"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.273
DOI: https://doi.org/10.3846/enviro.2017.273

The Analysis of Modifications in Cooling Systems for High-Performance Data Centers. A Case Study

Artur Rusowicz[1], Adam Ruciński[2], Rafał Laskowski[3]

Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Warsaw, Poland
E-mails: [1]artur.rusowicz@itc.pw.edu.pl (corresponding author); [2]rucinski@itc.pw.edu.pl; [3]rlask@itc.pw.edu.pl

Abstract. One of main issues concerning server room operation is appropriate cooling of electronic modules to prevent excessive heat generation resulting in their damage. Since high cooling powers are required, precision air conditioning systems are used that are specially designed for cooling server and equipment rooms, server cabinets, etc. These devices require very large energy supplies.

The paper proposes an upgrade of a cooling system for three server rooms in which refrigeration equipment with a cooling power of 1.873 MW is installed. The average actual cooling power demand is 890 kW, and some units work as a standby. Thir-eight direct-evaporation air-conditioning cabinets are installed. The refrigerant is R407C. The devices have been operated for 14 years; therefore, the refrigeration equipment should be replaced with modern units. The paper compares three approaches: replacing the units with similar ones based on newer technology, introducing contained aisle configurations of rack cabinets and units based on newer technology with additional EconoPhase modules. The application of free cooling was not analyzed since mounting additional heat exchangers was impossible (due to the lack of space and limited roof loading capacity). The paper provides capital and operating costs of the solutions.

The introduction of up-to-date units and replacing condensers resulted in lowering the electric power demand by 16%. The simple payback time (SPBT) of this solution is 18.8 years. The energy savings achieved through the second solution (contained aisle configurations of rack cabinets) amount to 37.8%, with SPBT equal to 8.38 years. Variant III, consisting in using modern units with additional EconoPhase modules, significantly improves energy savings (48.3%) but it requires large capital expenditure, with simple payback time of 12.1 years.

Keywords: Data center, Air conditioning, Infrastructure energy efficiency.

Conference topic: Energy for Buildings.

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 (Rusowicz *et al.* 2014). Data centers are widely used in different industrial applications where large/high-speed data processing is necessary, such as telecommunications, data storage and processing in banks, market transactions and other special and private applications (Rusowicz *et al.* 2013; Jaworski 2012). Recent studies showed that data centers have a huge share in the total power consumption of modern cities. It was reported that data centers consumed 61 billion kWh or about 1.5% of U.S. total electricity consumption in 2006. A large portion of this consumed energy (almost 50%) is necessary for cooling servers to maintain their temperature within allowable limits (Nada *et al.* 2016). It is also planned to increase cooling capacity used for cooling data centers globally so as to double it every five years (Fakhim *et al.* 2011).

The present paper proposes a decrease in power consumption in a complex of three data centers, two LAN/WAN rooms and a UPS room. Their total usable area is 1630.9 m^2, while the installed cooling capacity is 1873.0 kW; see Table 1. The cooling system contains 38 precision air-conditioning units, of which 11 are standby devices. All the air-conditioning units are located inside the rooms, along opposite walls. Each cabinet pumps the air under the raised floor. The air from the data center returns to the units through the top of the room. Condensers for the precision air-conditioning units are air-cooled and located outside the building on a service terrace. Precision air-conditioning units were manufactured in 2003 and have operated since then. The cooling units work on a continuous basis for the whole year, with short breaks; it can be assumed that their duty cycle is 99.95% (Flucker, Tozer 2012; Todorovic, Kim 2014).

Since an upgrade was required, three variants were proposed: (I) to replace the units with state-of-the-art models; (II) to replace these units with modern models and arrange racks in a system of cold and hot corridors; and (III) to extend variant I with EconoPhase modules with a Pumped Refrigerant Economizer (LIEBERT 2016). Variant III, where compressor operation is totally or partially replaced with pump operation, is an interesting solution. Its application strongly depends on ambient conditions under which the cooling system operates. No experience concerning the operation of such arrangements in data centers has been collected in Poland so far. For the facility under consideration, the use of water-based systems with optional indirect free-cooling or the use of direct free cooling could not be proposed (Rusowicz 2008).

