The 9th International Conference "ENVIRONMENTAL ENGINEERING"
22–23 May 2014, Vilnius, Lithuania
SELECTED PAPERS
eISSN 2029-7092 / eISBN 978-609-457-640-9
Available online at *http://enviro.vgtu.lt*

Section: Energy for Buildings

Energy conservation in buildings using refrigeration units

Artur Rusowicz, Andrzej Grzebielec, Adam Ruciński

Warsaw University of Technology, Institute of Heat Engineering, Nowowiejska 21/25, Warsaw 00-665, Poland

Abstract

The present paper shows the use of refrigeration units in a 12-building complex with a view to reduce power and heat consumption. Public utility buildings with a total usable area of 55,425.9 m^2 are considered. Cooling power of the installed cooling system is 1188 kW. Free cooling was proposed to be used in the cooling system, as cool sources are operational for the whole year without interruptions. With refrigeration units up and running, refrigerant superheat recovery was also proposed for hot water preparation. Next, chillers were replaced by more energy-efficient devices. Technologies and costs involved in the proposed modification, and payback time are also presented. A summary of the resulting power and cost savings for proposed variants is included.

Keywords: refrigeration unit; free cooling; superheat; energy efficiency; energy conservation.

Nomenclature

i	specific enthalpy (kJ/kg)
l	specific work (kJ/kg)
m	mass flow rate (kg/s)
q	specific heat (kJ/kg)
Subscripts	
D	subcooling
P	superheat
S	condensation
SKR	in condenser
SPBT	Simply Pay Back Time

1. Introduction

Power conservation and reducing or eliminating carbon emissions by improving power usage effectiveness in buildings is and will be a priority in the near future. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings obligates member states to ensure that, from 2021, all new buildings will be nearly zero energy buildings [1]. As far as existing buildings are concerned, reducing their power consumption still requires many efforts. The paper presents a proposal of reducing power consumption in a complex comprising twelve public utility buildings with a total usable area of 55,425.9 m^2 and a total capacity of 231,966.0 m^3. The buildings were built in stages between 1983 and 1999, and partly rebuilt between 2005 and 2008. The design thermal power of the complex's heating system is about 3462.0 kW, while the design thermal power for hot water preparation is 52.84 kW. Annual design power consumption for the heating of the buildings (taking into account the heating system efficiency and heating breaks) is about 102,093.6 GJ/year.

The analysis was based on possible more rational usage of refrigeration units in these buildings. The cooling system consists of one chiller with a single screw compressor with a cooling power of 1188 kW. R134a is a refrigerant. The chiller produces chilled water at 11/5 °C at the flow rate of 47.1 dm^3/s. The condenser is cooled with a 35% glycol/water solution at 39/44 °C at the flow rate of 77.7 dm^3/s. The compressor power consumption is 297 kW with the coefficient of performance (COP) equal to 4.0. The refrigeration unit performance can be variably adjusted from 25 to 100%. The glycol/water solution that flows from the refrigeration unit's condenser is chilled in two glycol coolers (dry coolers) with the

Corresponding author: Artur Rusowicz. E-mail address: rusowicz@itc.pw.edu.pl
http://dx.doi.org/10.3846/enviro.2014.281

cooling capacity of about 750 kW each. Currently, the refrigeration unit works on a continuous basis for the whole year, with short breaks. A nearly 100% performance of the unit can be assumed, but in calculations a 95% performance was assumed due to short breaks in the compressor's operation.

2. Free cooling

The solution proposed to improve the energy efficiency of the cooling system is the implementation of free cooling, as shown in Fig. 1 [2–3]. At sufficiently low ambient air temperatures, i.e. lower than or equal to +1 °C, the chilled water can flow through a cooler, by-passing the refrigeration unit's evaporator. In the cooler (a plate-fin heat exchanger), the chilled water is chilled using ambient air. According to meteorological data for Warszawa-Okęcie district, available at the Ministry of Infrastructure and Development website, air temperature below +1 °C occurs for 1843 hours a year; this is when the chiller (its compressor) may be stopped, which could translate into significant power savings. When ambient air temperatures are higher (up to 7 °C), partial flow of the chilled water through the refrigeration unit's evaporator and partial flow through ambient air-cooled heat exchangers is possible [4–6]. In this case, the refrigeration unit operates with reduced cooling power, and thus with lower electrical power consumption, as shown in Table 1. When ambient air temperatures are higher than that (e.g. in summer), the refrigeration unit's condenser is cooled with the liquid flowing through the cooler. Benefits are found also in this case, since the condensation point of the refrigerant in the refrigeration unit is lower. This results in higher coefficient of performance of the unit, and as a consequence in lower power consumption.

