Slobodan Dj. Pejković

Filter Frigo, d. o. o., Belgrade, Serbia

Highly Efficient Data Center Cooling Using Multiple Chiller System with Oil-Free Variable-Speed Turbo Compressors

Technical paper

Oil-free twin-turbo centrifugal compressor uses electromagnetic bearings and turbine variable-speed for significant increase of energy efficiency at partial load compared to conventional oil-lubricated centrifugal or screw compressors.
Each of the three water chillers installed in Telecommunication Data Center "Belgrade" in April 2008 has two turbo compressors and total cooling capacity of 1.97 MW. Such design solution with oil-free compressors was applied for the first time in Serbia as well as in the territory of ex-Yugoslavia. It has been estimated that in the 2008 cooling season this solution achieved more than 35% energy savings comparing to the previous solution with conventional centrifugal compressors.
This paper presents the results of preliminary measurement of the working characteristics of chillers and energy efficiency ratio for real working conditions.

Key words: *turbocor compressor, oil-free centrifugal compressor, energy efficiency*

Introduction

In the Telecommunication Data Center "Belgrade", back in 1973, water chillers ware installed with the conventional oil lubricated turbo compressor (fig. 1). The water chillers used R 12 as a refrigerant.

The engineers from Telecommunication Data Center "Belgrade" requested to retrofit the worn-out water chillers with new, state-of-the-art chillers with an environmentally friendly refrigerant. Due to disturbances that the old water chillers made in the electric network, especially when starting up the compressors (starting current of over 500 A) it has been decided to install water chillers with oil-free turbo compressors with starting current less than 5 A, and R134a as a refrigerant. The advantages of these water chillers over the conventional ones are:

- high energy efficiency, especially during reduced part-load, by use of the oil-free compressors with the variable-speed turbine and flooded evaporator,
- more efficient heat exchange in the evaporator and condenser (with no oil film causing additional heat resistances),
- higher evaporation temperatures, and therefore higher cooling capacity at the same temperatures of the water in the evaporator,

Author's e-mail: filfrigo@eunet.rs

– silent work and reduced vibrations,
– low starting current (2 to 5 A),
– light compressor weight (up to 140 kg), and
– precise temperature regulation thanks to software controlling the compressor.

Basic characteristics of modern water chillers with oil-free turbo compressors

Basic characteristics that set aside this family of water chillers with water cooled condenser (fig. 1) from the other water chillers with conventional centrifugal or screw compressors are:

– *High energy efficiency*

In air-conditioning systems, the water chillers operate a smaller part of their time in the maximum load regime. Therefore, it is very important to know the seasonal energy efficiency ratio [1], which has been defined as following: ESEER (European seasonal energy efficiency ratio) is used to define the average annual cooling efficiency of a water chiller system, and represents a ratio of total cooling energy exchanged in the evaporator during the year – seasonal use of water chiller, expressed in Wh, in relation to total absorbed energy used in the same period, expressed in Wh. ESEER is an average value of $EER_{cooling}$ – cooling efficiency level during the year, at different external air temperatures, and therefore in different operating regimes of the device.

This index presents energy efficiency of water chillers in more realistic terms, when compared to the energy efficiency ratio (EER), because time period during the annual operating season, in which the chiller works under full load, is shorter. Therefore, manufacturers try to develop the devices that would be more efficient during reduced load conditions. Chillers, with the same cooling efficiency level EER, do not need to have the same ESEER. A chiller with higher ESEER is more energy efficient.

ESEER is a weighed formula enabling to take into account the variation of EER with the load rate and the variation of air or water inlet condenser temperature.

Figure 1. New water chillers with Turbocor compressors
(full color figure is available in electronic version)

$$\text{ESEER} = 0.03\text{A} + 0.33\text{B} + 0.41\text{C} + 0.23\text{D}$$

where A = EER at 100% of load, B = EER at 75% of load, C = EER at 50% of load, and D = EER at 25% of load.

In water chillers with water cooled condenser, the ratios are determined for different loads at different entering water temperatures. For the minimum load (25%), water temperature of 18 °C is adopted, and for the maximum load (100%), the temperature of 30 °C.

