ON-SITE THERMAL DIAGNOSTICS OF COOLING SOURCES FOR AIR CONDITIONING SYSTEMS IN OFFICE BUILDINGS

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A b s t r a c t

The main goal of the Task 4 "Development of thermal diagnostics of buildings" of Strategic Research Project "Integrated System for Reducing Energy Consumption in the Maintenance of Buildings" was to develop new tools for thermal diagnostics of different types of buildings, including development of the rapid method of a cooling sources diagnostics. The paper presents a method for assessing the cooling sources based on on-site measurements. The cooling capacity of the cooling sources and the electric power consumed by the cooling sources were measured in two air-conditioned office buildings. The measurement results were used to calculate the cooling energy generated during the measurement period and the operational Energy Efficiency Ratio EER_O of the chillers. Electric energy consumed in the measuring period by the auxiliary equipment of the cooling system, i.e.: coolant pumps and fan coil fans, was estimated. The possibility of significant reduction of the energy consumption for air conditioning in both buildings was indicated.

S t r e s z c z e n i e

Głównym celem Zadania 4 "Rozwój diagnostyki cieplnej budynków" projektu "Zintegrowany system zmniejszenia eksploatacyjnej energochłonności budynków" było opracowanie nowych narzędzi diagnostyki cieplnej różnych typów budynków, w tym opracowanie metody szybkiej diagnostyki źródeł chłodu. Celem prezentowanych badań było opracowanie metody oceny zużycia chłodu na potrzeby klimatyzacji budynku oraz wyznaczania eksploatacyjnego współczynnika efektywności źródła chłodu na podstawie pomiarów *in situ*. Przeprowadzono pomiary wydajności chłodniczej źródeł chłodu oraz mocy elektrycznej pobieranej przez źródła chłodu w dwóch klimatyzowanych budynkach biurowych. Wyniki pomiarów wykorzystano do wyznaczenia ilości chłodu wytworzonego w okresie pomiarowym oraz eksploatacyjnego współczynnika efektywności energetycznej agregatów EER_O. Oszacowano zużycie energii elektrycznej w okresie pomiarowym przez urządzenia pomocnicze instalacji chłodniczej: pompy chłodziwa i wentylatory klimakonwektorów. Dokonano oceny efektywności energetycznej oraz sposobu eksploatacji agregatów chłodniczych. Wskazano możliwości znacznego zmniejszenia zużycia energii na potrzeby klimatyzacji w obu badanych budynkach.

K e y w o r d s: **Air-conditioning; Cooling energy consumption; Cooling sources; On-site measurements; Office buildings.**

1. INTRODUCTION

Directive 2002/91/EC [1] of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings introduced the obligation of regular inspection of air conditioning systems. With regard to reducing energy consumption and limiting carbon dioxide emissions, Member States shall lay down the necessary measures to establish a regular inspection of air-conditioning systems of an effective rated output of more than 12 kW. Effective rated output is the maximum cooling capacity given by the manufacturer, which the unit delivers during continuous operation. The inspection shall include an assessment of the air-conditioning efficiency and the sizing compared to the cooling requirements of the building.

Appropriate advice shall be provided to the users on possible improvement or replacement of the air-conditioning system and on alternative solutions.

As a result, there has been a need for on-site diagnostics of air conditioning installations, which should include energy efficiency assessments whether it meet the requirements of the building. Strategic Research Project "Integrated System for Reducing Energy Consumption in the Maintenance of Buildings" financed by the Polish National Centre for Research and Development has been carried out since 2010. The purpose of Task 4. "Development of thermal diagnostics of buildings" (consortium leader – Silesian University of Technology in Gliwice) was to develop a new tool for thermal diagnosis of different types of buildings [2]. The objective of Task 4 was to develop the new rapid methods for:

- the on-site thermal diagnostics of a building envelope, the results are presented in [3,4]
- the on-site thermal diagnostics of heating and domestic hot water systems, the results are presented in [4-6],
- the on-site thermal diagnostics of cooling sources, ventilation and air conditioning systems, the results are presented in [4, 7, 8] and in the current paper,
- the on-site the diagnostics of indoor environment quality, the results are presented in [4, 9],
- the measurement based drawing up of energy performance certificates, the results are presented in [4, 10-13].

Full diagnostics is understood as a combination of inspection and diagnostic measurements. Inspections are diagnostic activities performed on the basis of technical documentation analysis and consisting in evaluating of the system and equipment based on the visual survey and observation during operation as well as on gathering users opinions about its operation [14].