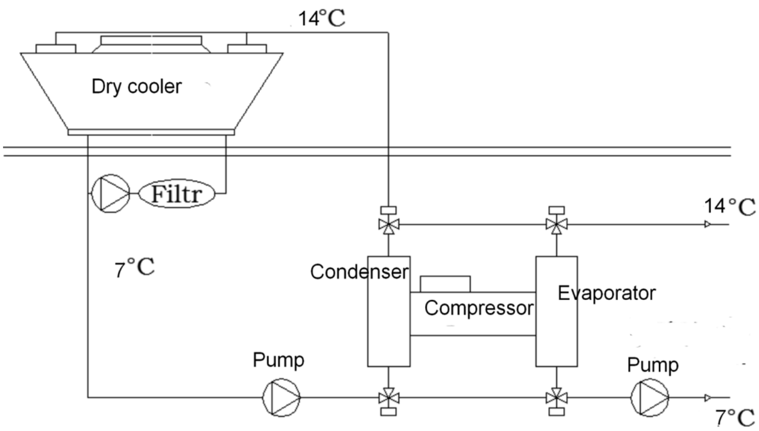

Fig. 1. Free cooling application

Table 1. Power consumption of the refrigeration unit

Ambient airtemperature [°C]	Chiller performance [%]	Free cooling time [h]	Power consumption with free cooling [kWh]	Power consumption without free cooling [kWh]
Below +1	0.00	1843	0	520
+1 to +2.25	23.75	585	41,264	165
+2.25 to +3.5	47.50	593	83,657	167
+3.5 to +7	71.25	1178	292,280	332,373
	Total:	4199	417,202	1,184,747

The above calculations show that using free cooling, when possible, decreases the consumption of power required to supply the chiller down to 35.2% of the total power consumption.

For the whole year the power consumption of the refrigeration unit is:

- currently 2,471,634 kWh/year;
- with free cooling 1,704,088 kWh/year.

Hence, the reduction in power consumption amounts to 767,545.9 kWh/year. The above analysis shows that using free cooling translates into the reduction of power consumed by the refrigeration unit's compressor by 31.05% a year. Hence, the estimated energy savings amount to: 767.55 · 466.81 = 358,300.02 PLN/year, given an average electricity price of 466.81 PLN/MWh (gross). Table 2 is a summary of costs associated with upgrading the system to include free cooling, given the exchange rate of 4.20 PLN/EUR. The simple payback time would be: SPBT = 647,816.40 / 358,300.02 = 1.81 years.

Table 2. Costs related to upgrading the system to include free cooling

No.	Item	Net value [EUR]	Gross value [PLN]
1.	Glycol cooler	80,000.00	413,280.00
2.	Control and hydraulics systems	15,000.00	77,490.00
3.	Labour and additional works	30,400.00	157,046.40
	Total	125,400.00	647,816.40

3. Superheat recovery in the chilled water production

As far as the refrigeration unit is concerned, the heat of condensation q_K is a waste. However, users of refrigeration units tend to be quite interested in the opportunities to use this heat. This stems from an increasing role of economic calculation [7–9]. Combined energy management [10–11] allows to use waste heat from one process (e.g. cooling) in other processes that require supplying heat. Instead of releasing the waste heat to the environment, it can be used in other point, providing large savings. The user of the refrigeration unit not only bears no costs of power needed to drive the unit but also reduces the costs of energy which has to be used in other processes. A common heat recovery solution is a space heating system, where the heat of condensation is used to heat water flowing in the system (to heat residential, social and industrial facilities, warehouses, etc.). These solutions are justified by a continuous power demand for space heating during the heating season (6–7 months in Poland). The continuous demand for recovered heating significantly simplifies a control system which consists only of solenoid valves to enable and disable the heat recovery nodes. A very common heat recovery solution is heating hot water which can be used as hot process water. The heat recovery system typically works with hot water storage tanks, as shown in Fig. 2.