From fig. 2, one can see that the water chiller with oil-free Turbocor compressor is more efficient than the water chillers with screw compressor, especially at loads less than 75%.

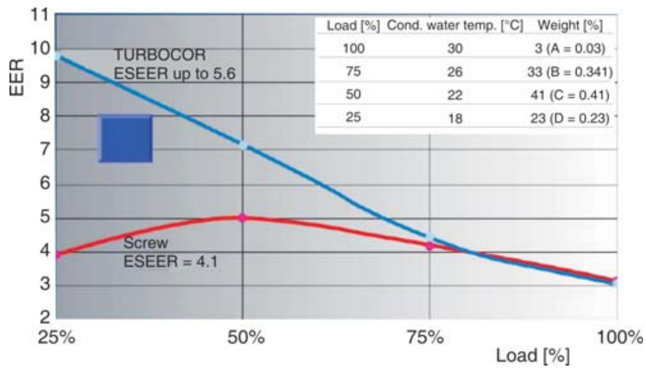

Figure 2. Energy efficiency ratio of water chiller at different loads

– *Continuous regulation of the compressor's cooling capacity*

In modern water chillers, water temperature is controlled at the outlet from the evaporator by changing the speed of the impeller (turbine) and the opening degree of the inlet guide vane (IGV) at centrifugal compressor's inlet side (fig. 3).

In this way the work of the water chiller shall be precisely adapted to the air-conditioning system dynamics.

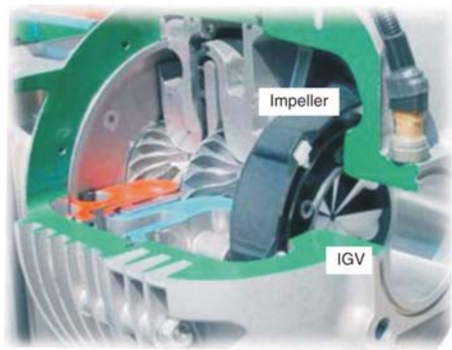

Figure 3. Cross-section of Turbocor compressor
(full color figure is available in electronic version)

Compressor of small size and small weight is equipped with two impellers driven by electric-motor with continuous frequency regulation. High-speed variable-frequency operation maintains outstanding part-load efficiency, compact- ness and extraordinary soft-start capacity. Compressor's rotor shaft and impellers levitate during rotation and float on a magnetic cushion (fig. 4). The rotor shaft position (fig. 5) is monitored and self-corrected by 10 sensors. Each shaft shift exceeding 0.5 μ shall be read and position correction shall be made accordingly. This technology, which has been transferred from the space research program, has many advantages:

Figure 4. Electromagnetic compressor bearing
(full color figure is available in electronic version)

- There is no oil for compressor lubrication, which enables more efficient exchange of heat in the evaporator and condenser (there is no oil film creating additional heat resistances).
- Extended compressor life due to lack of existence of wear surfaces; no metal-to-metal contact of rotating components.
- There are no vibrations in any of the work phases of the water chiller, including start.

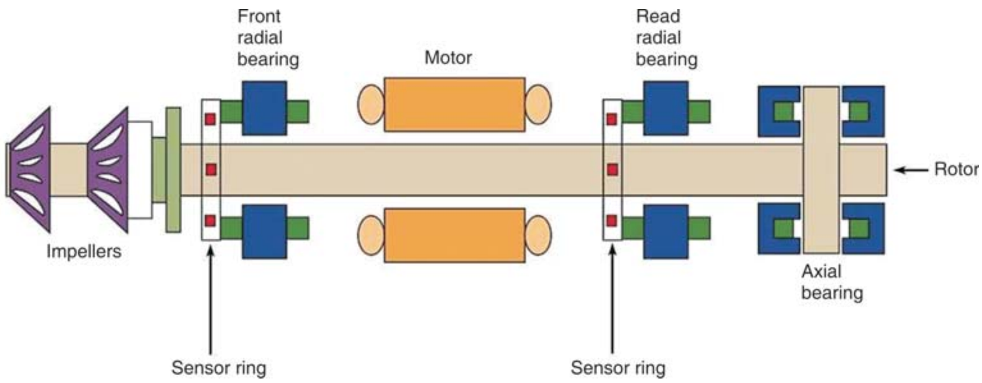

Figure 5. Schematic diagram of basic compressor elements
(full color figure is available in electronic version)

