Influence of Building Envelope on the Sensitivity of HVAC System Energy Consumption

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Abstract

The energy performance of HVAC systems depends, in addition to their configuration and operational parameters, on the characteristics of the buildings they are coupled with. At the same time, the performance of buildings strongly depends on the outdoor climate. Among the climate factors that affect the energy consumption of buildings external temperature is the most influential. This fact is of concern since buildings are going to be exposed to increasingly higher external temperatures during their typically long lifetimes, according to the currently prevalent climate change scenarios.

In this paper the influence of building envelope characteristics on temperature-sensitivity of HVAC system energy consumption is investigated in a sample of five commercial buildings located in Ljubljana, the capital of Slovenia. The presented analysis is based on continuous 15-minute measurements of electric energy consumption of selected HVAC systems.

Keywords – HVAC system energy consumption; weather sensitivity; energy analysis; energy signature

1. Introduction

Climate change and phasing out fossil fuels as the major energy source are the major challenges facing mankind (apart from overpopulation) in the next century. Buildings play an important role in overcoming these obstacles, since they represent 30-40% of primary energy consumption in developed countries [1]. For example, the use of electrical energy for Heating, Ventilation, and Air-Conditioning (HVAC) systems in the 27 members of the European Union (EU) in 2007 represented 11% of total electric energy consumption or 313 TWh out of 2800 TWh [2]. Since the impact of climate change will result in a shift from heating energy to cooling energy according to Crawley [3], special focus must be put on energy efficient air-conditioning.

An important factor when dealing with HVAC systems energy efficiency, which is often neglected, is the building envelope. The effect of an energy efficient air conditioning system is nullified if the building has architectural and construction conditioned high cooling loads. Moreover, careless architectural design together with the predicted temperature rise, i.e.

2-4°C annual mean temperature increase by 2080 [4], may lead to inefficiency and malfunction of HVAC systems in addition to the increase in energy consumption and carbon emissions.

In this article an analysis of the influence of building fabric characteristics on the climate-sensitivity of energy performance of HVAC systems, based on real energy consumption data, is presented.

2. Methods

Five commercial buildings in Ljubljana, of which two are office buildings and three are retail buildings, were chosen for the analysis here denoted with capital letters from A to E, with different sizes (ranging from a single-story to a 21 story building) and characteristics (Table 1).

All buildings are equipped with one or multiple single duct (SD) constant air volume (CAV) air handling units (AHUs), whereby buildings B, C, D and E also have fan coil units (FCUs) installed to provide cooling (heating). Two of the buildings, namely buildings A and D, are also equipped with an ice thermal storage system.

For the analysis three building fabric characteristics were considered, namely the glazing ratio (R_g), heat capacity per unit area of wall area (C/A_w) and the roof ratio (R_r), which we defined as the ratio between the roof area and the overall envelope area. Building B stands out in terms of the building envelope because the air-conditioned area is only partly enclosed, therefore the considered building envelope characteristics were not determined for it.

HVAC energy consumption data was obtained from continuous 15-minute measurements of electrical demand of HVAC system components carried out within the IEE project ISERVcmb, i.e. AHU fans, chillers and chilled water pumps, whereby only chiller performance data was considered in this study. Meteorological data at 30-minute resolution was obtained from a local weather station. The collected data spans from four (building E) to eight months (building A) which is a sufficient amount even for daily resolution data according to Katimpula et al. [5].

The performance data was analyzed using the so-called energy signature method [6]. Energy signatures are essentially plots of energy consumption against the outdoor dry-bulb temperature or some other weather variable and can be used for monitoring and analyzing weather-related energy use. Since all of the observed buildings exhibited at least one change in the temperature dependency of chiller electric energy consumption (Fig. 1), piecewise linear regression [7] had to be applied to determine the changeover point and the regression coefficients on both sides of the latter. The regression coefficients serve as indicators of the temperature-sensitivity of the built-in air conditioning systems in this study and are termed coefficients of temperature-sensitivity (K_θ) here.