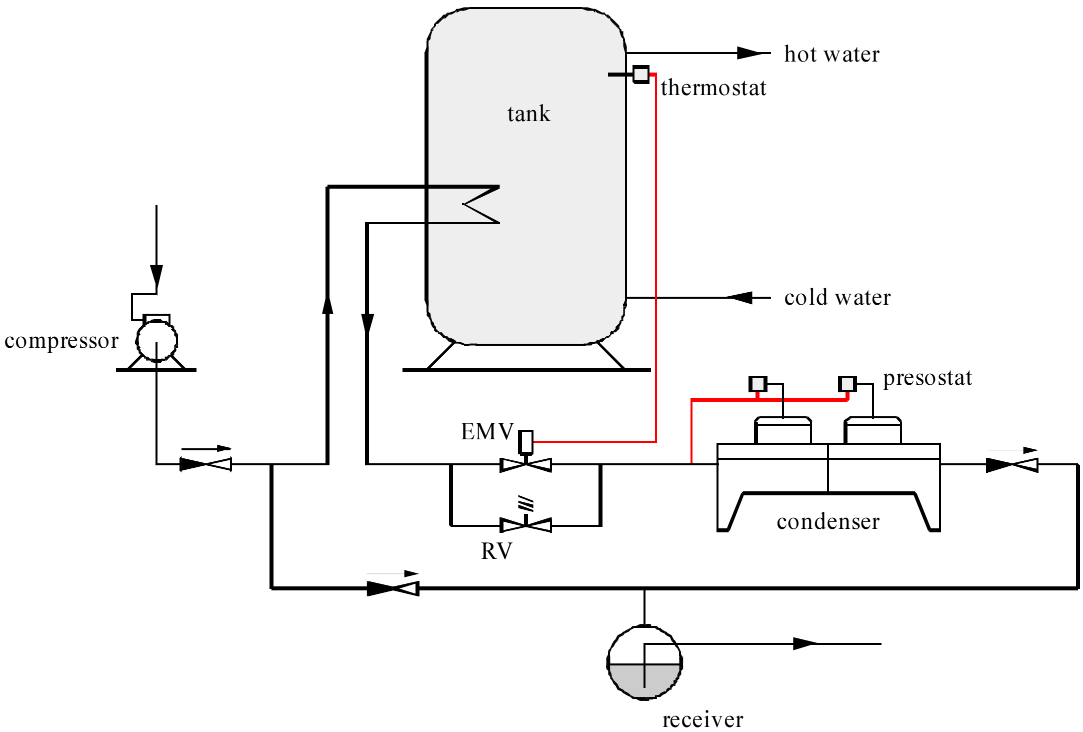

Fig. 2. Schematic diagram of a hot water preparation system in a heater with the recovery of the heat of condensation (with direct heat transfer), (EMV – electromagnetic valve, RV – regulation valve)

To clarify heat recovery issues, the heat transfer process (giving off heat by the refrigerant) in the condenser is outlined below. This process may be reflected in a pressure-enthalpy chart (Fig. 3) of a typical single-stage refrigeration cycle.

The compressor sucks the refrigerant vapours at the pressure $p_1 = p_o$ (point 1 at the p-i chart) and compresses it to the pressure $p_2 = p_k$ (point 2). To change the refrigerant state from point 1 to point 2, certain work has to be performed. A unit value of this work can be described as the difference between the refrigerant enthalpies at the beginning and at the end of the compression process.