Table 1. Parameters of data center rooms under consideration

Item	Segment	Room	Aream [m^2]	Installed cooling capacity [kW]	Actual load [kW]
1	A	Data center A	398	507.0	250
2	B	Data center B	362.8	463.0	190
3	D	Data center D	440.8	576.0	250
4	D	LAN/WAN 1	72	53.0	25
5	A	LAN/WAN 2	70.3	53.0	25
6	C	UPS 1	287	221.0	150
		Total	1,630.9	1,873.0	890

In the rooms considered the following indoor air parameters are maintained throughout the year: temperature t_{in} = +22 °C ±2 °C, and relative humidity φ_{in} = 45% ±10%.

Replacing precision air-conditioning units with more energy-efficient models

As the first variant, a replacement of precision air-conditioning units with similar but more modern ones was proposed. The new units require less electric power and offer a lower EER and precise control of refrigerating capacity. In both solutions each unit has two refrigeration circuits, with an independent condenser used for each circuit. In the new cooling units, condensers with fans driven by inverter-controlled motors were used. Ratings of the units are compared in Table 2. Ratings according to data sheets are given for the same operating conditions: indoor temperature 24 °C and humidity 50%, and condensation point 45 °C (Srinarayana *et al.* 2014).

Table 2. Performance of old and new precision air-conditioning units

Model	Himod 81UA	PX068
Refrigerant	R407C	R410A
Total cooling capacity [kW]	84.1	66.1
Sensible cooling capacity [kW]	76.5	62.2
Electric power supplied to the compressor and fans [kW]	25.6	16.2
Electric power supplied to condensers [kW]	4.2	3.48
Air flow [m^3/h]	20,488	18,500
SHR	0.91	1.00
EER	3.28	4.08
Number of refrigeration circuits	2	2
Weight [kg]	940	887
Dimensions (width × depth × height) [mm]	2550×890×1980	2550×890×1970
Control	2 rates	Variable from 10%

The actual demand for cooling capacity in data center A is Qo = 250 kW. To meet the requirements of data center A, air-conditioning units Himod 81UA (5 units) with air-cooled condensers HCA 42 (10 units) and air-conditioning units Himod 99UA (4 units) with air-cooled condensers HCA 49 (8 units) were installed. The air-conditioning units and condensers are old types.

Each of LAN/WAN 1 and LAN/WAN 2 rooms is equipped with one Himod 65UA as an operating unit and one as a standby unit. Cooling capacity of Himod 65UA is 53.8 kW with EER equal to 3.34. Since the actual load is 25 kW, one refrigerating circuit in a unit, i.e. one condenser is operating. While selecting a new cooling unit, one can choose a PX054 unit with a double refrigerating circuit, cooling capacity of 55.1 kW, and EER of 3.53, with an option to operate using one circuit.

Changes similar to data center A can be proposed for data center B. Data center D can be equipped with three air-conditioning units PX068. The UPS 1 room can be equipped with three air-conditioning units PX068, with cooling capacity provided by two units and one circuit of the third unit. Electricity consumption is summarized in Table 3.

Based on suggestions, assuming a constant cooling load throughout the year, electricity consumed by the cooling equipment for producing cold can be determined as (1)

$$P_{el} = Q_o \cdot EER + n \cdot P_{el\_fan} \tag{1}$$

where: P_{el} – total electricity consumption, kW; Q_o – required cooling capacity, kW; EER – energy efficiency ratio; n – number of condenser fans; P_{el_fan} – electric power of a condenser fan, kW.

Table 3. Electricity consumption in the data center before and after replacing old devices with new ones

Item	Room	Actual load [kW]	Electricity consumption before an upgrade [kWh/year]	Electricity consumption after an upgrade [kWh/year]	Energy savings [%]
1	Data center A	250	778,058.9	658,703.9	15.34
2	Data center S/B	190	599,419.0	499,395.6	16.68
3	Data center S/D	250	778,058.9	658,703.9	15.34
4	LAN/WAN 1	25	102,360.8	92,524.5	9.61
5	LAN/WAN 2	25	102,360.8	92,524.5	9.61
6	UPS 1	150	474,193.7	428,755.6	9.58
	Total	890	2,834,452.1	2,430,608.0	14.24

The economic analysis of this variant (I) is based on the electricity price of 0.07 EUR/kWh net. The net price of the air-conditioning unit PX068 with two condensers is 34,545 EUR. The air-conditioning unit PX054 costs 31,818 EUR net. The costs of the proposed upgrade according to variant I are listed in Table 4.

