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Demand Side Management for Smart District Heating

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Abstract

The influence on the district heating network design and operation by using the energy storage capability inside the building is studied on different types of buildings under Danish climate. The building envelope has significant role in buildings energy consumption but also in building time constant. The results show that by the extensive renovation the energy consumption and the peak load could be reduced with more than 55% for two heating systems: radiant floor heating and radiators convective heating. Light renovation case has the peak load and energy consumption decreased with values between 25% and 35%. By making the light renovation, the heating system needs a minimum supply water temperature of 58ºC in order to cover the thermal comfort. Through extensive renovation, the supply water temperature could be reduced to 50ºC which makes it possible to transform the District Heating Temperature into Low Temperature. The building time constant for the extensive renovation is 86 hours which is double than a light building renovation and 53 hours higher than a non-renovated building. In the end of the paper is developed a formula which has the purpose to validate the results of virtual simulations. The relative percentage difference between the theoretical calculation and the virtual simulation results are between 2.5% and 17.5%.

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*Keywords:*Smart District Heating; Energy Performance; Thermal Response of Buildings; Time Constants.

1. Introduction

The aim of this paper is to investigate the impact of energy savings strategies on District Heating Network (DHN). The heating system type is also considered as it can affect the balance between energy consumption and peak loads. Other characteristics that will be looked into are the building's envelope proprieties which can influence the heat storage capacity of the building, the peak load, and the energy consumption. It is analyzed also the indoor temperature decay of three types of buildings by using virtual simulation and theoretical calculation. The software program used to make the virtual investigations presented above is mainly IDA ICE [EQUA 2013] version 4.6.1.

2. Methods

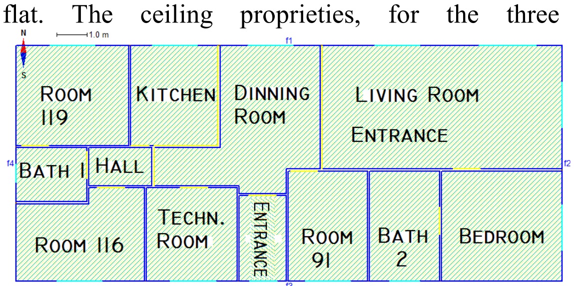
The following chapters include virtual simulations of indoor environments. The same building model was used for all investigations using the software IDA ICE 4.6.1 which is a dynamic simulation tool. Mainly, the simulations were focused on the yearly energy consumption and the peak loads. In the last chapter a mathematical calculation is developed and further the results are compared with the virtual simulations results.

2.1. Heating System Design

The space heating system is designed according to DS418. Two heating systems were designed: floor/radiant heating and radiators/convective heating. The heat output were adjusted by proportional controllers which have the target set points the "Operative temperature" of 20°C. The proportional temperature controller was set to a dead band of 0.5°C, which means that the radiators will start heating from a temperature of 19.75°C and will stop at the temperature of 20.25°C[1].

3. Building Description

In this section is described the characteristics of the building being investigated. It is investigated a single family house which has one floor, i.e., the ground floor with a total floor area of 140 m^2. The building has 12 rooms (Figure 7) with an interior height of 2.6 [m]. The roof of the building is considered flat. The ceiling proprieties, for the three investigated cases, are given in Table 1.



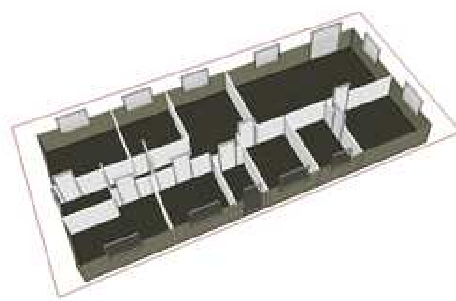


Fig. 1. (a) Building geometry; (b) 3D view

Table 1. Construction proprieties

Material	Thickness [m]	Thermal Conductivity [W/mK]	Density [kg/m^3]	Specific Heat Capacity[J/kgK]
Ceiling for existing and light renovation (from inside to outside)				
Wood	0.016	0.14	500	2300
Rockwool 45 wood 63	0.1	0.05587	47.6	858.3
Ceiling for heavy renovation (from inside to outside)				
Wood	0.016	0.14	500	2300
Rockwool 45 wood 63	0.4	0.05587	47.6	858.3

The building is located in Copenhagen, thus the weather file for this location were used. Three types of houses were investigated: the existing building which is built in 1950 and two cases of renovation: light and extensive renovation respectively (Table 2).

