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ESTIMATION OF THE SEASONAL DEMAND FOR COOLING BASED ON THE SHORT-TERM DATA

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Abstract

The paper analyzes the possibility of using the energy signature method based on the linear regression to determine the seasonal energy demand for cooling and ventilation in the office building. The "extended" energy signature method (*H-m* method) was described and applied. In accordance with Standard (EN 15603) the estimation of energy consumption for cooling can be performed for a period shorter than the entire season, but data range must be appropriate to obtain the correct accuracy of the results. The presented analysis concerns the uncertainty of estimation the seasonal demand for cooling and ventilation of the building based on monthly and 14-day data. The objective was to choose the shortest possible time period in order to obtain proper accuracy. It has been shown that the *H-m* method cannot be used to estimate cooling demand based on short-term (monthly or 14-days) data due to unacceptable uncertainty of results.

Streszczenie

W artykule przeanalizowano możliwość zastosowania metody sygnatury energetycznej opartej na regresji liniowej do wyznaczania sezonowego zapotrzebowania na energię do chłodzenia i wentylacji w budynku biurowym. Przedstawiono i zastosowano skorygowaną metodę sygnatury energetycznej (metodę *H-m*). Zgodnie z normą (EN 15603) szacowanie zużycia chłodu może być wykonywane dla okresu krótszego niż cały sezon, ale zakres danych musi być odpowiedni dla uzyskania właściwej dokładności wyników. Przedstawiona analiza dotyczy niepewności szacowania sezonowego zapotrzebowania budynku na chłód na podstawie danych miesięcznych i 14-dniowych. Celem był wybór najkrótszego możliwego do zastosowania metody okresu czasu, w którym uzyskuje się odpowiednią dokładność. Wykazano, że metody *H-m* nie można zastosować do szacowania zapotrzebowania na chłód na podstawie danych z krótkich okresów (miesięcznych, czy 14-dniowych), ze względu na nieakceptowane niepewności uzyskanych wyników.

Keywords: **Cooling; Energy demand; Energy performance; Energy signature; Linear regression; Office building.**

1. INTRODUCTION

In accordance with the requirements of the Directive on the energy performance of buildings [1], the energy performance of a building based on measurements may be an alternative for a computational one. In practice, it is important that the method should be relatively simple, based on short-term measurements in the real object. The annual heat consumption for heating and ventilation in reference climatic conditions is the basic component of the energy performance of buildings. The annual energy consumption for cooling and ventilation in public utility and office buildings in reference climatic conditions is the additional component. As part of the work carried out within the Strategic Research Project (described in the paper [2]) two methods of the measurement-based energy performance of buildings have been developed and tested: balance approach and signature. They are based on on-site short-term measurements. The shortest possible measurement period was sought in order to obtain the suitable accuracy.

Using the balance approach, it is possible to determine the heat consumption for heating and ventilation of the building in the reference heating season, based on on-site short 14-day measurements, with uncertainty of up to 20% [3]. The balance approach was also tested in cooled buildings equipped with the mechanical ventilation system. It has been shown that it is not possible to determine the seasonal demand for cooling using data from time periods shorter than the entire cooling season, due to the high uncertainty [4, 5].

The use of the energy signature method [6] based on the linear regression for estimating the seasonal heat consumption of the building based on monitoring data is described in the paper [7]. It has been found that the obtained results are close to the measured values if the minimum data of 2 months is available. Analyzes using the regression method for the estimation of heat consumption for heating and ventilation in the reference heating season, based on the results of on-site measurements carried out during time periods shorter than the entire heating season, are presented in [8, 9, 10]. It has been shown that the measurement period in which obtained uncertainty of results is less than 20% is a monthly period. In the case of periods lasting 14-days, the uncertainty is 40%.

The use of the linear regression method in cooled utility buildings is presented in [11, 12, 13]. The results of the simulation calculations for the whole year or available energy bills were used in the studies.

The aim of the analysis presented in this paper is to examine whether in cooled buildings it is possible to estimate the energy consumption for cooling in a reference cooling season based on the data of a period shorter than the cooling season, using the linear regression method. The method for determining of the cooling demand in the office building, based on data sets from the entire cooling season and short time periods, using the *H-m* method, is presented. The *H-m* method is the "extended" energy signature method described in Standard [6].

2. DESCRIPTION AND ASSUMPTIONS OF THE *H-m* METHOD

The energy signature method [6] using linear regression may be used solely for buildings with natural ventilation. It is used to determine the empirical relationship between the energy consumption (for heating or cooling) and the external temperature and then calculate the energy consumption in the heating or cooling season. Such a method is useful in buildings with stable internal gains and relatively low solar gains. This method can be used for measurement periods shorter than the whole heating/cooling season or full year but the minimum length of the period has not been specified. However, a large range of external temperatures is necessary to obtain a good accuracy of results. The *H-m* method, also described in Standard [6], is the "extended" energy signature method which may be applicable to buildings with high solar gains. The difference between internal and external temperature and in addition the influence of solar radiation are taken into account. These factors affect the energy consumption for cooling of the building.