Table 1. Considered buildings overview

Building	A	B	C	D	E
Location	Ljubljana, Slovenia				
Building type	retail	retail	office	office	office
Number of Floors	2	1	2	21	6
Area conditioned [m^2]	25376,86	2604,32	1437,75	19125,54	7171,49
Volume conditioned [m^3]	89556,12	13143,22	3664,43	58994,4325	20080,17
Glazing ratio	0,013	-	0,108	0,693	0,371
Roof ratio	0,877	-	0,771	0,050	0,230
C/A_w [Wh/m^2K]	86,59	-	40,62	45,05	37,67
HVAC system	6 SD CAV AHUs	SD CAV AHU + FCUs	SD CAV AHU + FCUs	7 SD CAV AHUs + FCUs	6 SD CAV AHUs + FCUs
Chiller type	air cooled vapor-comp. liquid chiller	air cooled vapor-comp. liquid chiller	air cooled vapor-comp. liquid chiller	2 water cooled vapor-comp. liquid chillers	3 air cooled vapor-comp. liquid chillers
Cooling capacity [kW]	714,5	346	122,2	537/537	120/120/182
Cold storage system	yes	no	no	yes	no

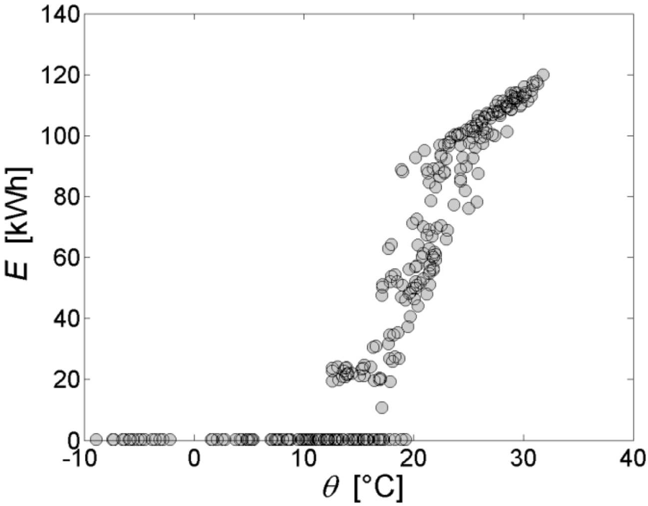

Fig. 1. Example of a chiller with a multiphased energy signature

3. Results

Before the analysis the data was pre-processed, i.e. to avoid occupancy variation the non-working days (weekends and holydays) were filtered out. Because buildings A and E were equipped with ice storage systems, as previously mentioned, periods during which ice was produced and used (Fig. 2) had to be avoided in addition to dividing the performance data with the air-conditioned volume to ensure that a comparison between buildings could be made.

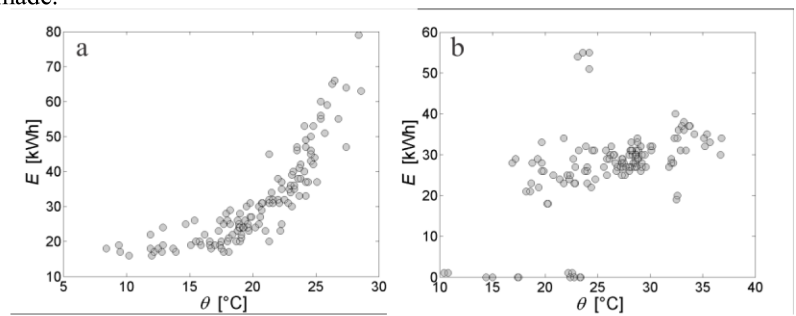

Fig. 2. Energy signature of building D: (a) during normal operation, (b) during ice utilization

The regression coefficients were determined from energy signatures plotted with 30 and 60-minute values from 9 a.m. to 10 a.m. Central European Time (CET). The values on the left side of the changeover points showed, in addition to higher scatter, little to no temperature-dependence as can be seen in Fig. 3 (probably parasitic energy use), therefore only the right-side regression lines along with their regression coefficients were considered relevant for the analysis. The results are listed in Tables 2-3 and shown in Fig. 4-6. It should be noted that a value of zero was allocated to the considered building envelope characteristics (C/A_w, R_g, R_r) for building B in order to compare its temperature-sensitivity coefficient K_θ against those of the other buildings.