Table 4. Summary of upgrade costs according to variant I

Item	Cost	Value [EUR]
1.	Air-conditioning units with condensers	443,636.-
2.	Installation	88,636.-
3.	Total	532,272.-

Simple payback time (SPBT):
Capital expenditure: 532,272.- EUR.
Savings: 0.1424 × 2,834,452.1 [kWh/year] × 0.07 [EUR/kWh] = 28,253.8 EUR/year
SPBT = 18.84 years

Replacing precision air-conditioning units and isolating areas of hot and cold air

With variant II, modern air-conditioning units would be used, such as in variant I, while areas of cold and hot corridors would be arranged, which would provide different operating conditions for the air-conditioning units. Ratings according to data sheets are given for the same operating conditions: indoor temperature 37 °C and humidity 50%, and condensation point 45 °C. Ratings of the air-conditioning units are compared in Table 5.

Table 5. Ratings of new air-conditioning units with a corridor arrangement

Model	Himod 81UA	PX068
Refrigerant	R407C	R410A
Total cooling capacity [kW]	84.1	90.1
Sensible cooling capacity [kW]	76.5	87.5
Electric power supplied to the compressor and fans [kW]	25.6	16.1
Electric power supplied to condensers [kW]	4.2	3.48
Air flow [m^3/h]	20,488	18,500
SHR	0.91	1.00
EER	**3.28**	**5.60**
Number of refrigeration circuits	2	2
Weight [kg]	940	887
Dimensions (width × depth × height) [mm]	2550×890×1980	2550×890×1970
Control	2 rates	Variable from 10%

Ratings of the PX068 unit according to data sheets are given for the following operating conditions: temperature 37 °C, condensation point 45 °C.

Considering a continuous cooling demand in the data center for the whole year, it was assumed that the equipment operates for 365 days a year. The results for variant II are summarized in Tables 6 and 7.

Table 6. Electricity consumption in the data center before and after replacing old devices with new ones with a corridor arrangement

Power consumption	Old devices	New devices	Savings [%]
Power consumption by compressors and equipment in internal devices [kWh/year]	667,682.9	391,071.4	41.43
Condenser fans	36,792×3= 110,376.0	30,484.8×3= 91,454.4	17.14
Total power consumption [kWh/year]	778,058.9	482,525.8	37.98

Table 7. Electricity consumption in the data center before and after replacing old devices with new ones with a corridor arrangement

Item	Room	Actual load [kW]	Electricity consumption before an upgrade [kWh/year]	Electricity consumption after an upgrade [kWh/year]	Energy savings [%]
1	Data center A	250	778,058.9	482,525.8	37.98
2	Data center S/B	190	599,419.0	373,426.3	37.70
3	Data center S/D	250	778,058.9	482,525.8	37.98
4	LAN/WAN 1	25	102,360.8	77,581.6	24.21
5	LAN/WAN 2	25	102,360.8	77,581.6	24.21
6	UPS 1	150	474,193.7	295,612.5	37.66
	Total	890	2,834,452.1	1,789,253.6	36.87

The economic analysis of this variant (II) is based on the electricity price of 0.07 EUR/kWh net. The net price of the air-conditioning unit PX068 with two condensers, offering continuous capacity control and designed for a corridor arrangement, is 36,818.- EUR. The air-conditioning unit PX054 costs 33,409.- EUR net. The costs of such an upgrade are listed in Table 8.

Table 8. Summary of upgrade costs according to variant II

Item	Cost	Value [EUR]
1.	Air-conditioning units with condensers	471,818.-
2.	Installation	141,545.-
3.	**Total**	**613,363.-**

Simple payback time (SPBT):
Capital expenditure: 613,363.- EUR.
Savings: 0.3687 × 2,834,452.1 [kWh/year] × 0.07 [EUR/kWh] = 73,154.4 EUR/year
SPBT = 8.38 years

Replacing precision air-conditioning units with more energy-efficient models with additional EconoPhase modules cooling

The proposed variant III is an extended variant I with additional EconoPhase modules. In this case according to a data sheet (LIEBERT® ECONOPHASE™ 2016) electric power is used for 51% of the unit operation time only by condenser fans and the pumping system of the EconoPhase unit; for 16% of the time by condenser fans, one compressor in the unit and the pump system of the EconoPhase module; and for 32% of the time by the whole unit, i.e. by condenser fans and compressors.