- The compressor drive motor is a synchronous permanent-magnet brushless DC motor, with the power of 105 kW, with the size of a conventional fan induction engine, and power of 0.75 kW. It is cooled directly with refrigerant (R134a), works at high speed (20000 to 48000 rpm), and there is no need for "Soft start system", and the motor is completely protected.
- Small dimensions and weight (just 140 kg). The screw compressors with the same cooling capacity are up to 5 times heavier and up to two times bigger in size.
- Low starting currents up to 5 A, during compressor's start, instead of 500-600 A for screw compressors of the same cooling capacity.

– *Shell-and-tube flooded evaporator*

The evaporator of the water chiller is the shell-and-tube in its appearance, and is of a flooded by its function. It has been made of steel shell and a bundle of copper tubes, mechanically expanded in the steel pipe-plates. The shell is thermally insulated. Thanks to the special drop liquid separator system there is no possibility for the compressor to suck in liquid refrigerant, and overheating of the refrigerant at the inlet of the compressor is less than 3 K. The level of the liquid refrigerant is controlled and maintained with the help of special electronic level sensors and by a modular expansion valve. The water circulates through the bundle of copper tubes, and the refrigerant (R134a) is around the tubes.

This is possible to execute, because there is no oil in the refrigerant, as in conventional oil-lubricated compressors; oil runs away from the compressor and appears in the refrigerant side of the heat exchangers (evaporator and condenser). In this way, the refrigerant boiling has been enabled throughout the total external surface of the copper tube bundle. For this reason, the heat transfer ratio has been significantly increased, and small temperature difference has been secured between the outlet water temperature from the evaporator and the evaporating temperature (less than 2 K). This results in increased cooling capacity, with slight increase of absorbed power, leading to an increased energy efficiency of the water chiller.

– *Interactive remote control*

By the installed software through local area network, or internet, one can monitor the work of the water chiller from any computer anywhere in the world.

Factory measurement of water chiller's working parameters

Expert team consisting of mechanical and electric engineers from Filter Frigo has attended factory tests of the water chiller. The tests have been performed on April 3rd, 2008 in the test cabin no. 3.

The results of measurements for one of three water chiller have been presented in tab. 1.

Table 1. Original factory testing report of the water chiller TECH-HF 2AS

03-04-08	CABINA 3 - Stampa N° "06"	ore 12:24:25	
Cliente..	EKO ELEKTROFRIGO D.O.O.	C.O. 8020148	COM. 01054343
Matricola..	B9V6281012	Unita' TECS-HF 2AS	
Stato Unita'.	CHILLER	Doc. CW1	
Ventilazione.			
Funzionamento:100%			
	DATI ELETTRICI		
Corrente fase R	217.0	amp	
Corrente fase S	216.0	amp	
Corrente fase T	214.0	amp	
Tensione di linea	407.0	volts	
Potenza assorbita	138.4	kW	
Cos Ž	0.91		
	MISURA EVAPORATORE		
Temp.ingresso	12.24	°C	
Temp.uscita	7.22	°C	
Portata	107.80	m3/h	
Potenzialita'	**629.25**	**kW**	
E.E.R.	4.55		
	MISURA CONDENSATORE ACQUA		
Temp.ingresso	29.94	°C	
Temp.uscita	35.02	°C	
Portata	129.94	m3/h	
Potenzialita'	**767.55**	**kW**	
E.E.R.	5.52		

Table 2 shows calculated cooling capacity and absorbed powers at different loads of the water chiller and different water temperatures for condenser cooling.