It is assumed that the average cooling power delivered to the building $P_{C,av}$ depends on the solar irradiance I_{sol} and the difference between internal and external temperature $\Delta\theta$. This relationship can be described as $P_{C,av} = a \cdot I_{sol} + b \cdot \Delta\theta$, where a i b are coefficients.

In the *H-m* method, the H value is the apparent heat loss coefficient of the building. This is the ratio of the average power delivered to the building in a given day to the difference of internal and external temperature $\Delta\theta = \theta_{i,av} - \theta_{e,av}$, then $H = P_{C,av} / \Delta\theta$ (W/K).

The value of m is a "meteorological" variable defined as $m = I_{sol} / \Delta\theta$ (kW/(m^2·K)), that is the ratio of the solar irradiance to the difference of internal and external temperature.

For the data of the measurement period relationship between H and m values, that means relationship between $P_{C,av}/\Delta\theta$ and $I_{sol}/\Delta\theta$ and then the regression line shown in equation (1) is determined.

$$\frac{P_{C,av}}{\Delta\theta} = H = a \cdot m + b \qquad (1)$$

where:

a, b – linear regression coefficients,

$P_{C,av}$ – average daily cooling power, kW,

m – "meteorological" variable, $m = I_{sol}/\Delta\theta$, kW/(m²·K),

I_{sol} – mean energy of the total solar irradiation over the day, per square meter of horizontal plane calculated from the measured values, kW/m²,

$\Delta\theta=\theta_{i,av}-\theta_{e,av}$ – difference between mean daily values of internal and external temperature, calculated from the measured values, K.

Average cooling power during the measurement period can be calculated from the regression equation.

In the case of preparation of the energy performance of a building, the value of energy consumption for cooling in the reference climatic conditions is important. In order to determine the energy consumption for cooling and ventilation in the reference cooling season in building with natural ventilation, using the *H-m* method, the following steps *H-m* should be performed:

- calculate the mean daily value of the cooling power supplied to the building (on the basis of on-site measurements),
- calculate the average daily values of: external temperature, internal temperature and solar irradiation on the horizontal plane (on the basis of on-site measurements),
- determine the linear regression equation for the value of *H* which is dependent from *m* value,
- calculate the average cooling power supplied to the building in the reference cooling season $P_{av,ST,C}$ based on the determined regression equation,
- calculate the energy consumption for cooling in the reference cooling season Q_{SC} based on the value of average cooling power $P_{av,ST,C}$ supplied to the building in the reference cooling season, assuming a defined period of the cooling season.

For the calculation the average daily values of external temperature and total solar irradiation on the horizontal plane, per square meter, in the reference cooling season are required. The reference climatic data should been adopted for the locality in which the building is situated from the website [14].

In order to determine the average value of the cooling power supplied to the building in the reference cooling season, the value of $H = P_{C,av}/\Delta\theta$ versus m should be plotted and then the linear regression equation (1) should be drawn. Knowing the regression coefficients *a* and *b* the average cooling power in the reference cooling season $P_{av,ST,C}$ (kW) can be calculated from the equation:

$$P_{av,ST,C} = a \cdot I_{sol,ST,C} + b \cdot \Delta\theta_{ST,C} \tag{2}$$

where:

$I_{sol,ST,C}$ – average daily total solar irradiation on the horizontal plane in the reference cooling season, per square meter, kW/m²,

$\Delta\theta=\theta_{i,av}-\theta_{e,av,ST}$ – difference between mean daily values of internal and external temperature in the reference cooling season, K.

The energy consumption for cooling in the reference cooling season $Q_{ST,C}$ (expressed in GJ) should be calculated from the equation:

$$Q_{ST,C} = P_{av,ST,C} \cdot \tau_{ST,C} \cdot 24 \cdot 0{,}0036 \tag{3}$$

where: $\tau_{ST,C}$ – number of days in the reference cooling season – 214 days – from April to October

Length of the cooling season

National regulations do not set the length of the reference cooling season for calculations of the heat balance of buildings. According to Standard [15] on calculation of energy use for space heating and cooling and in Regulation on energy performance certificates [16] the energy consumption for cooling and ventilation is calculated using the monthly energy balance method for all the months of the year. The need for cooling in buildings is the result of the heat balance in which internal gains (from people and equipment) and solar gains from are the dominant components. Gains from people and equipment depend on the type of a building and the way of its usage and practically do not depend on the season. The solar gains are variable throughout the year and are the greatest in the spring and summer. In some types of buildings with high internal gains from people and equipment, cooling is practically necessary throughout the year (e.g. educational objects with auditoriums, shopping centers, etc.). In this case the cooling season lasts the whole year. In buildings with significant glazing area, with standard internal gains (e.g. office and residential buildings), cooling is mostly required during spring and summer, mainly due to the simultaneous internal and solar gains. In the winter when the heating system operates and greater internal gains occur, the heating power decreases (as a result of a local regulation) and cooling is not necessary. Therefore, for office buildings it is proposed to set the duration of the reference cooling season equal 214 days – this is the period from early April to late October.