The aim of the paper is to present a method for assessing the cooling energy consumption of air conditioning system in building and to determine the operational efficiency of the cooling source based on the on-site measurements. Using the developed diagnosis method, the output and the power consumed by the cooling source were measured in two air-conditioned office buildings. The measurement results were used to determine the amount of cooling energy produced during the measurement period and for determination of the average operational value of the Energy Efficiency Ratio index EER_o. The consumption of electricity by auxiliary equipment of cooling system coolant pumps and fan in fan-coils was estimated.

Results of the cooling source diagnostics were used to determine the energy performance of a building based on measurements [13].

2. DESCRIPTION OF THE TESTED COOLING SOURCES

The tested cooling sources are located in two office buildings. Brief description of the construction of the buildings and the performed thermal diagnostics of the ventilation systems in these buildings is presented in the paper [8].

Cooling source in the office building 1

Four air cooled chillers, each of cooling capacity 51.7 kW, monoblock type with a built-in hydraulic module, are the cooling source for the air conditioning system in the office building 1 (Fig. 1). The chillers are located in the basement room. Chiller condensers are cooled by the outdoor air, which flows into the room through the special inlets in the exterior wall. The heated air is removed outside the building through the discharge ducts with outlets in the exterior wall. Fan coils are used for air cooling in all air-conditioned rooms. To separate the primary coolant circuit from the coolant circuit through fan coils a hydraulic clutch is applied.

Two of the four chillers (chillers 1 and 4, see Fig. 1) didn't work during visual inspection as well as during three-week measurement session. Chillers 2 and 3 were turned on and ready for cooling. Due to the low energy demand for cooling during the measurement session only chiller 2 was working. The scheme of the cooling system with marked location of the measurement points is shown in Fig. 2.

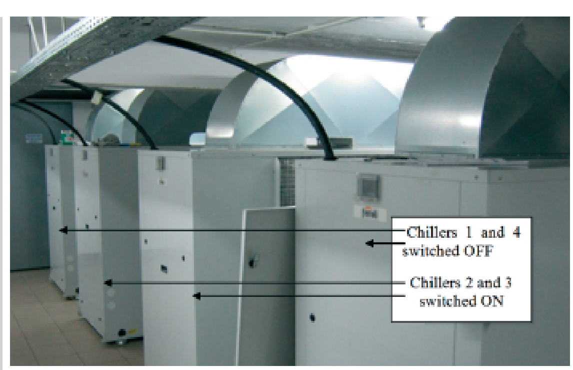

Figure 1.
Cooling source in the office building 1 – four chillers monoblock type

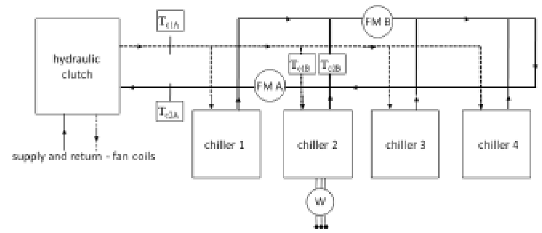

Figure 2.
The scheme of the cooling system in the building 1with marked location of the measurement points: cooling capacity of chillers group – flow meter FM A, temperature sensors T_{c1A} , T_{c2A} ; cooling capacity of the chiller 2 – flow meter FM B, temperature sensors T_{c1B} , T_{c2B}; electric power of the chiller 2 – electric power meter W

Figure 3.
Chiller, coolant pipes, coolant vessel and remote air cooled condensers

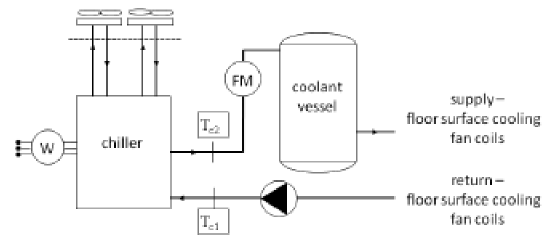

Figure 4.
The scheme of the cooling system in building 2 with marked location of the measurement points: measurement of cooling capacity of the chiller – flow meter FM, temperature sensors T_{c1}, T_{c2}, measurement of the delivered electric power– electric power meter W

Cooling source in the office building 2

The chiller of the cooling capacity 113 kW with two cooling circuits and scroll compressors is the cooling source in the office building 2. Chiller, circulating pumps and the coolant vessel are in the boiler room of the building. Two remote air cooled condensers are located on the roof of the building (Fig. 3). The scheme of the cooling system in building 2 with marked location of the measurement points is shown in Fig. 4. The floor surface cooling (heating) system is used in the building 2. In selected office rooms the cooling function is complemented by the two-pipe fan coils. The wall mounted thermostats are used to temperature control in all air-conditioned rooms.