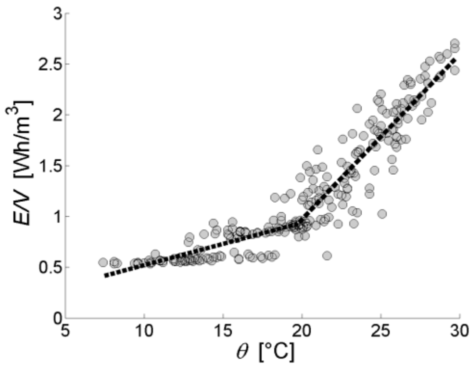

Fig. 3. Energy signature of building E from 30-minute values at 9-10 a.m.

Table 2. Changeover temperatures and coefficients of temperature-sensitivity determined at 9-10 a.m. with 30-minute values

Building	A	B	C	D	E
θ_{co} [°C]	16,62	22,28	19,73	22,58	21,75
K_θ [Wh/m^{3}K]	0,076	0,114	0,163	0,120	0,157

Table 3. Changeover temperatures and coefficients of temperature-sensitivity determined at 9-10 a.m. with 60-minute values

Building	A	B	C	D	E
θ_{co} [°C]	18,10	22,58	21,23	22,52	23,27
K_θ [Wh/m^{3}K]	0,177	0,236	0,364	0,245	0,360

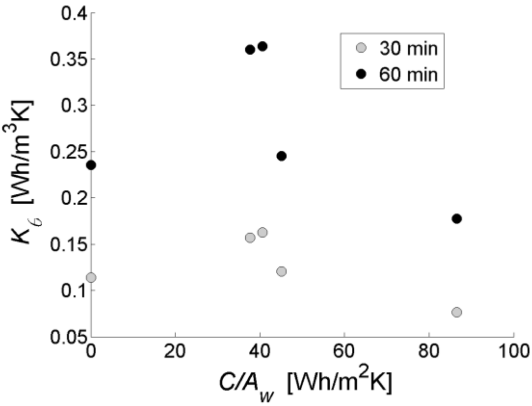

Fig. 4. Coefficient of temperature-sensitivity K_θ as a function of heat capacity per unit area of wall area C/A_w

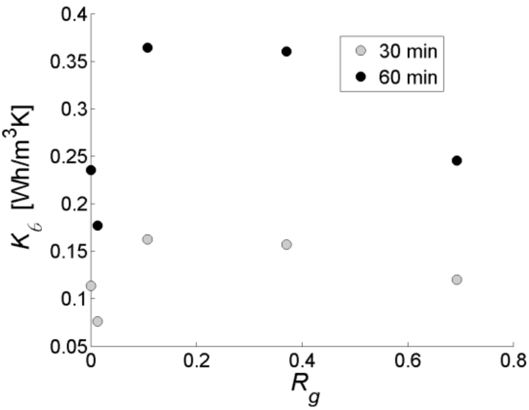

Fig. 5. Coefficient of temperature-sensitivity K_θ as a function of glazing ratio R_g

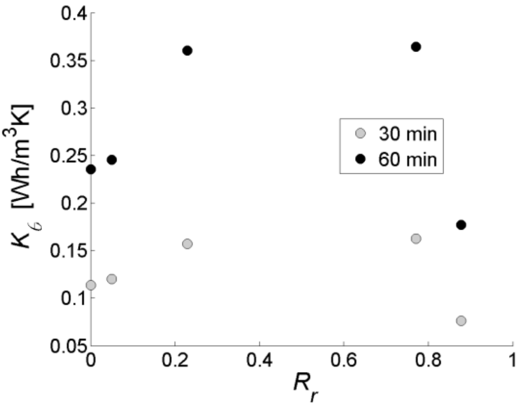

Fig. 6. Coefficient of temperature-sensitivity K_θ as a function of roof ratio R_r