3. DESCRIPTION OF THE STUDIED OFFICE BUILDING

The office building selected for the analysis presented in this paper is located in Gliwice (Fig. 1). Detailed description and results of the comprehensive diagnostics of this building are presented in the guidebook [4].

This is a 3-storey building with the basement. Characteristic parameters are as follows: volume of approx. 4000 m^3, heated area of 1041 m^2, cooled area of 850 m^2 (floor cooling), room height in the range of 3.6-3.9 m. It is built in reinforced concrete structure with columns and reinforced concrete floors. The external walls of the building create the mixed facade composed of double glazing windows system, PVC frame and Polytec50 facade panels. The U-values of exterior facade and windows are respectively 0.36 W/m^{2}K and 1.8 W/m^{2}K.

Figure 1.
Tested office building

The building is equipped with the installation of mechanical exhaust ventilation and gravity ventilation in the staircase. During carried out diagnostics it was found that the airtight windows do not have diffusers, which results in the lack of air flow in the exhaust ventilation system [4]. A detailed description of selected elements of mechanical ventilation is presented in the paper [17]. In practice there is only the natural ventilation in the building.

The gas-fired condensing boiler (the heat source for the building) co-operates with the floor heating installation and the installation with radiators in the staircase. The floor cooling system is supplied by the chiller, whose work is described in details in the paper [18]. Within the scope of diagnostics carried out in the building, unfortunately, complete measurement data of the energy consumption for cooling of the building was not recorded, because in the summer time many rooms were not used due to the restructuring of the company. Therefore the model of building was prepared using TRNSYS program [19] and simulations were performed, so the hourly

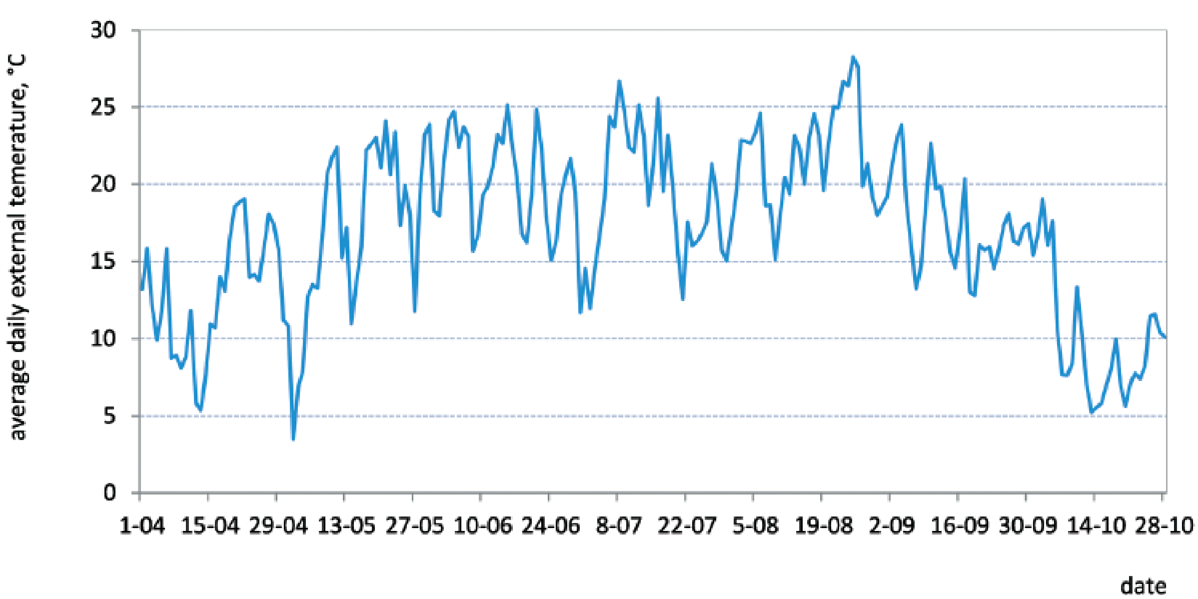


Figure 2.
Average daily external temperature for weather data of actual cooling season 2011 in Gliwice

data of cooling power were obtained. TRNSYS is the advanced tool for dynamic simulation and energy analysis for heated and cooled buildings. The simulation model was built based on the architectural documentation and data obtained from the carried out diagnostic measurements and questionnaires among users. The office area and the auxiliary area (corridors, toilets, utility rooms) are localized on the each floor. In the office rooms the value of internal gains equal to 20 W/m^2, and in the rest of building – 3 W/m^2 were adopted during hours of the building use – between 7 a.m.-5 p.m. Monday to Friday. The internal temperature of 26°C in the cooled rooms was established for the calculation of cooling demand. Natural ventilation was modeled for the entire building. The performed building model was validated with the measurement data, what was described in the paper [9].