3. THE METHOD OF DETERMINATION OF CHILLER COOLING CAPACITY

The chiller cooling capacity Q can be determined based on the measured values of the coolant flow and its temperature in the inlet and outlet pipes. Instantaneous cooling capacity Q_i can be calculated from the equation:

$$Q_i = V_{c,i} \cdot \rho_c \cdot c_c \cdot (t_{c1,i} - t_{c2,i}) \tag{1}$$

were:

Q_i – instantaneous chiller cooling capacity, W

$V_{c,i}$ – instantaneous coolant flow rate, m^3/s,

$t_{c1,i}$ – instantaneous coolant inlet temperature, °C,

$t_{c2,i}$ – instantaneous coolant outlet temperature, °C,

ρ_c – coolant density, kg/m^3

c_c – specific heat of coolant, J/kg·K

Based on the recorded n values of the instantaneous cooling capacity Q_i and the electric power N_i in the selected period of time of exploitation τ it can be determined:

average value of cooling capacity $\overline{Q}$,

$$\overline{Q} = \frac{\sum_{i=1}^{n} Q_i}{n} \tag{2}$$

cooling energy produced in the measurement period E_c ,

$$E_c = \overline{Q} \cdot \tau \tag{3}$$

the average electrical power of the chiller $\overline{N}$,

$$\overline{N} = \frac{\sum_{i=1}^{n} N_i}{n} \tag{4}$$

electric energy consumed by the chiller in the measurement period E_{el},

$$E_{el} = \overline{N} \cdot \tau \tag{5}$$

the average operational value of the Energy Efficiency Ratio EER_o,

$$EER_o = \frac{\overline{Q}}{\overline{N}} \quad (6)$$

In the case of chillers without built-in hydraulic modules, the instantaneous power output of the external hydraulic module $N_{h,i}$ should also be measured.

Based on the recorded n values of the instantaneous electrical power $N_{h,i}$ in the selected period of time of exploitation τ the average electric power value of the hydraulic module $\overline{N}_h$ and the electric energy consumption $E_{el,h}$ can be determined:

$$\overline{N}_h = \frac{\sum_{i=1}^{n} N_{h,i,}}{n} \quad (7)$$

$$E_{el,h} = \overline{N}_h \cdot \tau \quad (8)$$

In the systems with the remote condenser the instantaneous electrical power for the drive of the fans of the condenser N_s should be measured at the same time. The average power value of the condenser fan drive $\overline{N}_s$ and the electric energy consumption $E_{el,s}$ in the measurement period τ can be calculated from the equations:

$$\overline{N}_s = \frac{\sum_{i=1}^{n} N_{s,i}}{n} \quad (9)$$

$$E_{el,s} = \overline{N}_{el,s} \cdot \tau \quad (10)$$

4. RESULTS

In order to assess the cooling energy consumption for the air conditioning of the building, the coolant flow and its inlet and outlet temperature were measured for 24 and 20 days in building 1 and building 2, respectively. In the measurement period from 29th June to 23rd July 2012 the average outdoor temperature was 17.6°C, the maximum daily outdoor temperature exceeded 30°C only in 6 days. Measurements were carried out using the flow meters with the function of the heat meter SIEMENS SITRANS FUE1010 type. Based on the measurements of the coolant flow and its temperature the instantaneous values of the cooling capacity Q_i, the average cooling capacity $\overline{Q}$ and the produced cooling energy E_c in the measuring period were determined. Additionally, the instantaneous electrical power N_i was measured. Based on the average cooling capacity $\overline{Q}$ and the average electrical power of the chiller $\overline{N}$, the average operational value of the Energy Efficiency Ratio EER_o was determined.

Cooling source in the office building 1

To assess the cooling energy consumption the coolant flow and its temperature were measured in the collective inlet and outlet pipes of four chillers for 24 days from 29th June to 23rd July 2012 with 1 minute time step interval. The coolant flow in the switched OFF chillers 1 and 4 was cut off by means of valves. In chiller 2 and 3 throughout the measurement period the pump modules worked, but the cooling energy was produced only by the chiller 2.