$$l = i_2 - i_1 \tag{1}$$

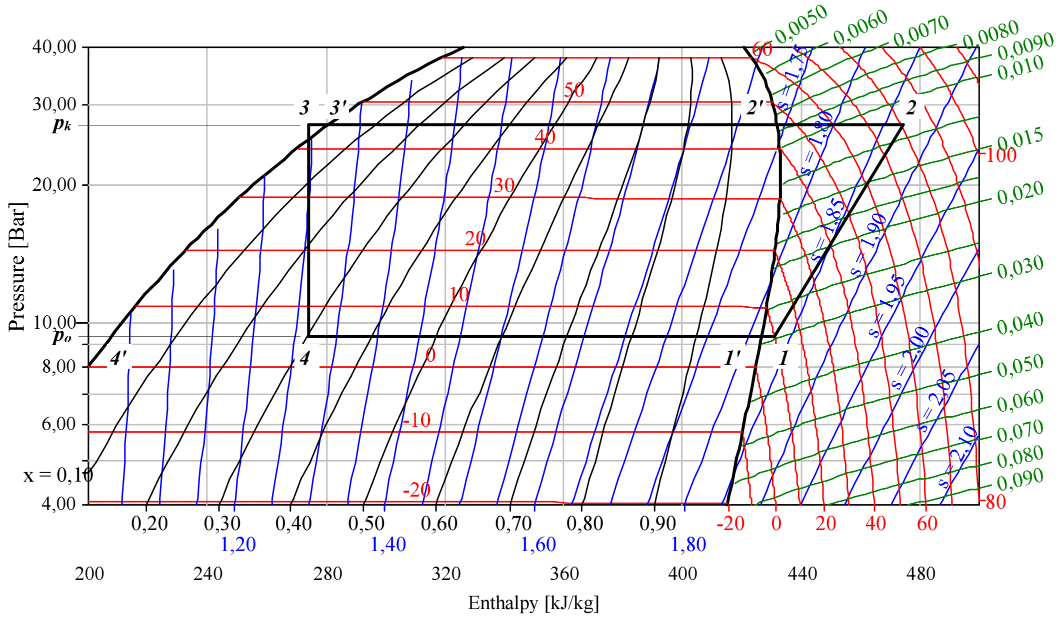

Fig. 3. Typical single-stage refrigeration cycle

At the same time, as a result of compression, the refrigerant temperature increases to t_2 which is higher than the saturation temperature matching the pressure p_k. Then the superheated refrigerant vapours are moved from the compressor to the condenser. In the condenser, the superheat of the refrigerant vapours is received; its value can be given as

$$q_P = i_2 - i_{2'} \tag{2}$$

The refrigerant vapour with properties at point 2 in the chart is a dry saturated steam at the temperature t_k. The actual condensation of the refrigerant vapours starts only after achieving this state. The value of the actual heat of condensation can be written as

$$q_S = i_{2'} - i_{3'} \tag{3}$$

Point 3’ marks a liquid saturated refrigerant at the temperature t_k. Also, subcooling of the liquid refrigerant usually occurs in the condenser. To this end, the liquid refrigerant temperature has to be decreased to t_D, which allows to receive the superheat:

$$q_D = i_{3'} - i_3 \tag{4}$$

The total heat absorbed from the refrigerant in the condenser is a sum of the superheat of the refrigerant vapours, the heat of actual condensation, and the heat from subcooling the liquid refrigerant. Thus:

$$q_{SKR} = q_P + q_S + q_D \tag{5}$$

Note that each component of the heat of condensation is given off at different temperatures. The superheat of the refrigerant vapours q_P is given off at varying temperatures (dropping from t_2 to $t_{2'}$), the heat of condensation q_S is given off at fixed temperature equal to the temperature of condensation t_k, and the heat of subcooling the liquid refrigerant q_D is given off at varying temperatures (dropping from t_k to t_3). This is quite important, since by dividing the heat of condensation into components, mass flow rates of the heated medium (e.g. water) at different temperatures can be obtained. Opportunities which arise from receiving the superheat in the system located in the complex of buildings are presented below (Fig. 4) [9, 12].

Carrying away of heat from the refrigeration unit is often not synchronized with demand. In this case, using a storage tank to accumulate the excess heat could prove a solution. This is found particularly in hot water heating applications. One such arrangement includes a storage tank with a coil mounted directly in the tank to heat water (Fig. 3). An advantage of this solution is high efficiency, as the heat transfer between the refrigerant and water occurs directly in the tank. In the present state, the superheat is not used. What can be achieved, however, is preparing hot water at about 55 ^{o}C. The value of superheat in the present solution is [9]

$$Q_P = m \cdot (i_2 - i_{2'}) \tag{6}$$

where:

m = 8.4 kg/s – mass flow rate of the refrigerant R134a in the refrigeration unit;

i_2, $i_{2'}$ – enthalpies of the refrigerant in particular operating points of the refrigeration unit [kJ/kg].