4. SIMULATION RESULTS OF COOLING DEMAND FOR THE OFFICE BUILDING

Calculation of the cooling demand for the studied office building was made for the climatic data recorded in 2011 by the meteorological station in Gliwice. The duration of the cooling season adopted lasted from April to October, i.e. 214 days.

Fig. 2 and Fig. 3 show the characteristics of the actual climate used for calculations: the average daily and monthly external temperatures and the monthly sums of solar radiation incident on the horizontal plane.

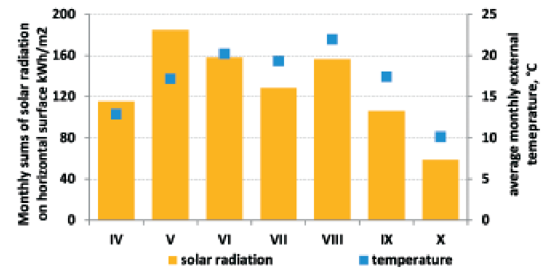


Figure 3.
Monthly sums of solar radiation incident on the horizontal plane and average monthly external temperature for weather data of actual cooling season 2011 in Gliwice

Table 1.
Calculated demand for cooling in the office building for the recorded meteorological data in 2011 in Gliwice

Month of cooling season	IV	V	VI	VII	VII	IX	X	Cooling season
Demand for cooling, GJ	22.5	47.3	49.1	37.1	53.2	31.1	8.8	248.9

As the result of the simulations, the values of daily cooling power were obtained in each hour of the cooling season 2011 from April to October. The seasonal demand for cooling amounted to 249 GJ. Tab. 1 presents the cooling demand for each month and whole cooling season, and Fig. 4 shows the average daily cooling power in the analyzed office building.

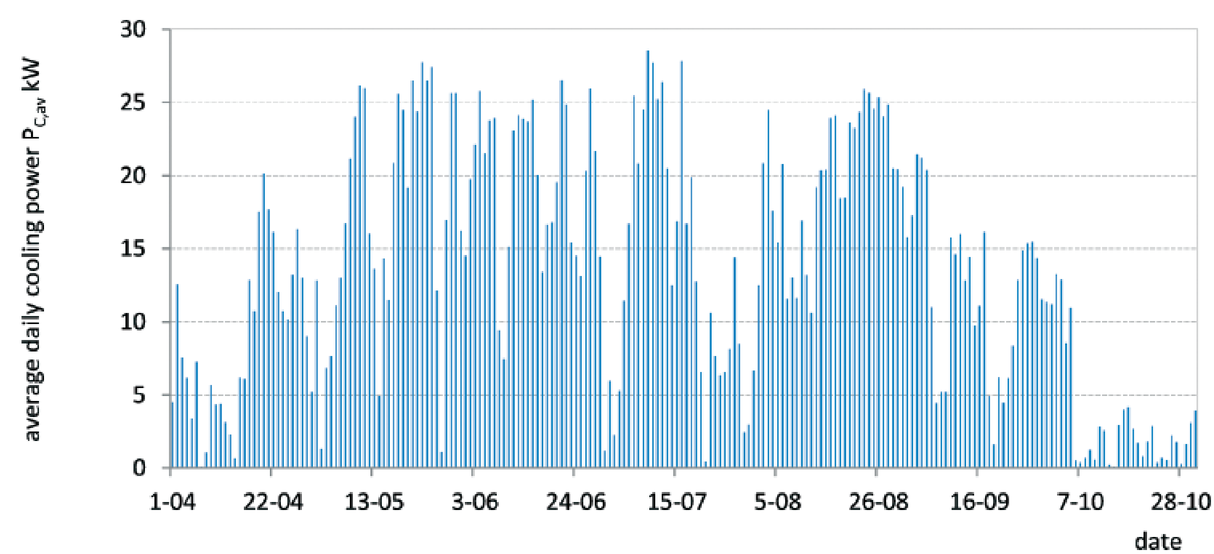


Figure 4.
Calculated average daily cooling power in the office building from April to October for recorded meteorological data in 2011 in Gliwice

5. ANALYSIS OF THE POSSIBILITY OF USING THE METHOD *H-m*

The analyzes were carried out to study the possibility of applying the linear regression method *H-m* for estimation of the seasonal demand for cooling in buildings with natural ventilation, based on the input data of different lengths. The accuracy of estimation of seasonal cooling demand, depending on the length of the measurement period was studied. Analyzes were executed for the entire cooling season, as well as shorter periods: 14-days and monthly. Such periods have been chosen similar to the calculations preformed in order to designate the energy performance of the heated building using linear regression [8]. The analyzes presented below were based on the measured values of solar radiation and external temperature in Gliwice in 2011. The daily cooling power was generated by simulation calculations (due to lack of the measurement data in the building – as described in point 3). The seasonal demand for cooling was estimated in actual climate conditions in 2011 instead of the reference climate. Such an approach is sufficient to evaluate the application possibility of the method. In the case of executing the energy performance of the building, the values would have to be recalculated to reference climatic conditions. Therefore, in Eq. (2) and (3) instead of mean values for the reference cooling season, mean values for the actual season were used and the length of the cooling season (season 2011) was assumed the same as the reference.