As expected the coefficient of temperature-sensitivity decreases (exponentially) with C/A_w. The outliner (at zero C/A_w) corresponds to building B and can only be explained with the poor correlation between the energy consumption and temperature (Fig. 7) as temperature is not the only factor affecting the cooling load.

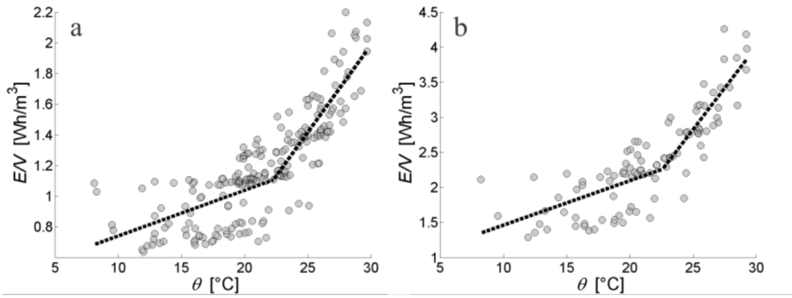

Fig. 7. Energy signature of building B at 9-10 a.m.: (a) from 30-minute values, (b) from 60-minute values

The relationship between the temperature-sensitivity coefficient and the glazing ratio seems confusing at first glance. Even if we neglect the data point corresponding to building B (at R_g=0), there is no apparent relationship between the K_θ and the glazing ratio. The reason for this lies in the observed time interval (i.e. 9-10 a.m.). Since all of the selected buildings are oriented in a southeast-northwest direction, only the southeast façade and the roof are directly illuminated by the sun (at the considered time). Hence the glazing ratio is relevant only for the southeast façade as none of the considered buildings have transparent surfaces on the roof. Because the southeast façade represents a relatively small fraction of the overall building envelope area for all buildings (i.e. 1-18%), the influence of the glazing ratio on the temperature-sensitivity was not further investigated in this study.

As previously mentioned only the southeast façade and the roof of the buildings in this study were exposed to direct solar radiation. Therefore, one would expect buildings with higher roof ratios to be more temperature sensitive, i.e. have higher coefficients of temperature-sensitivity. All the results coincided with this expectation with the exception of building A, i.e. it had the highest R_r and the lowest K_θ among all the buildings. This deviation is due to the fact that building A has approximately 34% of air-conditioned spaces underground.

4. Conclusions

One of the most important factors that effect the energy efficiency of air-conditioned buildings is the architecture and construction of the building. Poor architectural planning, which is later expensive or impossible to resolve or retrofit, often leads to a higher cooling load. Even more of a concern is that buildings prone to overheating in combination with the projected temperature increase may cause air-conditioning systems to malfunction or fail which could consequently lead, beside to the obvious rise of energy use, to an increase of heat related deaths in the worst case scenario.

In this paper the influence of three building fabric characteristics on the temperature-sensitivity of air-conditioning system energy consumption was investigated on a sample of five tertiary sector buildings for which chiller electric energy consumption data of 15-minute and meteorological data of 30-minute resolution were obtained.

The difference between the building with the lowest and highest temperature-sensitivity was more than 200%. Heat capacity per unit area of wall area proved to be the most influential factor affecting the temperature-sensitivity of energy consumption, while the results for the glazing and roof ratio proved to be inconclusive due to the limitations of a comparison on a small sample, e.g. two HVAC systems equipped with cold storage systems, partly enclosed envelope of one building. Hence future studies will have to be carried out on a larger sample of buildings in order to obtain more conclusive results.

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