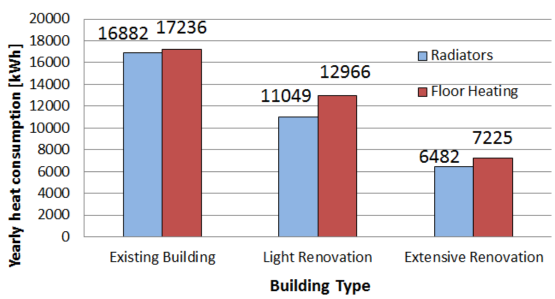
4. Possibilities of Low Temperature District Heating

The aim of this chapter is to investigate if the existing system could be used for low-temperature district heating, if the building will be renovated at different stages. By making the light renovation the heating systems needs a maximum supply temperature of 58°C in order to cover the thermal comfort. Through

Table 2, Windows proprieties

	Existing Building	Light Renovation	Extensive Renovation
g (SHGC)	0.76	0.63	0.5
T	0.7	0.6	0.38
Tvis	0.81	0.78	0.65
U [W/m^{2}K]	3.2	1.5	0.9
Frame fraction [0 -1]	0.1	0.1	0.1
Frame U [W/m^{2}K]	3.2	1.5	0.9
Envelope Infiltrations [L/m² floor]	0.3269	0.27793	0.27793

extensive renovation the supply temperature could be reduced to 50°C which makes it possible to transform the DH into Low Temperature. Therefore, if it is desired Low Temperature District Heating, heavier renovations should be considered, but also with light renovations lower temperatures can be achieved. The yearly heating demand and peak load are presented in Figure 2. It can be observed that the renovation levels have a significant impact on the building energy consumption. Regarding the two heating systems investigations, there are recorded different consumptions and peak loads. For the existing building study, the difference is smaller in comparison with the two cases where the houses were renovated. The yearly energy consumption for the floor heating is higher with 2%, 15% and 10% in comparison with radiators consumption. The peak load for radiators is smaller with 14%, 19% and 17% in comparison with the floor heating peak loads.



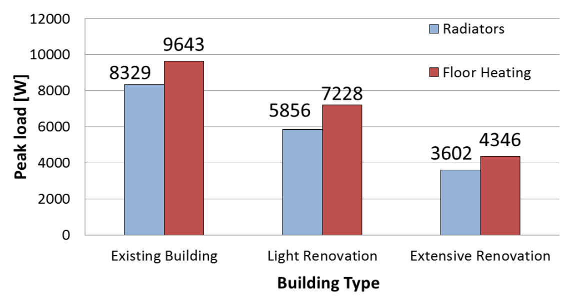


Fig 2. *(a)* Yearly heating demand (b) Peak load of different buildings type

In both graphs it can be seen that floor heating has higher energy consumption and peak load compared with the radiators [2]. This could be explained by the fact that radiant heating systems need to heat the thermal mass of the floor and afterwards the air temperature is heated by convection, thus the floor hot surface warms up the indoor air [3]. Another reason of higher consumption is due to the floor connection with the soil. While in the case of radiators the thermal energy is transferred much easier to the indoor air by direct convection.

The building envelope has a significant influence on the DHN design and operation. The yearly energy consumption and the peak load are greatly reduced by simple renovations and this leads to lower pipes dimensions and lower power DH plants when future networks are planned. By making a light building renovation the yearly energy consumption is reduced with 35% for the radiators convective heating and 25% for the radiant floor heating, and the peak load is reduced by 30% for the radiators case and 25% for the FH heating system. The extensive renovation has even higher reductions over 55% for the peak load and yearly energy consumption for both heating systems.

5. Building Time Constant

5.1. Temperature Response of different Building Types Having One Zone Representation

The time constant could be computed by executing a few simulations in IDA ICE. Firstly, it was investigated the time constant of a building having a single zone (Figure 3) [4]. It was created a weather

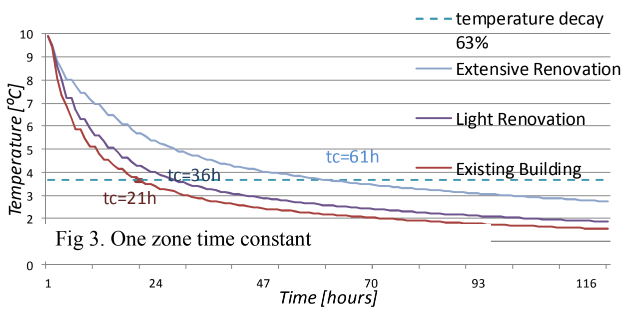


Fig 3. One zone time constant

file having a constant temperature of 10 degrees, with no solar radiation no wind conditions and no air humidity and the model has no internal gains [5].

The constant temperature was kept until a steady thermal indoor condition was reached; afterwards a step change was applied so the ambient temperature was reduced to 0 °C. From that point the indoor temperature drop is recorded. Thus, the stored energy in the building thermal mass is released to the ambient air, and depending on the thermal mass properties (light, heavy...) it will determine the temperature drop.