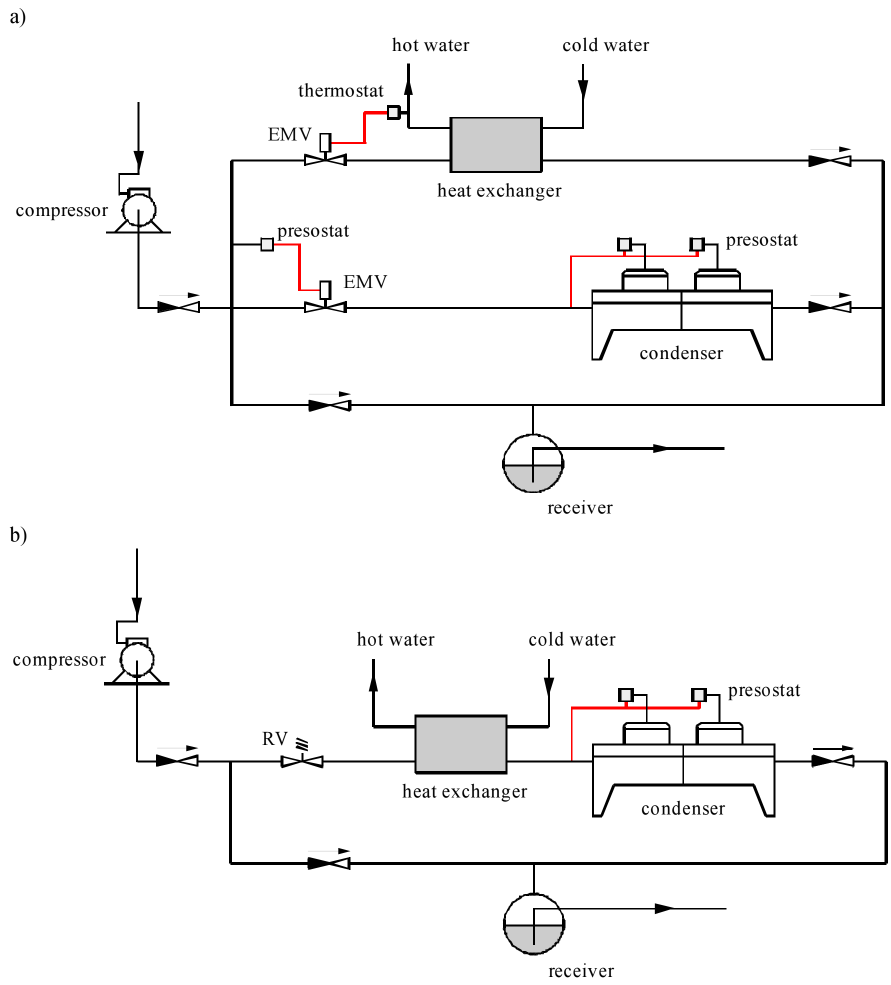

Fig. 4. Recovering heat from a cooling system (a) in parallel, and (b) in series, using a refrigerant/water heat exchanger

For the refrigeration unit under consideration:

$$Q_P = 8.4 \times (435 - 423) = 100.8 \text{ kW}.$$

The total energy recovered in the system in a year will amount to 883,008 kWh. For calculations of energy, environmental and economic effects it was assumed that the chilled water preparation and heat recovery system would operate at the annual average performance of about 85% and that the loss of energy during the transfer to a heating node would amount to about 10%. Hence, the effective energy recovered would be 883.01 · 0.85 · 0.90 = 675.50 MWh/year = 2,431.80 GJ/year. Hence, the estimated energy savings amount to: 2431.80 · 31.08 = 75,580.30 PLN/year.

If the superheat recovery and free cooling are used in combination, the amount of the recovered energy for producing hot water would drop to 459,748.8 kWh. Hence, the effective energy recovered would amount to about 459,748.8 · 0.85 · 0.90 = 351.71 MWh/year = 1,266.16 GJ/year. Two solutions can be applied: with a plate heat exchanger and with a storage tank. In this paper, the solution with the tank is recommended, as it allows for more flexible system operation and mitigating adverse effects of uneven hot water consumption.

The estimation of costs related to adapting the system to enable heat recovery is shown below:

Table 3. Summary of costs related to adapting the system to enable heat recovery

No.	Item	Net value [EUR]	Gross value [PLN]
1.	Heat recovery system with a tank	15,000.00	77,490.00
2.	Additional costs of a control system	2000.00	10,332.00
3.	Labour and additional works	5500.00	28,413.00
4.	Additional transfer system to a heating node	9371.00	39,360.00
	Total:	31,871.00	155,595.00

The simple payback time would be: SPBT = 155,595.00 / 75,580.30 = 2.06 years.

4. Chiller replacement

Taking into account that the existing chiller is approaching the end of its life-cycle, its replacement could be considered, and a similar unit could be proposed, based on a single screw compressor, and the same refrigerant R134a, but with newer compressor technology. In the case of screw compressors the coefficient of performance exceeds 5. The electric power required for the operation of such a unit under rated conditions would be 237 kW. Comparing the current unit to a new one with the same cooling power reveals that annual power savings could amount to 20%, i.e. the current consumption of 2,471,634 kWh/year could be reduced down to 1,977,307.2 kWh/year.

