot{m}$ is equal to 0.113 kg/s. It is assumed that c_p of water is 4.187 kJ/kgK. By plugging in the values to the equation, q_w is found to be 757 W. It means that the water can absorb 757 W while circulating at an average temperature of 20.80^oC. It is found in section Panel design that the total heat transfer to the water pipes of the system is equal to 26.71 W/m^2. Therefore at most 28 m^2 of wall area is needed to provide this average water temperature. In the hypothetical house 205 m^2 cooling panel is available which means 8 sections of pipe is needed.

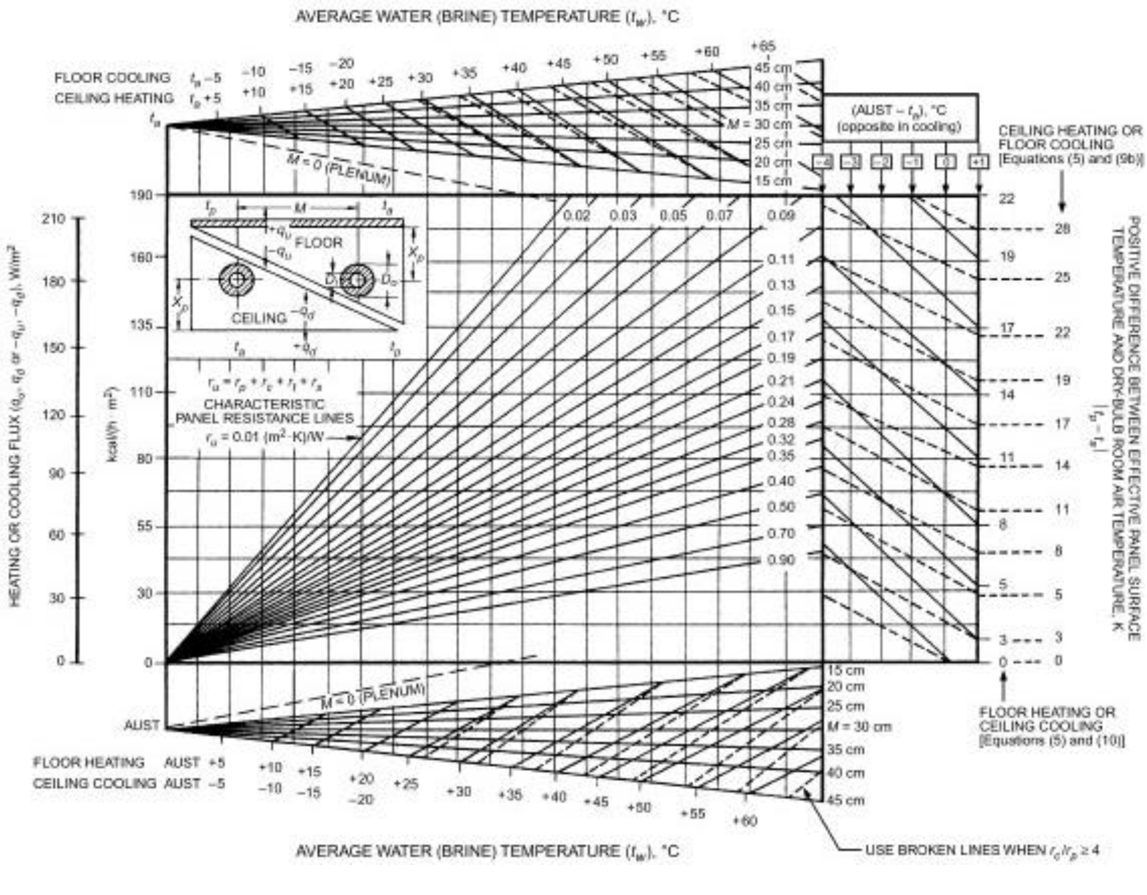

Fig. 5. Design graph for sensible heating and cooling with floor and ceiling panels (ASHRAE, 2008) [2]

4. Pressure Drop and Pump Work

Pressure drop in pipes affects the system efficiency: Lower pressure drop means higher system efficiency, because it directly affects the needed pump work of the system. In order to achieve low pressure drop, due to its relatively small friction factor PEX pipes are used. In order to calculate friction factor in pipes the following equation is used (Cengel, 2003) [9]:

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon \div D}{3.7} + \frac{2.51}{R_e\sqrt{f}}\right) \tag{13}$$

where f is the friction factor, Ɛ/D is the relative roughness of the inside surface of the pipe and Re is the Reynolds number. Reynolds number is given by the following equation (Cengel, 2003) [9]:

$$R_e = \frac{\rho V D}{\mu} \tag{14}$$

where ρ is the density, V is the velocity, D is the diameter of the pipe and μ is the dynamic viscosity. The density of water is taken to be 998.43 kg/m^3, the velocity of the flow is 0.5 m/s, pipe inner diameter is 0.017 m and dynamic viscosity is 0.001 Pa·s. Then the Reynold's number is found to be 8,486 and thus the pipe flow is assumed to be turbulent. The relative roughness of the PEX pipe is taken to be 7.6 x 10^{-5} and the friction factor, f, is calculated as 0.03238. The pressure drop of the water flow inside the pipe is then calculated using the following formula (Cengel, 2003) [9]:

$$\Delta P = f\frac{L}{D}\frac{\rho V^2}{2} \tag{15}$$

where L is the length of one section of the pipe. For the hypothetical house L is calculated to be 198 m. Thus the pressure drop in one such pipe section is 47.07 kPa.

In order to determine the system efficiency, the pump power input is calculated. In the hypothetical house for one section of piping the volume flow rate is equal to 0.113 L/s. In the hypothetical house there are 8 pipe sections, therefore the total volume flow rate is equal to 0.904 L/s. Major head loss is evaluated to be 4.8 meters. Minor head losses are neglected. With these values, the necessary pump work for the hypothetical house is found by using the following equation (Munson et al., 2012) [10]:

$$\dot{W} = \gamma Q h \tag{16}$$

where γ is the specific weight of the water, Q is the mass flow rate and h is the pump head. For the hypothetical house the minimum required pump work is found to be 42.48 W.

5. Conclusions

In this paper, a study of using municipality water for building cooling has been presented. First the cooling load of a hypothetical house is determined. The total cooling load is found as 5.48 kW. In order to meet this cooling load, the panel surface temperature is taken as 23 ^{o}C and the heat transfer flux by convection and radiation is calculated. Panel thermal layers are specified and the corresponding thermal resistance value is calculated. Then the distance between adjacent pipes is specified as 0.15 meter and by using the obtained values average water temperature is determined as 20.80 ^{o}C. After that, the required lengths of the pipe sections are determined. Later the pressure drop in one section of piping is evaluated and the necessary pump power is calculated.

The obtained results show that use of municipality water system for building cooling is a feasible and energy saving system in comparison to other conventional cooling systems. The system would need less than 50 W of pump power to provide 5.48 kW of cooling for the proposed hypothetical house. In this system cooling capacity of municipality water is used. Therefore it decreases the energy consumption of cooling units and presents an environmental friendly method for space cooling. Since the system's circulating fluid is regular water, there is no risk of contamination of environment. The envisioned system would provide higher total human comfort level.

However it is not possible to use this system for all buildings of a city. Therefore, there should be a permission from municipality to use this system. However, this system can be used in governmental buildings such as hospitals, police stations, municipality service buildings, etc. Therefore the proposed system is a promising one and deserves further research.

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