5.1. Calculations based on data from the entire cooling season – 214 days

The cooling demand obtained as the sum of hourly values from the performed simulations is 249 GJ. Based on the prepared data from the entire cooling season the graph of the relation between $H=P_{av}/\Delta\theta$ and $m = I_{sol}/\Delta\theta$ and the linear regression equation was performed (Fig. 5). The mean daily cooling power $P_{C,av}$ = 12.65 kW was determined based on the regression equation (Eq.2) and the seasonal demand of cooling was calculated as Q_C = 233.9 GJ using equation (3). The value of the seasonal cooling demand determined using the *H-m* method differs from the one obtained from the simulation by 6%. The next step in the analysis was to examine the possibility of estimating the seasonal demand for cooling using shorter data sets: monthly and 14-days.

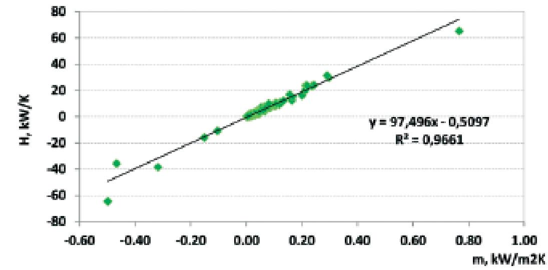


Figure 5.
Linear Regression according to the *H-m* method for determination of seasonal cooling demand for the weather data of actual cooling season 2011 in Gliwice

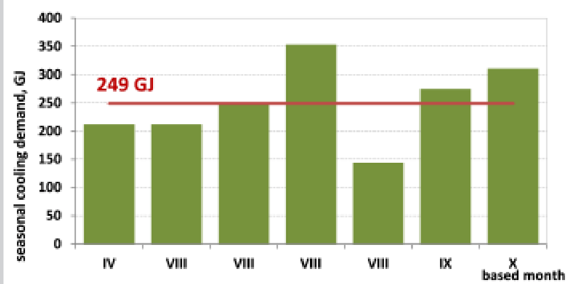


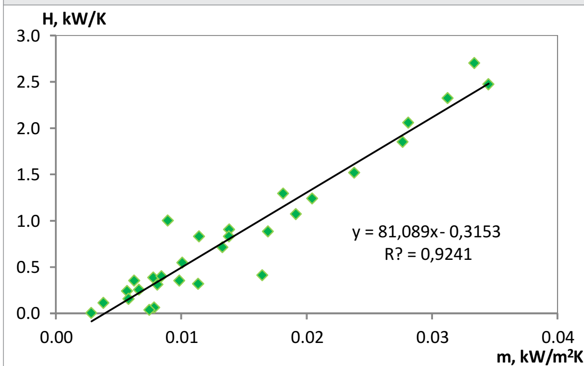
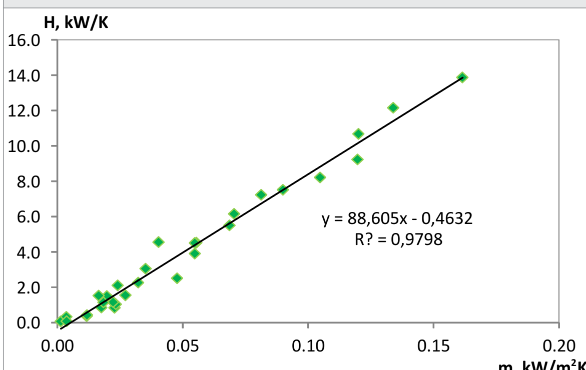
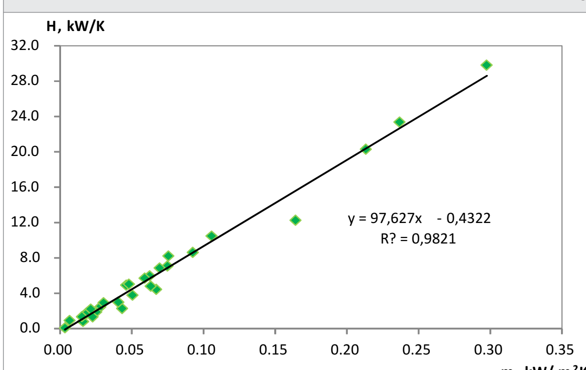
Figure 6.
Seasonal demand for cooling in the office building forecasted based on the monthly periods (green bars) using linear regression method (*H-m*) in the actual climate conditions 2011 in Gliwice; the seasonal demand for cooling based on the results of simulation in the entire cooling season is marked with the red line

5.2. Calculations based on monthly data

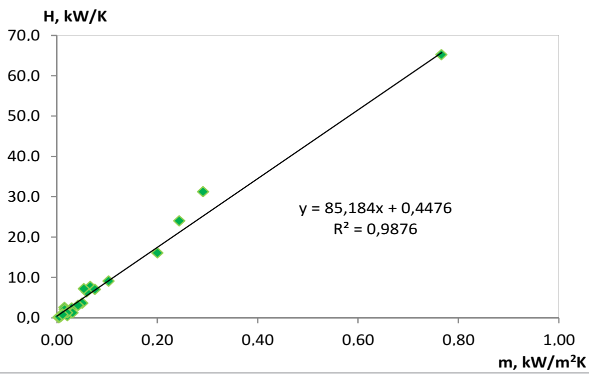
Tab. 2 summarizes the results of the seasonal demand forecasts based on the monthly data (April to October). Graph *H-m*, mean monthly data (with index "m") and seasonal values (with index "s"). Presented seasonal cooling demand $Q_{C,s}$ was forecasted on the basis of monthly data for each month of the cooling season.