To determine the EER_o value, simultaneous 24-hour measurements of the instantaneous cooling capacity Q_i and instantaneous electrical power N were carried out. The value of the EER_o was determined from the data recorded in the selected 4.5-hour period of time, in which the compressor of the chiller was switched on for more than 30 minutes and the cooling capacity was stabilized. Additionally, the EER_o value was determined based on the data recorded in 30-minute continuous operation of the compressor. Measurement results of the cooling energy produced by chillers group as well as the cooling energy produced by chiller 2 and electric energy consumed by chiller 2 are presented in Tab.1 and in Figs. 5 and 6.

Table 1.
Measurement results of the cooling energy produced by the group of four chillers as well as the cooling energy produced by chiller 2 and electric energy consumed by chiller 2

Group of four chillers – cooling energy measurement results		
Measurement period, τ, h (days)	576 (24)	
Average cooling capacity, $\overline{Q}$, kW	15.6	
Cooling energy produced in measurement period, E_c, kWh	8600	
Chiller 2 – cooling capacity and electric power measurements results		
Measurement period, τ, h	0.5	4.5
Average cooling capacity, $\overline{Q}$, kW	53.7	25.9
Average electric power $\overline{N}$, kW	15.8	7.91
Average operational Energy Efficiency Ratio EER_O	3.40	3.28

To determine the demand for auxiliary energy for the cooling system operation, the measurement results of the cooling capacity of the chillers group were analyzed. It was estimated that the demand for cooling

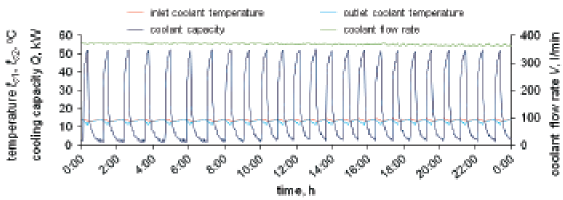

Figure 5.
Selected daily records of coolant temperature, flow rate and cooling capacity of the group of four chillers

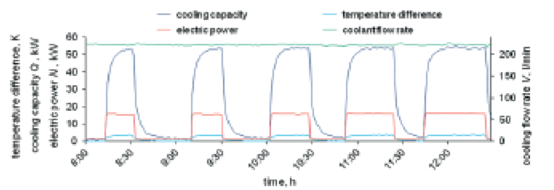

Figure 6.
Records of the coolant temperature difference, the coolant volume flow, the cooling capacity and the electric power

within 24 days of the measurement occurred only for about 100 hours. Moreover, it was verified that the coolant circulation pump was switched on in all the measurement period of time but the cooling energy was delivered only by approximately 20% of the fan coils installed in the building. The demand for auxiliary energy during the 24-day measurement session is presented in Tab. 2.

Table 2.
The demand for auxiliary energy for the cooling system operation in the building 1 during the 24-day measurement session

Device type	Delivered electric power, kW	Operation time, h	Electric energy consumption, kWh
Fan coils (20% of installed units)	2	100	200
Coolant circulation pump	5.5	576	3168
Total auxiliary electric energy consumption, E_{aux} , kWh			3368

Cooling source in the office building 2

Measurements of the coolant flow and coolant inlet and outlet temperature were carried out for 20 days from 3rd to 22nd July 2012 with 1 minute time step interval. The value of *EERe* was calculated based on the values of instantaneous cooling capacity $Q_{o,i}$ and the instantaneous electrical power N that was registered in a period of 21 hours, excluding the start-up period – the first 3 hours of chiller operation.

The measurements results of the cooling energy generated by the chiller and the electric energy consumption are presented in Tab. 3 and in Fig. 7.

Table 3.
The measurements results of the cooling energy generated by the chiller and the electric energy consumption

Cooling energy measurement results	
Measurement period, τ, h (days)	480 (20)
Average cooling capacity, $\overline{Q}$, kW	9.1
Cooling energy produced in measurement period, E, kWh	4370
Cooling capacity and electric power measurement results	
Measurement period, τ, h	21
Average cooling capacity, $\overline{Q}$, kW	11.2
Average electric power $\overline{N}$, kW	2.7
Average operational Energy Efficiency Ratio EER_O	4.13

