Cooling Demand and Indoor Temperatures of a Detached House in Southern Finland: Feasibility of a Monthly calculation Method

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Abstract. The aim of this study was to compare dynamic thermal modelling with a monthly calculation method based on a European standard and Finnish regulations. Effect of thermal insulation level of a building envelope, solar shading, solar heat gain coefficient and window area on cooling demand were also studied. Increasing the thermal insulation of building shell increased indoor temperatures and hence cooling demand considerably. Solar shading by blinds between window panes decreased indoor temperatures effectively, indicating the performance of passive cooling in Finnish climate. There were rather large differences between calculated indoor temperatures and cooling demands between the two methods although both methods were able to take into account differences between variations in building shell. According to the study, the monthly calculation method underestimates the cooling need which can be significant considering the energy consumption of buildings. Therefore, it is recommended to investigate both summer temperatures and the cooling energy needs of detached houses by modelling.

Keywords: Thermal comfort, energy efficiency, cooling demand

1. Introduction

1.1. Background of the study

The efforts of European Union (EU) towards energy efficient buildings have caused building energy efficiency regulations to change over the past decades. In some countries, especially in northern Europe, this has led to increasing insulation levels, which can cause overheating in summer [1].

Sirén and Hasan [2] evaluated the cooling energy demand of an office building as part of the Finnish implementation of the Energy Performance of Buildings Directive (EPBD) [3]. The study concluded that for the cooling estimation, the monthly quasi-steady state method should be used as part of the Finnish implementation for the EU Directive. Van Dijk et al. [4] have also concluded that simplified models are sufficient for the analysis of the energy demand and consumption for heating and cooling in the support of policymaking. On the other hand, Corrado et al. [5], Ballarini et al. [6] and Kokogiannakis et al. [7] have found considerable deviations between energy needs calculated by a quasi-steady state method and by dynamic models.

According to the Part D5 of National Building Code of Finland (NBCF) 2007 [8], cooling energy calculations could be performed by a monthly calculation method. The method described in NBCF was based on European Standard EN ISO 13790 [9], now replaced by EN ISO 52016-1 [10]. The standard included a monthly quasi-steady state method, based on a monthly balance of heat losses and heat gains determined in steady-state conditions [11]. In these methods, dynamic effects are taken into account by using correlation factors [4]. Once these factors are determined, the calculations are rather straightforward. However, the factors must be determined individually for various situations, including different climate zones, building types and schedules of users or occupants [11]. Part D5 of NBCF 2007 [8] provided a practical alternative for simulation and was properly adapted to Nordic climate conditions. In 2012, the code was revised requiring dynamic calculation method for calculating indoor temperatures and cooling energy need. However, the legislation left out the cooling energy calculation requirement for detached houses.

Indoor temperatures have been regulated since 2003 when Part D2 of NBCF 2003 came into effect. It recommended to keep temperatures below +25 °C. During periods when outdoor temperature is higher than +20 °C for five hours, the limit was +30 °C. According to the present Decree of the Ministry of the Environment (1009/2017), the upper limit of indoor temperature is +25 °C during heating season and +27 °C outside heating season.

Effects of the climate change will increase cooling need in Finland. Cooling energy demand is expected to increase 40–80% by 2100 in residential houses [12] and 20-75 % in offices and flats [13]. Growing number of heat pumps will obviously lead to growing cooling energy use. Air-to-air pumps have become very popular because of energy saving potential in houses with direct electric heating (radiators or floor heating). Ground-source heat pumps provide energy savings in houses with water radiators when, for instance, old oil burners need to be replaced. About 730000 heat pumps of all types were installed in Finland by the end of 2015 [14] and the number has been constantly growing.

1.2. Research aims

The aim of this study was to find out how the EN ISO 13790 -based calculation method of D5 NBCF 2007 compares with a dynamic calculation model when calculating summer temperatures and cooling energy consumption. D5 NBCF 2007 has no legal status any more but is still perhaps the most advanced method in its category. It includes the necessary information and calculation formulas for analysing energy efficiency and thermal comfort in Finnish climate conditions. Another goal of this study was to find out if there is a need for regulatory demand for cooling energy calculations in detached houses, and how should those be implemented when aiming for energy efficiency. The influence of different thermal insulation levels, solar heat gain coefficient, window area and solar shading was also studied. Because of geographical position of Finland at high latitudes, approximately between 60° and 70° N, sunrays meet Earth at smaller angles than at lower latitudes. This naturally affects on the performance of different passive cooling methods. On the other hand, total amount of energy absorbed during a long summer day is even higher than those at the equator, underlining the importance of thermal comfort control in summer.