Hence, the estimated power cost savings would amount to 494.33 · 466.81 = 230,758.20 PLN/year. The simple payback time would be: SPBT = 1,783,045.00 / 230,758.20 = 7.73 years.

5. Conclusions

Implementation of free cooling in the existing chilled water system could result in electrical power savings of 31.05% a year. If the refrigerant superheat is used, thermal power of 100.8 kW can be obtained from the refrigeration unit, and hot water at about 50 °C can be prepared. If the storage tank is utilized, the demand for hot water in the buildings could be fully met. Buying a new chiller with a higher coefficient of performance (COP = 5) and the same cooling power would lead to reducing electrical power consumption by 20%. It should be noted that the proposed power savings do not sum algebraically, as using free cooling partly or completely precludes recovering the superheat from the refrigeration unit. Replacing the chiller with a new one requires re-estimating the savings from free cooling and superheat recovery. Modifying the cooling system would require an upgrade of the facility management and control system [5, 10, 13, 14]; this analysis does not take such an upgrade into account, although it is a significant capital investment.

Table 4. Costs of a new cooling system with a new compressor

No.	Item	Net value [EUR]	Gross value [PLN]
1.	Chiller	210,000.00	1,084,860.00
2.	Condensers	80,000.00	413,280.00
3.	Control system	2500.00	12,915.00
4.	Labour and additional works	52,650.00	271,989.90
	Total	345,150.00	1,783,044.90

References

[1] Rusowicz, A.; Grzebielec, A. 2013. Project funding for building energy-saving, in *Proc. of the XLV Refrigeration's Days*, Poznań Poland, 103–110.
[2] Rusowicz, A. 2008. The analysis of the use of „free-cooling" at the air-conditioning in the data processing centre. *Polska Energetyka Słoneczna* 1–4: 29–31.
[3] Rusowicz, A. 2008: The analysis of the use of „free-cooling" at the air-conditioning in the data processing centre, Renewable Energy, Innovative Technologies and New Ideas, Warsaw, 326–330.
[4] Bulut, H.; Aktacir, M. A. 2011. Determination of free cooling potential: A case study for Istanbul, Turkey, *Applied Energy* 88: 680–689. http://dx.doi.org/10.1016/j.apenergy.2010.08.030
[5] Foit, H.; Świerc, A.; Szewczyk, M. 2013: Equivalent external temperature for energy performance of buildings, *Rynek Energii* 3(106): 108–112.
[6] Ghiaus, C.; Allard, F. 2006. Potential for free-cooling by ventilation, *Solar Energy* 80: 402–413. http://dx.doi.org/10.1016/j.solener.2005.05.019
[7] Olsen, E. L.; Chen, Q.Y. 2003. Energy consumption and comfort analysis for different low-energy cooling systems in a mild climate, *Energy and Buildings* 35: 561–571. http://dx.doi.org/10.1016/S0378-7788(02)00164-0
[8] Royal, R. 2010. Heat Recovery In Retail Refrigeration, *ASHRAE Journal* (Feb):14–22.
[9] Rachwał, P.; Rusowicz, A. 2011. Analysis of heat recovery overheating for meat processing plant, in *Proc. of the* XLIII Refrigeration's Days 30.11-1.12.2011 Poznań, Poland, 193–200.
[10] Grzebielec, A.; Rusowicz, A. 2013. Analysis of the use of adsorption processes in trigeneration systems, *Archives of Thermodynamics* 34(4): 35–49. http://dx.doi.org/10.2478/aoter-2013-0028
[11] Rusowicz, A.; Grzebielec, A.; Baranowski, P. 2013. Data security improvement with electronics cooling, *Rynek Energii* 5(108): 112–116.
[12] Vakiloroaya, V.; Ha, Q. P.; Skibniewski, M. 2013. Modeling and experimental validation of a solar-assisted direct expansion air conditioning system, *Energy and Buildings* 66: 524–536. http://dx.doi.org/10.1016/j.enbuild.2013.07.073
[13] Lis, P.; Lis, A.; Janik, M. 2012. Aspects of the analytical heat consumption monitoring in local buildings population, *Rynek Energii* 5(102): 67–75.
[14] Szabłowski, Ł.; Milewski, J.; Kuta, J. 2013. The use of artificial neutral networks to predict the electrical demand, *Rynek Energii* 1(104): 26–31.