Table 2. Calculated operating parameters of the water chiller

Water chiller		TECS-HF 2AS			
Load	[%]	100	66	50	33
Cooling capacity	[kW]	657.4	433.88	328.7	216.94
Total absorbed power	[kW]	128.4	57.5	34.2	20.7
ERR	[Wh/Wh]	5.11	7.55	9.61	10.47
Water entering the evaporator	[°C]	14	12.3	11.5	10.6
Water exiting the evaporator	[°C]	9	9	9	9
Water flow through the evaporator	[m^3h^{-1}]	113.2			
Water entering the condenser	[°C]	29.5	26	22	18
Water existing the condenser	[°C]	34	28.8	24.1	19.4
Water flow through the condenser	[m^3h^{-1}]	149.7			

Facility requirement for cooling

For cooling of equipment and air-conditioning in the building of Telecommunication Data Center “Belgrade”, a total cooling capacity is needed of 1.2 MW. For those requirements, three water chillers, with water cooled condensers were selected, each with cooling capacity of 658 kW, in the following work regimes:

– water temperature at the evaporator inlet 14 °C,
– water temperature at the evaporator outlet 9 ° C,
– water temperature at the condenser inlet 29 °C, and
– water temperature at the condenser outlet 34 °C.

The installed capacity is much higher (1.97 MW) than needed, due to the reason of redundancy safeguards. Processor (Manager 3000), controls the work of all three water chillers. The simultaneous work of all three water chillers was enabled at reduced load, when the electric power consumption has been significantly decreased.

Regulation of the cooling capacity of the water chillers (from 10% to 100%) is executed in two ways:

– by changing the speed of the turbine, according to factory data from 20000 to 48000 min^{-1}; measured from 22500 to 34000 min^{-1}, and
– by changing the opening degree of the IGV at the inlet side of the compressor.

It was found that combined regulation has a good performance.

When two water chillers operate at high external temperatures, in order to satisfy the cooling requirement (fig. 6), their total cooling capacity is 2 × 612.6 = 1225.2 kW, while the absorbed power is 2 × 139.8 = 279.6 kW. The cooling capacity is less than nominal, and the absorbed power is higher, due to higher temperature of water for cooling of the condenser.

The condensing temperature is t_k = 40 °C (tab. 4, the first colum).

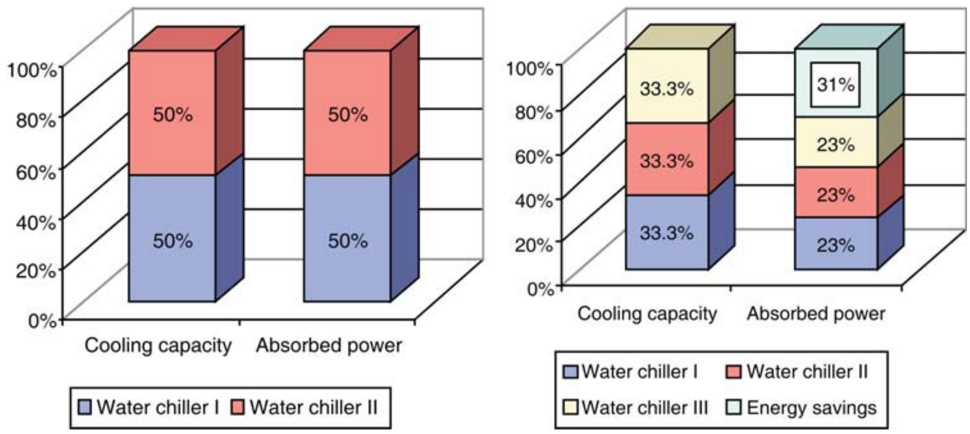

Figure 6. Comparative presentation of energy consumption, if two or three water chillers are operational for the same total cooling capacity
(full color figure is available in electronic version)

When all three water chillers operate at decreased speed in order to satisfy the same cooling requirement, their total cooling capacity is $3 \times 407.5 = 1222.5$ kW while the absorbed power is $3 \times 64.0 = 192.0$ kW, that is 31% less.

The condensing temperature is $t_k = 32$ °C (tab. 3).

The use of *Multiple chiller system* allows unusual redundancy safeguards.

These values have encouraged us to determine the annual seasonal energy consumption by calculation for the data center cooling, using multiple chiller system.

Three cases have been discussed in order to be able to determine an optimum operating method for the system. Cooling of equipment in the winter is working in the free cooling mode.