Fig. 6 compares the values of the seasonal demand for cooling forecasted using the regression method based on the short-term data (monthly data) with the value calculated using the simulation for the entire cooling season. Calculated percentage differences between values forecasted on the basis of the monthly data and the value defined based on the entire cooling season range from -42% (using the data of July) to 42% (using the data of August). The smallest difference occurs in the case having data of June and is equal to 1%.

Table 1.
Description of tested beams

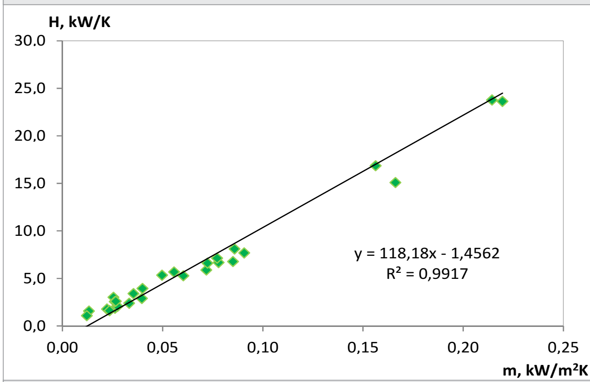
Signature method *H-m* - graph	Mean values from monthly period	Values for the whole season
Month: April		
	$I_{sol,m}$ = 0.16 kW/m^2 $\theta_{i,av,m}$-$\theta_{e,av,m}$ = 13.14 K $P_{C,av,m}$ = 8.85 kW $Q_{C,m}$ = 22.94 GJ	$I_{sol,s}$ = 0.18 kW/m^2 $\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K $P_{C,av,s}$ = 11.51 kW $Q_{C,s}$ = 212.6 GJ
Month: May		
	$I_{sol,m}$ = 0.25 kW/m^2 $\theta_{i,av,m}$-$\theta_{e,av,m}$ = 8.85 K $P_{C,av,m}$ = 17.91 kW $Q_{C,m}$ = 47.94 GJ	$I_{sol,s}$ = 0.18 kW/m^2 $\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K $P_{C,av,s}$ = 11.51 kW $Q_{C,s}$ = 212.61 GJ
Month: June		
	$I_{sol,m}$ = 0.22 kW/m^2 $\theta_{i,av,m}$-$\theta_{e,av,m}$ = 5.81 K $P_{C,av,m}$ = 18.94 kW $Q_{C,m.}$ = 49.08 GJ	$I_{sol,s}$ = 0.18 kW/m^2 $\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K $P_{C,av,s}$ = 13.37 kW $Q_{C,s.}$ = 247.30 GJ

Month: July



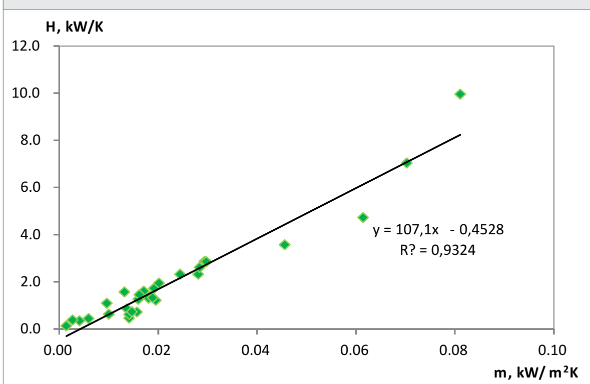
$I_{sol,m}$ = 0.17 kW/m^2	$I_{sol,s}$ = 0.18 kW/m^2
$\theta_{i,av,m}$-$\theta_{e,av,m}$ = 6.69 K	$\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K
$P_{C,av,m}$ = 17.72 kW	$P_{C,av,s}$ = 19.09 kW
$Q_{C,m}$ = 47.46 GJ	$Q_{C,s}$ = 353.00 GJ