2. Materials and methods

2.1. Calculation methods

The calculations with the monthly average values of temperature and cooling energy demand were performed according to part D5 NBCF 2007 [8]. Several parameters have been taken from parts D2 and D3 NBCF 2012 [15] [16] as these three documents have several cross-references. The monthly weather data used with the NBCF is presented on D3 NBCF 2012 [16] tables L2.1 and L2.2.

The comparative energy simulations were carried out using a dynamic simulation tool IDA Indoor Climate and Energy (IDA ICE) v4.7 software [17]. Dynamic models allow taking into account boundary conditions that change with respect to time. IDA ICE calculates energy balance dynamically utilizing hourly climatic data and heat fluxes. The physical systems from different domains are described using equations based on modelling stated in the Neutral Model Format. IDA ICE has been validated against several standards [18] and reviewed by Ryan and Sanquist [19], Bring et al. [20], Nageler et al. [21] and Travesi et al. [22].

The simulations are performed using hourly weather data from the Helsinki-Vantaa test reference year 2012. Information on the test reference year can be found in article by Kalamees et al. [12].

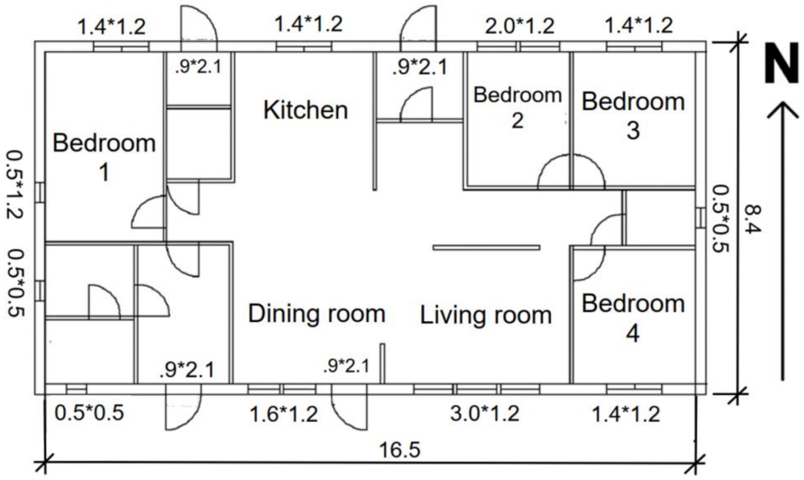
2.2. Studied building

2.2.1. Overview of the building. The study was performed as a case study. The analysed building was a hypothetical detached house in southern Finland at latitude 60°31'N, longitude 24°94'E, in climate conditions with roughly 4500 heating degree days at +17 °C basis. It was a lightweight timber-framed, one-story building with a concrete ground slab. The net area of the house was 138.6 m^2 and the height of the rooms was 2.5 m. The total window area was 15.99 m2 and the solar heat gain coefficient (SHGC) for the windows was 0.32 in the base case.

Possible cooling was implemented by electricity with room units. Two different heating methods were studied. The case A was heated by district heating and the case B by electric heating. To meet primary energy consumption requirements, case B received some energy efficiency improvements. The airtightness was improved; q50 was 0.5 instead of 2.0 compared with the case A. The case B also used the amount of 2000 kWh/a heating energy from a fireplace and 1000 kWh/a from an air-to-air heat pump. There was also totally 12 m^2 of solar collectors that partially heat domestic hot water (DHW). The energy savings with solar panels equalled 1872 kWh/a calculated with D5 NBCF 2012.

The building shell has very low thermal mass, as a typical Finnish lightweight timber-framed buildings does. Value for effective heat capacity inside the building has been adopted from Part D5 NBCF 2012 [15]. The used value, indicated per 1 m^2 floor area, was 70 Wh/(m^{2}K). The slab-on-ground floor structure contributes considerably to the value, almost a half of the number being due to slab-on-ground structure. For heavyweight construction, the effective heat capacity would have been almost threefold. The standard value of NBCF is 200 Wh/(m^{2}K) for heavyweight buildings. Therefore, heat transfer coefficients (U-values) of shell structures have a crucial role to the energy efficiency of the building. In Finland, low U-values of building shell are highly desirable considering heating energy consumption during wintertime. Energy regulations also require high U-values to save heating energy. Therefore, choosing U-values according to the heating need is a common approach on the Finnish building sector, in spite of the concern about summer overheating.