The first case is the analysis of the work of an old Westinghouse water chiller, with cooling capacity of 1.2 MW, with conventional oil-lubricated centrifugal compressor. According to the method recommended by KGH (Serbian Society for HVAC&R), we have assumed that the water chiller operates only 240 days a year, 14 hours per day. The calculated seasonal electric power consumption is 571.2 MWh during the year. For securing the facility requirement for the cooling, only one water chiller was used, and the other served as a reserve.

The second discussed case is a parallel work of two new water chillers with Turbocor compressors. During that, the third water chiller serves as a reserve. For the same number of hours of work, as in the previous case, the seasonal energy consumption is 364.8 MWh, which is 36% less than in the first case.

The third case is the parallel operation of all three new water chillers. For the same number of hours, seasonal energy consumption was 212.6 MWh, which is 63% less than in the first case.

According to the world price lists for electricity utilization, the financial effects, that is, annual savings in this operating regime of the water chillers would be \$37650. *The current project indicates a simple payback for the third water chiller of approximately 2.5 years.*

Measurement of chiller working parameters in the facility

The measurements have been performed in August and on October 14th, 2008.

Measuring equipment

For basic measurement of temperatures and pressures, the measuring equipment which has been installed in the factory in water chillers, has been used.

For control measurements of temperatures and pressures, the measuring equipment, product of ROBINAIR, has been used.

For indirect measurements of the speed of turbine, opening degree of inlet guide vane - IGV and for determining the requested load of the water chiller, a computer has been used (fig. 7) with the software package from *Danfoss Turbocor Monitoring Tool Version 2.1.0.80.*

For electrical network characteristics measurement, instrument CHAUVIN ARNOUX C.A 8334 has been used (fig. 8).

Figure 7. Measuring equipment
(full color figure is available in electronic version)

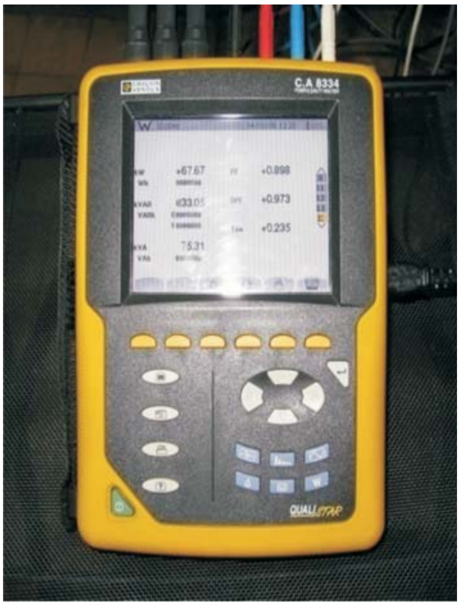

Figure 8. Instrument CHAUVIN ARNOUX C.A 8334
(full color figure is available in electronic version)

For basic measurement of the water flow rate orifice meter have been used in conection with OVENTROP flow-meter OV-DMC 2 (fig. 9).

For control measurement of water flow rate, the ultrasonic flow-meter UFM 610P has been used, product of KROHNE (fig. 9).

By detailed measurement and analysis of current characteristics of the water chiller, the influence of the variable speed electric motor has been observed to so-called “defilement“ of power grid.

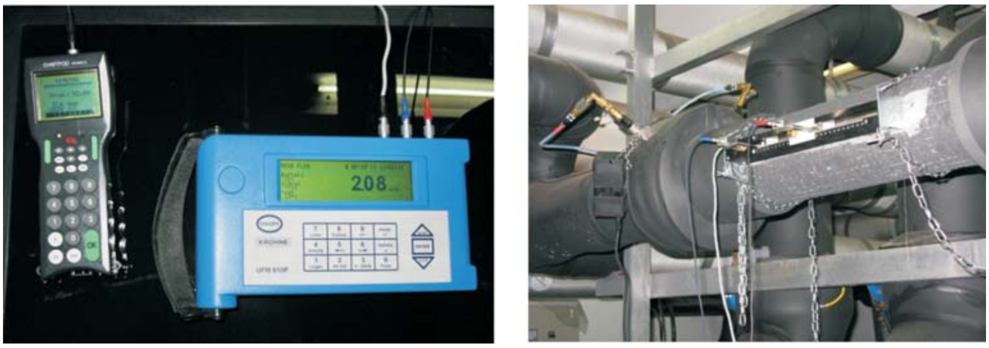

Figure 9. Instrument OVENTROP OV-DMC 2 and ultrasonic flow-meter KROHNE UFM 610P
(full color figure is available in electronic version)

From the voltage diagram (fig. 10), it can be observed that there is small voltage distortion because voltage oscillograms are not ideal sinusoids.