Month: August



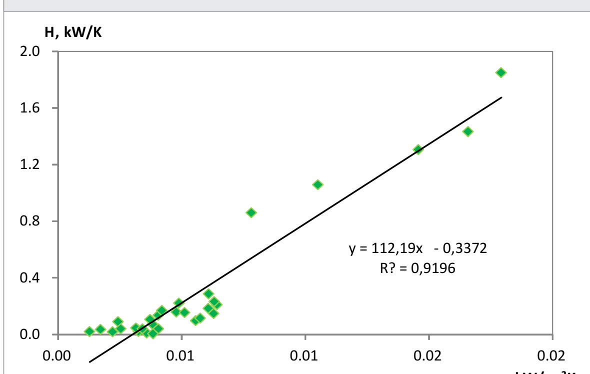
$I_{sol,m}$ = 0.21 kW/m^2	$I_{sol,s}$ = 0.18 kW/m^2
$\theta_{i,av,m}$-$\theta_{e,av,m}$ = 4.06 K	$\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K
$P_{C,av,m}$ = 18.94 kW	$P_{C,av,s}$ = 7.79 kW
$Q_{C,m}$ = 50.72 GJ	$Q_{C,s}$ = 144.11 GJ

Month: September



$I_{sol,m}$ = 0.15 kW/m^2	$I_{sol,s}$ = 0.18 kW/m^2
$\theta_{i,av,m}$-$\theta_{e,av,m}$ = 8.89 K	$\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K
$P_{C,av,m}$ = 11.93 kW	$P_{C,av,s}$ = 14.86 kW
$Q_{C,m}$ = 30.92 GJ	$Q_{C,s}$ = 274.81 GJ

Month: October



$I_{sol,m}$ = 0.08 kW/m^2	$I_{sol,s}$ = 0.18 kW/m^2
$\theta_{i,av,m}$-$\theta_{e,av,m}$ = 15.9 K	$\theta_{i,av,s}$-$\theta_{e,av,s}$ = 17.00 K
$P_{C,av,m}$ = 3.48 kW	$P_{C,av,s}$ = 16.8 kW
$Q_{C,m}$ = 9.32 GJ	$Q_{C,s}$ = 310,69 GJ

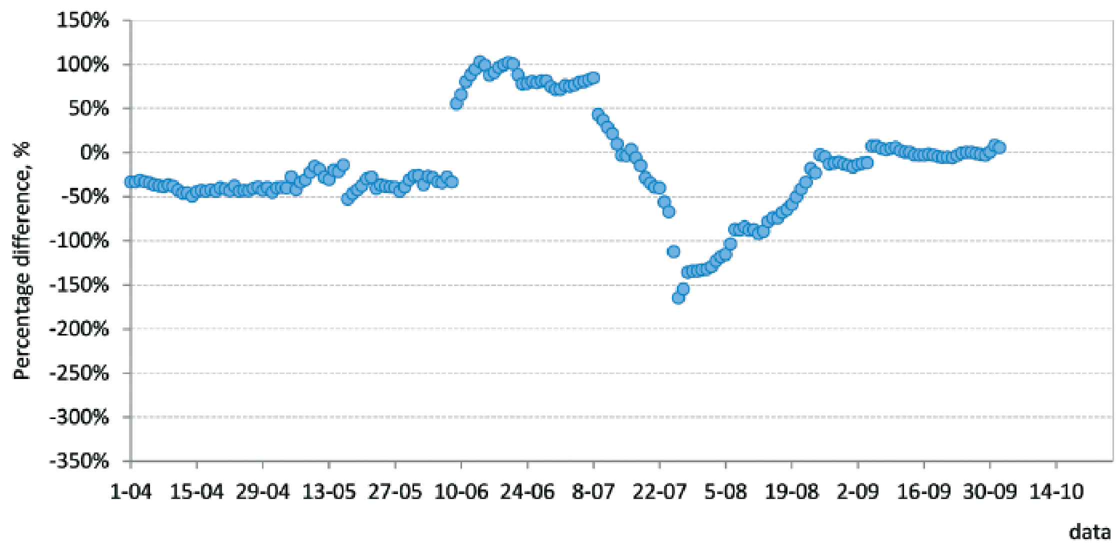


Figure 7.
Percentage differences between the calculated cooling demand for the entire cooling season and the cooling demand forecasted based on all the analyzed monthly periods from April to October (the date defines the middle of the period)