The floorplan of the house as well as the heat transfer coefficients are seen in figure 1.



U-values of the structures
Case A = district heating case
Case B = electric heating case
Units in (W/m^{2}K)

Structure	Case A	Case B
Roof/ ceiling	0.09	0.08
Exterior walls	0.17	0.11
Ground slab	0.25	0.25
Windows	1.0	0.72
Exterior door	1.0	0.66
Partition walls (in simulation)	0.47	0.47

Figure 1. Floor plan and shows the heat transfer coefficients (U-values) of the case A and B. In floor plan, north points upwards and units are in meters.

The ventilation rate was 0.4 $dm^3/(s{\cdot}m^2)$ for both cases, this being a standard value of building code D3 NBCF 2012 [16]. The heat exchanger of case A had an annual efficiency of 45%, the supply fan power was 1.5 $kW/(m^3/s)$ and exhaust fan power 0.5 $kW/(m^3/s)$. For Case B, the heat exchanger had an annual efficiency of 73%, the supply fan power was 0.9 $kW/(m^3/s)$ and exhaust fan power 0.4 $kW/(m^3/s)$. The supply air temperature was 18 ºC in both cases.

Heat loads were assumed evenly distributed. Internal heat loads from lighting and appliances equal the electricity consumption. The assumed use of the building was 24 hours per day 7 days a week and the thermal loads were 8 W/m^2 for lighting, 3 W/ m^2 for appliances and 2 W/m^2 per person (latent), which represents 1 person per 43 m^2. Utilization rate was 0.1 for lighting, and 0.6 for appliances and occupancy. For the district heating system, water radiators had an annual efficiency of 0.9. For the electric heaters in case B, the annual efficiency was 1.0. All these heat loads, utilization rates and efficiency coefficients were taken from building codes [15] [16].

The DHW transfer efficiency was 0.96 for both cases. Case B had a DHW tank with a heat loss from storing the DHW of 650 (kWh/a), half of which was calculated as heat load. Case A did not have DHW storage. The energy consumption for heating the water was 4200 kWh/a. The heat losses of DHW storage and circulation were added to this number.

2.2.2. Studied variations. The impact of passive cooling methods and performance of the monthly calculation method were studied. Table 1 shows the studied design strategies and a brief description of each strategy. Variation 1 was the base case, which would represent a typical house. In variation 2, simple passive cooling by solar shading was adapted. Variations 3 and 4 represented attempts to decrease heating energy need, without considering cooling energy need.

Table 1. Simulated case variations.

Description	Case variation code	
	Case A	Case B
Base case	A-1	B-1
Solar Shading: Blind between panes May - September	A-2	B-2
Solar Heat Gain Coefficient 0.61 instead of 0.32	A-3	B-3
Window area for the south facade increased 50%	A-4	B-4

3. Results

3.1. Indoor temperatures

During heating season, typical indoor temperatures in Finnish detached houses are within +21…+23 ºC. In this study, +21 ºC was used as heating set point. On the other hand, value of +25 ºC can be considered upper limit value for thermal comfort [23].

In the NBCF method, average rooms temperatures were calculated for the whole house as a single zone. Indoor temperatures reached peak values in July although extended temperatures occurred between May and September. Results of the calculations of the room monthly average temperature without cooling using the D5 NBCF (2007) are seen in figure 2 and figure 3. An obvious risk of summer overheating can be seen. The figures also indicate temperature rise during heating season (roughly between September and May) which obviously helps to save heating energy.

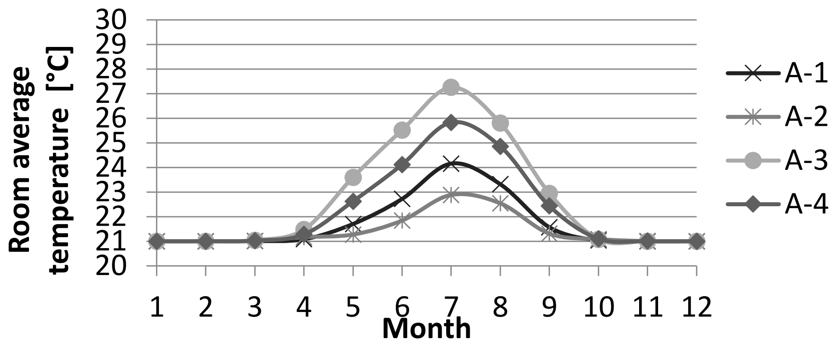


Figure 2. Average monthly room temperatures for case A calculated with D5 NBCF 2007.