In the case of data centers A and D, with four PX068 units:

- for 32% of the operation time 100% of rated power is used: 0.32 × 658,703.9 kWh = 210,785.4 kWh
- for 16% of the operation time 8 condenser fans, 4 compressors (out of 8), and 4 pumping units, 0.6 kW each, are running:
  0.16 × (8 × 1.74 + 4 × 16.2 + 4 × 0.6) × 365 days × 24 h = 113,697.8 kWh
- for 51% of the time (full free cooling) only the condensers (8 units) and 8 pumping units operate, while refrigerating compressors are not in operation:
  0.51 × (8 × 1.74 + 8 × 0.6) × 365 days × 24 h = 83,633.5 kWh

Total annual electricity consumption by data center A equals 408,116.7 kWh.

Similarly, in the case of data center B, with three PX068 units in operation:

- for 32% of the operation time 100% of rated power is used: 0.32 × 499,395.6 kWh = 159,806.6 kWh
- for 16% of the operation time 6 condenser fans, 3 compressors (out of 6), and 3 pumping units, 0.6 kW each, are running:
  0.16 × (6 × 1.74 + 3 × 16.2 + 3 × 0.6) × 365 days × 24 h = 85,273.3 kWh
- for 51% of the time (full free cooling) only the condensers (6 units) and 6 pumping units operate, while refrigerating compressors are not in operation:
  0.51 × (6 × 1.74 + 6 × 0.6) × 365 days × 24 h = 62,725.1 kWh
  Total annual electricity consumption by data center B equals 307,805.0 kWh.
  In the case of the UPS room, where 2.5 PX068 units are running:
- for 32% of the operation time 100% of rated power is used: 0.32 × 428,755.6 kWh = 137,201.8 kWh
- for 16% of the operation time 10 condenser fans, 2.5 compressors (out of 5), and 2.5 pumping units, 0.6 kW each, are running:
  0.16 × (10 × 1.74 + 2.5 × 16.2 + 2.5 × 0.6) × 365 days × 24 h = 83,255.0 kWh
- for 51% of the time (full free cooling) only the condensers (5 units) and 5 pumping units operate, while refrigerating compressors are not in operation:
  0.51 × (10 × 1.74 + 5 × 0.6) × 365 days × 24 h = 91,139.0 kWh
  Total annual electricity consumption by the UPS 1 room equals 311,595.8 kWh.
  In the case of the LAN/WAN 1 room, with the PX054 unit running with one refrigeration circuit:
- for 32% of the operation time 100% of rated power is used: 0.32 × 92,524.5 kWh = 29,607.8 kWh
- for 16% of the operation time 2 fans of one condenser, 0.5 compressor, and 0.5 pumping unit (0.6 kW) are running:
  0.16 × (2 × 1.74 + 0.5 × 15.6 + 0.5 × 0.6) × 365 days × 24 h = 16,651.0 kWh
- for 51% of the time (full free cooling) only the condensers (2 units) and 1 pumping unit operate, while the refrigerating compressor is not used:
  0.51 × (2 × 1.74 + 1 × 0.6) × 365 days × 24 h = 18,227.8 kWh

  Total annual electricity consumption by the LAN/WAN 1 room equals 64,486.6 kWh.

Where one refrigeration circuit is running, the operation of 0.5 compressor or 0.5 pumping unit was assumed, which contradicts the equipment physical performance, but for energy efficiency analysis such an assumption is acceptable. Power consumption and savings in variant III are summarized in Table 9.

Table 9. Electricity consumption in the data center before and after replacing old devices with new ones with the addition of EconoPhase modules

Item	Room	Actual load [kW]	Electricity consumption before an upgrade [kWh/year]	Electricity consumption after an upgrade Variant III [kWh/year]	Energy savings [%]
1	Data center A	250	778,058.9	408,116.7	47.5
2	Data center S/B	190	599,419.0	307,805.0	48.6
3	Data center S/D	250	778,058.9	408,116.7	47.5
4	LAN/WAN 1	25	102,360.8	64,486.6	37.0
5	LAN/WAN 2	25	102,360.8	64,486.6	37.0
6	UPS 1	150	474,193.7	211,595.8	55.4
	Total	890	2,834,452.1	1,464,607.4	48.3

The economic analysis of this variant (III) is based on the electricity price of 0.07 EUR/kWh net. The net price of the air-conditioning unit PX068 with two condensers and EconoPhase module is 69,318.- EUR. The air-conditioning unit PX054 costs 65,909.- EUR net.