In Figure 3 is shown the time constants of the three types of buildings. It can be seen that even though there is no thermal mass, the time constants are still high. As it was expected the existing building is the first building which has the fastest temperature drop, followed by the light renovation building and the extensive renovated building

5.2. Temperature Response of Different Building Types Having 12 Zones representation

In the multiple zone building, the time constant must be analysed individually for each zone. However, the same methodology, to find the time constant, was applied as for the one zone investigation. Generally, the small zones have a higher time constant due to their low exposure to the outdoor environment (Fig. 2).

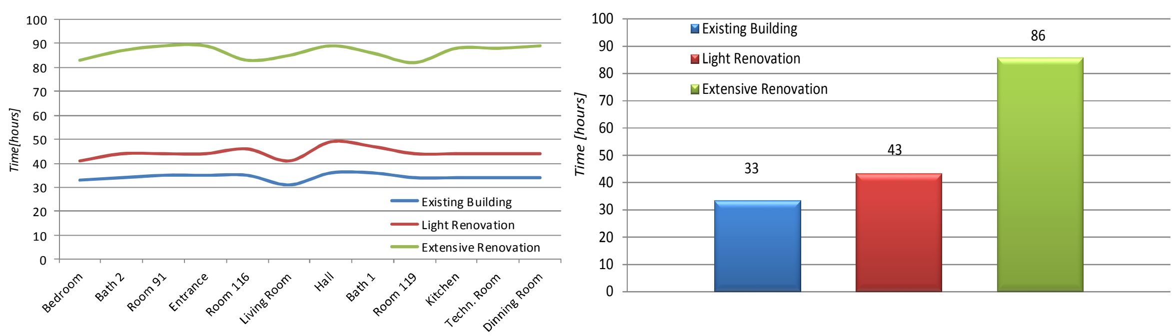


Fig 4. (a) Multiple zones time constant; (b) Zones summing up

The time constant for each building (Figure 4 (b)) was found by summing up the zones. The new time constants are higher than the one zone time constant. But, the increase of the time constant is different for each type of building: for the existing building time constant is higher with 36%, Light renovation with 16% and the extensive renovation is bigger with 29%. As it can be seen in the figures above the time constant is considerably influenced by the internal masses especially by the internal walls [6]. Therefore, the building time constant cannot be accurately determined by a single zone representation of the entire building.

5.3. Thermal Decay of Radiant Floor Heating and Radiator Convection Heating

In this section simulations of the two heating systems are made in order to find the room temperature response when the two different heating units are turned off. One week simulations are made with the same settings as for a realistic situation, except on internal heat gains which were set to zero. During this week the temperature set point is 20°C. On the fifth day of the week the heating system is completely turned off. The temperature decay analysis was made at room level (Bedroom-Figure 5).

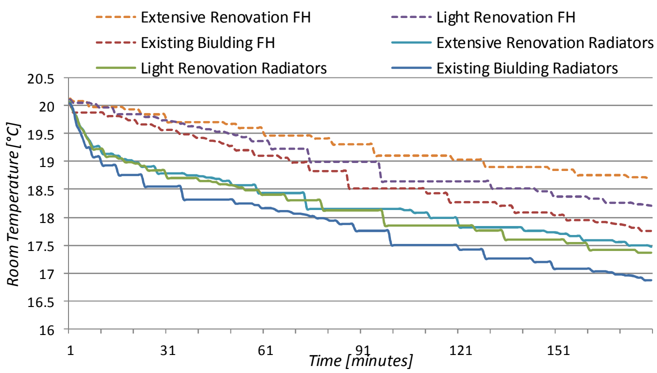


Fig 5. Bedroom's Temperature Decay

Figure 5 shows the time when the heat supply was stopped. The radiant heating (FH) has a slower decrease of temperature compared with the convection heating (radiators) cases. Even the existing building with radiant heating has slower temperature decay than the extensive building with convection heating. This is due to the capacity of the floor to store heat. After the heat unit is stopped the floor is releasing heat indoors, so the temperature has a slower decrease in the first hours. In the case of extensive renovated building, in three hours, from 12:00 to 15:00 the temperature drop of radiators is 2.5°C, while the FH system reaches 1.3°. Also the other two buildings types have a different temperature drop between FH and radiators, but with a smaller difference of 0.9°C for the existing building and of 0.84°C for the light renovated building.

5.4. Room temperature Variation after Heating Load Reduction

This subchapter is made with the purpose to verify/validate the results obtained through virtual simulations, with the results found by using a formula. Therefore, it will be made a result comparison between the two methods. The two methods will be used to evaluate the room temperature variation after heating load reduction.