From the current intensity diagram, one can observe that the currents in phases are symmetrical. Simultaneously, this diagram shows that there is serious current distortion, because the current oscillograms are not ideal sinusoids, but have in each semi-period two symmetrical peaks, resulting from higher odd harmonics (fig. 10).

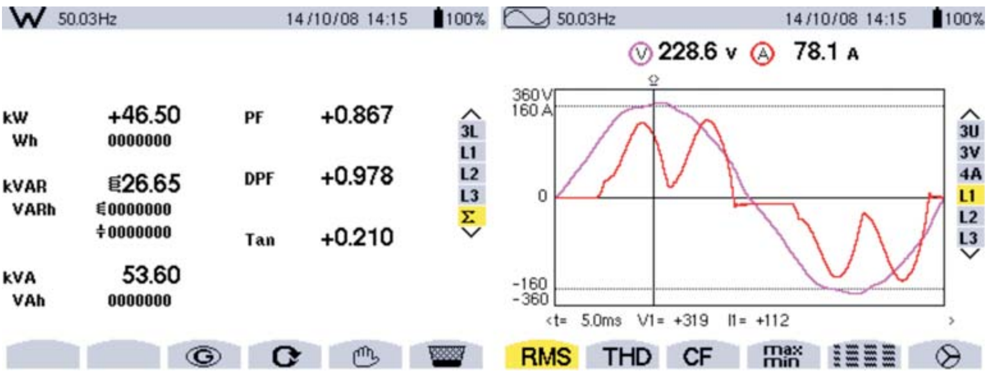

Figure 10. Results of the electrical parameters measuring (power, cosφ, voltage, current intensity)
(full color figure is available in electronic version)

In other words, good characteristics, like soft start (maxigraph compensation) and speed regulation, which is the compressor cooling capacity regulation, have for their consequence, the current and voltage distortion. This results in an appearance of interferences in the form of higher harmonics of voltage and current. In installations where such level of higher harmonics might cause problems, we use filters, based on inductive chokes mounted in the compressor's power line.

The measurements show that by decreasing the speed of the turbine, power factor cos φ also decreases, and it increases the percentage of reactive power in apparent power. Considering the costs of the reactive power, reactive power should be compensated. On the other hand, low starting current (up to 5 A) does not cause problems with "peaks" and it does not switch on maxigraph, which in conventional water chillers with starting currents from 500 A to 600 A significantly influences the price of the consumed electricity.

The software package *Danfoss Turbocor Monitoring Tool Version 2.1.0.80* offers possibilities for monitoring different parameters in the work of Turbocor compressor. From the program the operator can open up different windows, some of which were presented in the figs. 11 and 12.

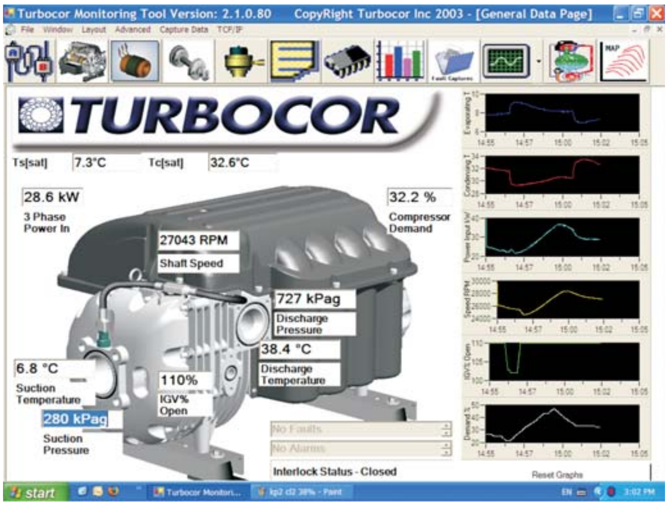

Figure 11
(full color figure is available in electronic version)