Table 10. Summary of upgrade costs according to variant III

Item	Cost	Value [EUR]
1.	Air-conditioning units with condensers	894,318.-
2.	Installation	268,295.-
3.	**Total**	**1,162,613.-**

Simple payback time (SPBT):
Capital expenditure: 1,162,613.-EUR.
Savings: 0.483 × 2,834,452.1 [kWh/year] × 0.07 [zł/kWh] = 95,832.8 EUR/year
SPBT = 12.1 years

Conclusions

Replacing the cooling equipment (variant I) translates into a significant change in EER, but the total energy savings amount to 14.24%. The new air-conditioning units are more technologically advanced than those currently installed, offer variable control and use a more modern refrigerant. By introducing modern units with variable capacity control and areas of cold and hot corridors (variant II), the energy savings are considerably higher (36.87%), while SPBT is relatively short (8.38 years). Variant III, consisting in using modern units and the introduction of Freon-based free cooling, significantly improves energy savings (48.3%) but it requires large capital expenditure, with simple payback time of 12.1 years. The variants are compared in Table 11.

Table 11. Comparison of upgrade costs and energy savings for the proposed variants

Parameter	Variant I	Variant II	Variant III
Energy savings [%]	14.24	36.87	48.3
Energy savings [EUR/year]	28,253.8	73,154.4	95,832.8
Capital expenditure [EUR]	532,272.-	613,363.-	1,162,613.-
SPBT [year]	18.84	8.38	12.1

What needs to be pointed out is the lack of complete data on Freon-based free cooling; this solution has not yet been tested to the full extent in Poland. While variants I and II are based on data sheets containing precise specifications, no such documented data are available for variant III. Therefore, variant II seems to be the most beneficial, safe in terms of investment, and based on proven technical solutions.

References

Fakhim, B.; Behnia, M.; Armfield, S. W.; Srinarayana, N. 2011. Cooling solutions in an operational data centre: A case study, *Applied Thermal Engineering* 31: 2279–2290. https://doi.org/10.1016/j.applthermaleng.2011.03.025

Flucker, S.; Tozer, R. 2012. Data centre energy efficiency analysis to minimize total cost of ownership, *Building Services Engineering Research and Technology* 34(1): 103–117. https://doi.org/10.1177/0143624412467196

Jaworski, M. 2012. Thermal performance of heat spreader for electronics cooling with incorporated phase change material, *Applied Thermal Engineering* 35: 212–219. https://doi.org/10.1016/j.applthermaleng.2011.10.036

LIEBERT® ECONOPHASE™ Pumped Refrigerant Economizer. 2016. Vertiv Headquarters, 1050 Dearborn Drive, Columbus, OH, 43085, USA. Available from Internet: www.vertivco.com/globalassets/products/thermal-management/room-cooling/liebert-econophase-data-sheet.pdf

Nada, S. A.; Elfeky, K. E.; Ali, M. A. Attia. 2016. Experimental investigations of air conditioning solutions in high power density data centers using a scaled physical model, *International Journal of Refrigeration* 63: 87–99. https://doi.org/10.1016/j.ijrefrig.2015.10.027

Rusowicz, A. 2008 The analysis of the use of „free-cooling" at the air-conditioning in the data processing centre, in Renewable Energy, Innovative Technologies and New Ideas. Warsaw, 326–330.

Rusowicz, A.; Grzebielec, A.; Baranowski, P. 2013. Data security improvement with electronics cooling, *Rynek Energii* 5(108): 112–116.

Rusowicz, A.; Grzebielec, A.; Ruciński, A. 2014. Energy conservation in buildings using refrigeration units, in *9th International Conference. Environmental Engineering*, 22–23 May 2014, Vilnius, Lithuania.

Srinarayana, N.; Fakhim, B.; Behnia, M.; Armfield, S. W. 2014. Thermal performance of an air-cooled data center with raised-floor and non-raised-floor configurations, *Heat Transfer Engineering* 35(4): 384–397. https://doi.org/10.1080/01457632.2013.828559

Todorovic, M. S.; Kim, J. T. 2014. Data center's energy efficiency optimization and greening – Case study methodology and R&D needs, *Energy and Buildings* 85: 564–578. https://doi.org/10.1016/j.enbuild.2014.09.001