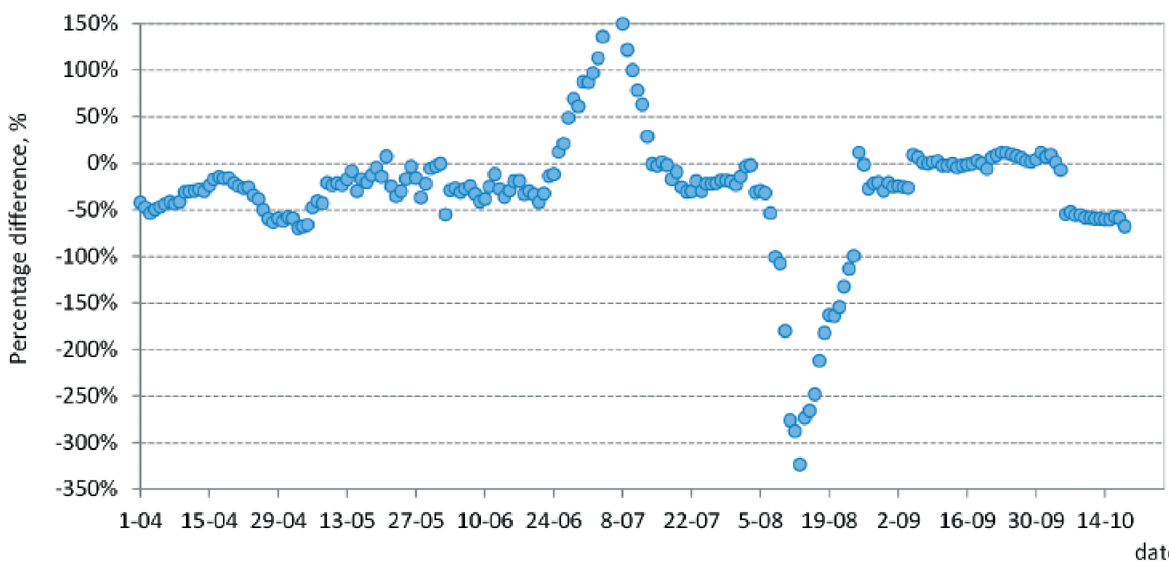


Figure 8.
Percentage differences between the calculated cooling demand for the entire cooling season and the cooling demand forecasted based on the all the analyzed 14-days periods from April to October (the date defines the middle of the period)

In order to expand the research area and get more results, analysis was carried out, creating the additional monthly periods: the succeeding time period was shifted by one day from the previous one, starting from the beginning of April. It was thus obtained: 185 periods lasting 30 days. The mean value of cooling power in each period was calculated using the REGLINX function in the MS EXCEL sheet. Fig. 7 shows the percentage differences (in relation to the calculated cooling demand in the entire season) in forecasting the seasonal demand for cooling based on the monthly periods. These differences range from –150% to 100%. Only for 35 out of 185 periods seasonal cooling demand was estimated with uncertainty less than 10% – these are monthly periods based on data from September. 50 periods have uncertainty in the range of 10-20% and most of them are based on September data (but on July data also).

As part of the work on the Strategic Research Project described in [2] a similar analysis for the studied building was made using the data of the reference season [14], which is milder in comparison with the actual climate of 2011 for Gliwice. Percentage differences from -50 to 30% were obtained.

According to the analysis, the uncertainty in the forecasting of seasonal demand for cooling based on the monthly data is unacceptable and therefore the *H-m* method cannot be applied using such the short-term data.

5.3. Calculations based on 14-day data

As can be expected, based on the analysis of monthly periods, shortening the data to the 14-day periods will worsen the uncertainty of estimating of seasonal cooling demand. Below is the answer to the question: what uncertainty can be then expected?

Analysis was carried out similar to the previous. The 14-days periods from the data of full cooling season were created: the succeeding time period was shifted by one day from the previous one, starting from the beginning of April. It was thus obtained: 201 periods lasting 14 days. The mean value of cooling power in each period was calculated using the REGLINX function in the MS EXCEL sheet. Fig. 8 shows the percentage differences (in relation to the calculated cooling demand in the entire season) in forecasting the seasonal demand for cooling based on the 14-day periods. These differences range from -300% to 150%. Only for 43 out of 201 periods seasonal cooling demand was estimated with uncertainty less than 10% and 69 periods have uncertainty in the range of 10-20% and most of them are based on the data from September and October.

As can be expected, the *H-m* method based on the data of short periods (14-days) cannot be used, as forecasting of seasonal demand for cooling can vary from actual even to 3.5 times.

6. SUMMARY

The analysis of the possibility of using linear regression method *H-m* in the office building was performed on the values of cooling power obtained from the simulation calculations for the tested object, using the actual climate in 2011 for Gliwice. The results of the analysis show that this method cannot be used to forecast seasonal cooling demand based on short-term data (monthly or 14-day), because the uncertainty of the results is too high.

The *H-m* method can be used to estimate the seasonal demand for cooling based on the values of cooling power exclusively from the entire cooling season. In this case, the difference between the value estimated using the regression method and the calculated seasonal demand for cooling in actual cooling season 2011 in Gliwice amounted to 6%.

Based on the presented results it can be concluded that forecasting annual/seasonal energy consumption for cooling using on-site short-term measurements is not possible. In order to determine the annual/seasonal energy consumption for cooling, it is necessary to know the values of daily cooling power supplied to the building during the entire year/cooling season. Based on such data it is possible to recalculate the energy consumption for cooling to the reference climatic conditions, in accordance with the procedure described in point 2 of this paper. This value can be used to compare the energy consumption of different buildings and for the determining the measurement-based energy performance of building. It may be expected that in the future, due to the increasing demands for energy efficiency and energy management in public and office buildings, the values of energy consumption for cooling and ventilation throughout the year will be available as a result of the operation of BEMS (Building Energy Management System).

The use of the *H-m* method in determining the energy performance of the buildings based on measurements is described in details in the guidebook [5].

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