5.5. First method: Forecast of Room Temperature by Theoretical Calculation (formula approach)

The formula to calculate the room temperature variation after heating load reduction is presented below:

$$T_i=(T_s-T_0)\mathcal{X}+T_0+(Ts-Ts\mathcal{X}+T0\mathcal{X}-T0)\exp(-t/\boldsymbol{\tau}) \quad (1)$$

where T_i is the room temperature after the heat reduction was applied, $\mathcal{X}$ is the heating load variation, $\mathcal{X}<1$ is the load reduction ($\mathcal{X}>1$: load increase; $\mathcal{X}=0$: no variation (constant heat supply)),

$$\mathcal{X}=q/q_0; \quad (2)$$

where q is the actual heating load during this time period, q_0 is the heating load calculated based on initial temperature difference (T_s-T_0), T_0 is the ambient temperature, T_s is the room temperature at the beginning (room temperature is constant 20ºC), $\boldsymbol{\tau}$ is the time constant[7].

Based on equation (1), it can be calculated the room temperature variation for each time step. The main reason of developing this formula is to find out the percentage of extra energy needed in different situations. For example if we want to increase the room temperature from 18 to 20ºC in 2 hours, what will be the percentage of extra energy? How much energy do we need to have 20ºC in 2 hours? In this investigation is involved multiple variables, among them the most important can be considered the weather conditions, the ambient temperature, the time constant of the building or the internal gains.

On the other hand, the same formula can be used for load heating reduction (Setbacks strategies). We would like to know the room temperature after a period time while the heat load was reduced with a specific percentage. For example what would be the room temperature after 1 hour, (or after 2, 3… hours) if the heat supply was reduced with 10% (or 15, 30%).

5.6. Second method: Forecast of Room Temperature by Virtual Simulations

Therefore, it is built up a model having no solar gains. The ambient temperature (T_0) is set to a constant temperature of -12ºC. Due to software's limitations, it is shown only static simulations results. The dynamic simulations give wrong/unexplained results; therefore they are not presented in the paper. The room temperature (T_s) is set also to be constant at 20ºC. The virtual simulation was running until the indoor temperature reached a constant temperature of 20 ºC. Afterwards the heating system was stopped and respectively the indoor temperature decreased.

Table 3. Room temperature variation after heat load reduction

Ts [°C]	T0 [°C]	X	Tsx [°C]	T0x [°C]	t [h]	τ [h]	Ti [h]
20	-12	0	0	0	10		
Existing Building	Equation (1)					33	11,63
	Virtual Simulations	with IG	Radiators				10
			FH				11,97
		No IG	Radiators				8,47
			FH				10,48
Light Renovation	Equation (1)					41	13,07
	Virtual Simulations	with IG	Radiators				12,04
			FH				13,41
		No IG	Radiators				11,18
			FH				12,05
Extensive Renovation	Equation (1)					83	16,37
	Virtual Simulations	with IG	Radiators				14,18
			FH				14,93
		No IG	Radiators				13,23
			FH				14,04

Note: *IG – internal gains, FH – floor Heating; Ts, T0, X, Tsx, T0x, t, τ, Ti – are explained in subchapter 5.5.1*

5.7. Results

It can be seen, also in this investigation, the advantage of radiant heating where the temperature decay is slower than the convective heating system. If we judge the system (radiant system) from this point of view, it has an asset in front. Mainly, in all the types of simulations the convective heating has faster temperature decay.
First thing which can be observed is that the FH system has closer results to the formula outcome. Thus the discrepancy between the FH and the hand calculation is smaller. In general the simulations with internal gains present more suitable results with the outcome of the formula.

In conclusion, the best fit between virtual simulation and the theoretical calculation is the case of radiant heating (FH) with the presence of internal gains. However, the formula does not take into consideration the internal gains. Thus, if we want to have a more reliable comparison between the theoretical calculation and virtual calculation, we need to consider only the case with no internal gains.

6. Conclusion

The yearly energy consumption and the peak load are greatly reduced by simple renovations and this leads to lower pipes dimensions and lower power for DH plants when future networks are planned. The temperature stability of the radiant heating system (FH) is better than the radiator heating, but the energy consumption is higher. The temperature decay and increase temperature speed is higher for the convection heating system. The time constant is different for every type of building depending on building envelope and internal masses. In order to determine accurately the time constant, the buildings must be modelled according to their thermal configuration, including their internal walls. The developed formula has closer results to virtual simulation for the radiant heating system. The theoretical calculation is in the first stage of development and it needs further improvements and validation. Moreover, it can be added more variables into its structure, but first it would be relevant to validate the base/simple form of it.

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