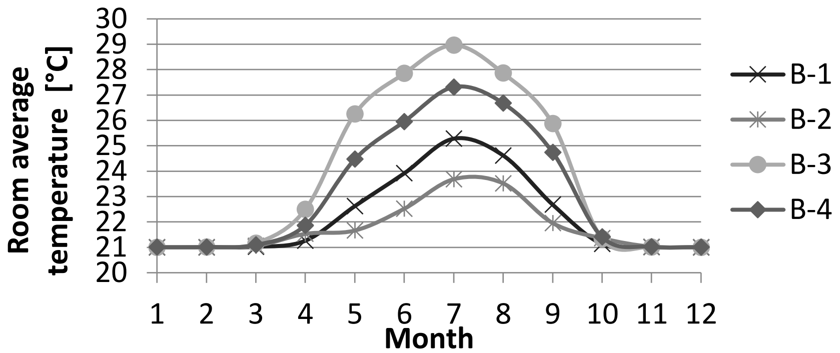


Figure 3. Average monthly room temperatures for case B calculated with D5 NBCF 2007.

In IDA ICE, the average temperature of the central space (dining/ living room, kitchen and hallway) corresponded quite closely to the average temperatures of the house and the temperatures of this room were calculated for comparison purposes. Table 2 presents the average indoor air temperatures calculated by both methods in July. NBCF estimated 0.2–2.4 °C higher average room temperature than IDA ICE did. The differences are greater in the more insulated case B than in case A.

Table 2. Average indoor air temperatures in July calculated by both studied methods in various cases.

Case variant number	Average indoor air temperatures [°C]			
	Case A		Case B	
	NBCF	IDA ICE	NBCF	IDA ICE
1	24.2	23.9	25.3	24.5
2	22.9	22.7	23.7	23.0
3	27.3	25.8	29.0	26.6
4	25.8	24.1	27.3	24.9

3.2. Cooling energy need

The cooling energy consumption was calculated by IDA ICE and D5 NBCF-2007 with different cooling set points. The results can be seen in figure 4, figure 5, figure 6 and figure 7. The results are expressed in kWh per square metre per year.

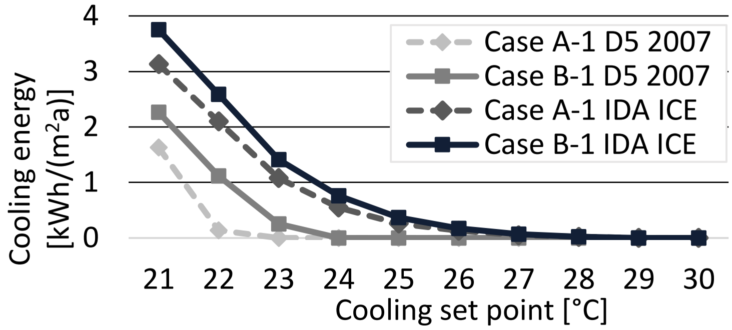


Figure 4. Cooling energy consumption of case variation 1 with different cooling set points.

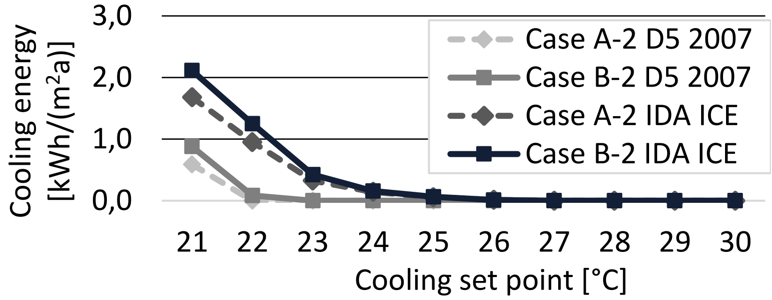


Figure 5. Cooling energy consumption of case variation 2 with different cooling set points.