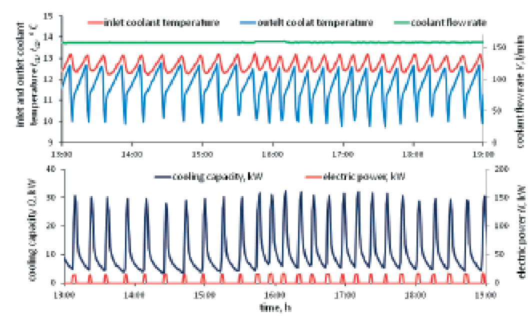

Figure 7.
Selected records of coolant temperature, flow rate, cooling capacity and electric power delivered to the chiller

Based on the analyze of the chiller cooling capacity record in the 20-day measurement session, it was estimated that a maximum cooling capacity of approx. 30 kW was registered, representing approx. 25% of the nominal chiller's cooling capacity and the electrical power consumption of the chiller was approx.16 kW, i.e. approx. 50% of the nominal value. These data show that during the entire measurement period, only one of the two compressor cycles of the chiller was used. When analyzing the electric power delivered to the chiller, recorded for 1 day and the cooling capacity recorded during the 20-day measurement period, it was estimated that the chiller operating time was approximately 15% of the measurement period. Based on this estimation electric energy consumption by the remote condenser drive was calculated. All pumps in the cooling system i.e.: the circulating pump, the pump suplying the coolant to the fan coils and 3 pumps supplying the coolant to the floor surface cooling instalation were turned on during the measurement session. Fan coils were not turned on by the users during the 20-day measurement session. The demand for auxiliary energy for the cooling system operation is presented in Table 4.

Table 4.
The demand for auxiliary energy for the cooling system operation in the building 2 during the 20-day measurement session

Device type	Delivered electric power, kW	Time of operation, h	Electric energy consumption, kWh
Remote condenser (3 fans)	1410	1410	101.5
Circulation pump-return from installation	195	195	93.5
Pump – fan coils supply	300	300	144
3 pumps – the floor installation supply	735	735	353
Total auxiliary electric energy consumption, E_{aux} , kWh			692

5. DISCUSSION

In the office building 1 the measured cooling capacity of the chiller 2 during its continuous operation is 53.7 kW and it is slightly higher than the rated value (51.7 kW) – that may indicate good technical condition of the chiller. The maximum registered cooling capacity of the chiller in the office building 2 was approx. 30 kW, that was approx. 33% of the nominal cooling capacity of the unit. In the measurement period the chiller worked for 2-5 minutes, 4-5 times in each hour. The short operating time of the chiller indicates a lower cooling requirement than the nominal chiller's cooling capacity.

In both buildings the chillers maintained an approximately constant coolant temperature for the installation during the whole measuring period (24 hours a day, without night and weekend breaks). In the building 1 the chiller switched ON when the coolant return temperature rose above 14°C and turned OFF when this temperature dropped to 11°C. In the building 2 the chiller kept the coolant return temperature in the range from 12.5 to 13.2°C. The coolant supply temperature was maintained in the range from 10 to 12.5°C. In the analyzed measurement periods, it was observed that the cooling energy demand for air conditioning in the buildings occurred in the hours from 8.00 a.m. to 6.00 p.m. On days with low outdoor temperatures there was no cooling demand at all.

The calculated operating value of the EER_o of the chiller in the building 1 is equal to 3.4 or 3.28 (Tab. 1) and is higher than the value given in the catalogue (EER = 2.65). This may indicate the correct operation of the chiller.

The operating value of the EER_o of the chiller in the building 2 is equal to 4.13 and is higher than the value given in the manufacturer technical data (EER = 3.33). However, due to the low cooling capacity recorded in 21-hour measurement period in the relation to the nominal cooling capacity of the chiller and the short continuous working periods, it is not possible to assess the correctness of the chiller operation based on the calculated operating value of the EER_o.

In both cases the energy consumption for cooling could be significantly reduced by modifying the control program of the cooling source. The cooling source should operate according to a schedule with the exclusion of nights, weekends and holidays.

Furthermore, the cooling source should be completely switched OFF at low outdoor temperatures and low solar gains. The amount of the consumed energy for cooling would have significantly decreased if the chillers had been switched OFF on weekends and working days between 6.00 p.m. and 6.00 a.m.

Due to the fact that significant parts of both buildings have not been occupied during the measurements, it is not possible to assess the fit of cooling sources to the thermal loads that might occurred in fully occupied buildings.

The measurement results of the produced cooling energy in both buildings can be used (when supplemented by outdoor climate and indoor temperature measurements) to determine the seasonal demand for cooling energy.

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