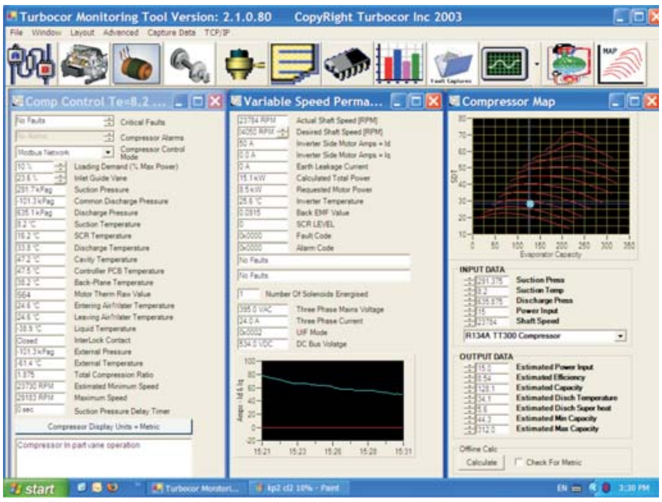

Figure 12
(full color figure is available in electronic version)

During the measurement opening degree of IGV was changing from 110 to 8.8%, as well as the compressor impeller's speed from 33978 to 22520 min^{-1}. The EER changed from 4.4 at maximum load to 9.1 at reduced capacity of 34% of the maximum load. By further decrease of load, the EER would also increase.

Table 3 shows the results of measuring the working parameters of water chiller no. 2 at high external temperatures (measured in August 2008). The water chillers no. 1 and no. 3 were in simultaneous operation.

Table 3. Results of measuring the working parameters of water chiller no. 2

Water Chiller: TECS-HF 2S φ_o = 658 kW, P_w = 130 kW, t_w = 14/9 °C	Compressors: TT300 (R134a)	Date: August 12, 2008.
Outside air temperature		37.9 °C
	Parameters	
Discharge pressure	[kPag]	702
Condensing temperature	[°C]	32
Discharge temperature	[°C]	38.5
Water flow (condenser)	[m^3/h]	126.3
Water temperature (condenser inlet)	[°C]	25.7
Water temperature difference-condenser	[K]	3.1
Heating capacity	[kW]	455.3
Suction pressure	[kPag]	290
Suction temperature	[°C]	7.6
Water flow (evaporator)	[m^3/h]	129.8
Water temperature (evaporator outlet)	[°C]	9.0
Water temperature difference-evaporator	[K]	2.7
Cooling capacity	[kW]	407.5
Shaft speed	[min^{-1}]	27371
Compressor load	[%]	34
IGV open	[%]	110
Power input	[kW]	64
cos φ	–	0.893
EER	–	6.4

The compressors worked with completely opened IGV, and with reduced impeller's speed of 27371 min^{-1}. Because the condenser's load was below 70%, this enabled the compressor to operate at condensing temperature of 32 °C and the efficiency level – EER should be significantly increased (6.4).

Table 4 shows the results of measuring the working parameters of water chiller no. 2 at different loads.