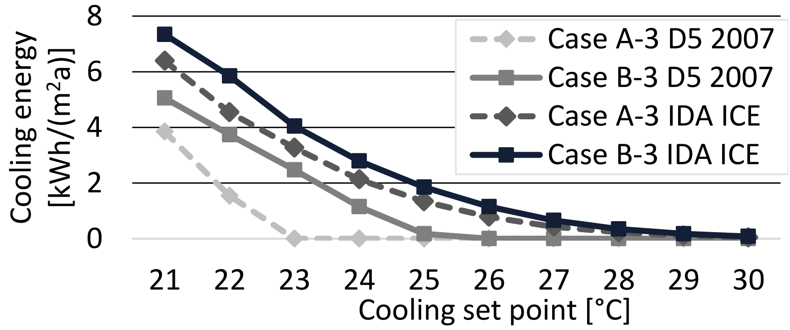


Figure 6. C. Cooling energy consumption of case variation 3 with different cooling set points.

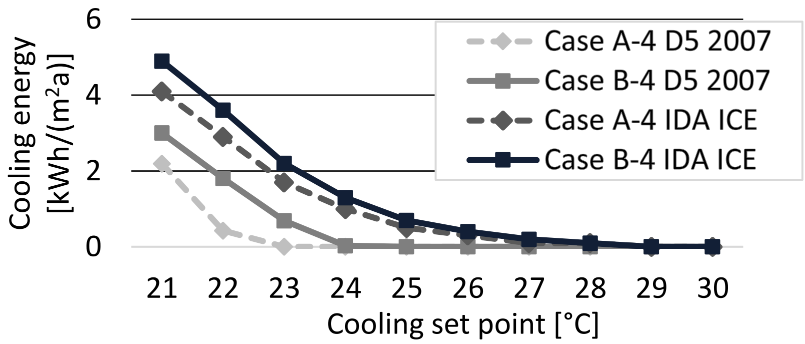


Figure 7. Cooling energy consumption of case variation 4 with different cooling set points.

Cooling energy consumption results of IDA ICE were higher than the NBCF results in all cases. According to simulations, cooling would be required with the set points as high as +28 °C. According to the monthly calculation method, cooling is not required with set points above +23 °C in case A and with set points above +24 °C in case B. Using blinds between panes during the summer months (May–August) (variant 2) decreased the cooling energy consumption by less with simulations. Using a higher SHGC value (variant 3) increased the cooling energy need proportionally less with simulations.

4. Discussion

In all studied cases, simulations resulted in higher cooling energy consumption than NBCF method did. In case B, the monthly cooling energy need calculations performed by NBCF method had better agreement with simulations than those in case A. The NBCF method required cooling with set point temperatures between +21 °C and +24 °C while simulation required cooling even with a set point of +28 °C. Therefore, it is questionable whether the studied monthly calculation method can recognize the cooling energy need. The problem has been noted in other countries, too. Revising the relevant parameters would improve the situation, at least on calculating year-round energy needs [11].

Heating and cooling energy needs have to be assessed together. Especially the studied variation 3 would result in uncomfortable summer conditions, thus creating a need for active cooling. The active cooling would somewhat compensate the energy savings due to solar gain during heating season. According to the present regulations, maximum total energy consumption values (E-values) for detached houses are within the range of 92…200 kWh/m^{2}a, depending on the size of the house [24]. Cooling energy demands can be at the magnitude of several %-units of these numbers, see figures 4-7. Hence, the cooling energy need is really an issue considering the whole building stock. Naturally, there are many ways to provide solar shading, e.g. long eaves. Combinations of several methods can also be used.

The monthly calculation method estimated higher average indoor temperatures than simulations. However, this did not cause cooling need according to the method. This is possible because the equation for cooling energy demand does not use room temperature as a variable but includes only cooling and heating set point temperatures and outside temperature. Moreover, it is to be noted that the monthly calculated method, which is based on average temperature, does not consider the highest temperatures of the month. Therefore, even if the average temperature is below the cooling set point, the cooling need can occasionally arise.

5. Conclusions

High indoor temperatures can be a problem even at high latitudes. Thus, reliable calculation methods are needed. A simple monthly calculation method can provide helpful assistance to building designers for evaluating the indoor temperatures in early stages of design. The studied method cannot always recognize the cooling need. The method could be improved but due to the development of dynamic simulation tools, the method may have only a little use in the future.

The most energy efficient solutions might not offer adequate summer thermal comfort. Thus, regulations should require assessing both cooling and heating energy needs when applying for a building permit so thermal comfort will not be neglected.

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