Table 4. Results of measuring the working parameters of water chiller no. 2

Water Chiller: TECS-HF 2S φ_o = 658 kW, P_w = 130 kW, t_w = 14/9 °C		Compressors: TT300 (R134a)			Date: 14/10/2008.		Outside temperature 21 °C	
Parameters/Time		12:48	13:08	13:16	14:15	14:34	15:32	15:37
Discharge pressure	[kPa]	887	793	769	702	618	613	595
Condensing temperature	[°C]	40	36	35	32	28	27	26
Discharge temperature	[°C]	50.5	47.4	41.2	36.2	33.8	32.8	32.0
Water flow (condenser)	[m^3h^{-1}]	126.1	125.8	125.6	125.6	125.9	125.8	126.3
Water temperature (condenser inlet)	[°C]	26.6	25.2	25.4	24.3	24.0	23.5	23.1
Water temperature difference-condenser	[K]	5.0	4.7	3.7	2.6	1.8	1.5	1.4
Heating capacity	[kW]	733.1	687.5	540.4	379.7	263.5	219.4	205.6
Suction pressure	[kPag]	3.0	2.67	2.8	2.89	2.92	2.95	2.98
Suction temperature	[°C]	9.2	5.9	7.0	7.6	8.2	9.1	9.2
Water flow (evaporator)	[m^3h^{-1}]	128.5	129.8	129.5	129.8	129.1	128.8	129.4
Water temperature (evaporator outlet)	[°C]	11.3	8.7	8.7	8.9	8.8	8.8	8.9
Water temperature difference-evaporator	[K]	4.1	3.9	3.2	2.2	1.6	1.4	1.3
Cooling capacity	[kW]	612.6	588.6	481.9	332.0	240.2	210.0	195.6
Shaft speed	[min^{-1}]	33802	33978	29182	25434	23784	22907	22520
Compressor load	[%]	90	74.8	42.8	26.8	10	10	11.7
IGV	[%]	110	110	110	110	23.6	8.8	8.8
Power input	[kW]	139.8	130.8	78.5	46.5	30.8	23.2	21.6
Reactive power	[kVaR]	60.6	56.9	36.6	26.6	21.3	19.2	18.2
cos φ	–	0.917	0.916	0.906	0.867	0.822	0.771	0.762
EER	–	4.4	4.5	6.1	7.1	7.8	9.0	9.1

Pumps for circulation of cold (evaporator) and cooling (condenser) water

Each of the water chillers has its own pair of pumps. Pump for circulating water through the evaporator shall start its operation before the start of the first compressor in the water chiller, and the pump for circulation of the water through the condenser, shall start when the condensing pressure reaches the set value. These pumps are important consumers of electricity and have not been calculated in when determining the EER.

Conclusions

- Oil-free twin-turbo centrifugal compressor uses electromagnetic bearings and a variable-speed turbine for significant increase of energy efficiency at partial load compared to the previous solution with conventional centrifugal compressor;
- Water chillers with water cooled condenser offer high energy efficiency level – EER at the highest external temperatures, because the water chillers operate with condensing temperature up to 40 °C;
- Part load energy efficiency is outstanding, with energy savings greater than 35% compared to the conventional oil-lubricated centrifugal or screw compressors;
- Totally oil-free operation has improved the heat transfer efficiency;
- Extended equipment life was provided with minimal scheduled maintenance;
- The current project indicates a simple payback for the third water chiller of approximately 2.5 years.
- The Multiple chiller system allows unusual redundancy safeguards with energy savings greater than 35%, and
- Reduced energy consumption provides a way to reduce utility generated greenhouse gas emissions.

Acronyms

EER – energy efficiency ratio, [$WhWh^{-1}$]
ESEER – European Seasonal Energy Efficiency Ratio, [$WhWh^{-1}$]

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Апстракт

Слободан Ђ. ПЕЈКОВИЋ

Филтер Фриго д. о. о., Београд, Србија

Енергетски ефикасно хлађење телекомуникационог центра применом чилера са безуљним расхладним турбо компресорима

Безуљни *twin-turbo* центрифугални компресор користи електромагнетне лежајеве и променљив број обртаја турбине да би значајно повећао енергетску ефикасност при парцијалном оптерећењу у односу на класичне компресоре чији се лежајеви подмазују уљем.

Три агрегата за хлађење воде (чилера) који су уграђени у Телекомуникационом Центру – Београд, у априлу 2008. имају сваки по два *Turbocor* компресора и укупну расхладну снагу од 1,97 MW. Овакво пројектно решење са безуљним компресорима је први пут примењено у Србији, а и на територији бивше Југославије. Процењује се да је овим решењем остварена уштеда енергије у току сезоне хлађења 2008. године већа од 35% у односу на претходно решење са класичним центрифугалним компресорима.

У овом раду су приказани резултати прелиминарних мерења радних карактеристика и коефицијената хлађења (*EER – energy efficiency ratio*) агрегата у реалним радним условима.

Кључне речи: *turbocor компресор, безуљни центрифугални компресор, енергетска ефикасност*

Електронска адреса аутора: filfrigo@eunet.rs

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