EXPERIMENTAL EVALUATION OF AN INDIRECT-FIRED ABSORPTION CHILLER OPERATING AT PARTIAL LOAD CONDITIONS

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Abstract. *Nowadays the absorption refrigeration systems are becoming more attractive, mainly because these systems have a low consume of electricity and also have a low environmental impact, due to the refrigerant fluid used. Another important advantage is the possibility of use low-grade energies sources, such as solar, waste heat discharged from industrial processes (cogeneration) and geothermal energy to provide cooling. The objective of this paper is to present an experimental evaluation of an indirect-fired single effect H_2O-LiBr absorption chiller with a nominal capacity of 35 kW (10 TR). The heat source for the chiller is hot water, that is proceeding from a heat recovery boiler. The results obtained by experimental tests are used to demonstrate system performance details, operational characteristics and typical working limits. The influence of the inlet temperature of hot, chilled and cooling water over the chiller capacity and heat demand will be analyzed, consequently, the coefficient of performance (COP) will be dertermined.*

Keywords*: Experimental evaluation, absorption chiller, H_2O-LiBr, partial load*

1. INTRODUCTION

The search for alternative energy sources has been the keynote in the current national and international scenario, when discussing the need to have reliable, clean, readily available power. However it is important to emphasize the difficulty in electricity supply to all the distant regions of Brazil, where poor access and lack of resources still leave many people without that benefit, impairing their quality of life (Lora and Haddad, 2006).

Added to these factors, the environmental impact caused by the growing demand for cooling is becoming a constant concern to the scientific community. The International Institute of Refrigeration has estimated that approximately 15% of all electricity produced worldwide is used in cooling and air conditioning process of various types (IIR, 1992).

Considering this scenario, the study and development of vapor absorption refrigeration systems became attractive, among other reasons, due to its low power consumption, reduced environmental impact and their potential use in cogeneration systems (Kim *et al*., 2002).

The use of cogeneration systems can help to decentralize and increase the reliability of the Brazilian electric transmission system, diversifying the energetic power sources and increasing the installed capacity of electricity generation using private capital (resources). Cogeneration systems integrating microturbines and absorption refrigeration chillers are being considered as a reasonable alternative for power and cooling on-site energy generation in Brazil (Lora and Haddad, 2006).

Although the amount of thermal energy used in absorption refrigeration systems is very high, the amount of mechanical energy required is very small. For this reason, the usage of waste heat energy, geothermal energy and solar energy in these systems may be cost effective.

Besides providing advantages to reduce the electricity consumption and the possibility of using waste heat from a specific process, these systems have reduced noise and vibration levels, when compared to vapor compression system. Among the working fluids, the binary solutions such as ammonia-water (NH_3-H_2O) and water-lithium bromide (H_2O-LiBr) are between the most used in absorption systems. These working fluids have zero Ozone Depleting Potential (Sözen, 2001).

In systems that require low temperatures the NH_3-H_2O mixture is used. And H_2O-LiBr systems are widely used where moderate temperatures are required, such as, air conditioning application (Kaynakli and Kilic, 2007).

However, these systems have some disadvantages, such as its low performance, the higher installation cost and crystallization possibility in the case of use of H_2O-LiBr solutions. Although, when a residual source of heat or a low cost heat source is available, the absorption refrigeration systems can be advantageous compared to vapor compression systems (Asdrubali and Grignaffini, 2005).

Manufacturers and designers seek to achieve a better performance of the absorptions chillers, which occur at or near their maximum cooling capacity. Thus, properly designed, these systems must operate near their maximum capacity during most of the time of operation (Gordon and Ng, 2000).

Considering the aforementioned, the objective of this study is to analyze the performance characteristics of an absorption refrigeration chiller during partial load operation. The effect of the chilled, hot and cooling water inlet temperature on the absorption chiller performance is investigated. The chiller capacity and the heat supplied to the desorber are quantified for the partial load conditions, thus permitting to calculate the COP (Coefficient of Performance).

2. DESCRIPTION OF THE ABSORPTION REFRIGERATION SYSTEM

The absorption chiller, model LT1 provided by Thermax, is a single effect vapor absorption refrigeration system, with a nominal capacity of 10 TR (35 kW). The heat supplied in the desorber is in the form of hot water. The chiller working solution is a mixture of water and lithium bromide (H_2O-LiBr). The cooling water circuit is arranged in a series flow configuration.

Table 1 shows the main working parameters for the Thermax chiller in the nominal conditions.

Table 1. Chillers parameters for nominal condition (Thermax, 2006)

		Evaporator	**Desorber**	**Absorber / Condenser**
Inlet temperature	**°C**	12.20	90.60	29.40
Outlet temperature	**°C**	6.70	85.00	36.80
Flow rate	**m³/h**	5.50	7.80	10.00
Capacity[1]	**kW**	35.20	50.80	86.10
COP	**-**	0.69		

[1] Water specific heat at constant pressure = 4.1868 kJ/ kg °C

The values presented in Tab. 1 are valid for an inlet cooling water temperature higher than 20 °C, minimum outlet chilled water temperature of 4.5 °C, and fouling factor of 0.0001 in the water circuits.

In relation to the physical characteristics of the absorption chiller, the evaporator consists of a tube bundle, an outer shell, distribution trays and a refrigerant pan. The chilled water flows inside the tubes and a pump circulates the refrigerant from the refrigerant pan into the distribution trays. From the trays the refrigerant falls on the evaporator tubes. These characteristics can be observed in the Fig. 1, which is a schematic representation of the absorption chiller.

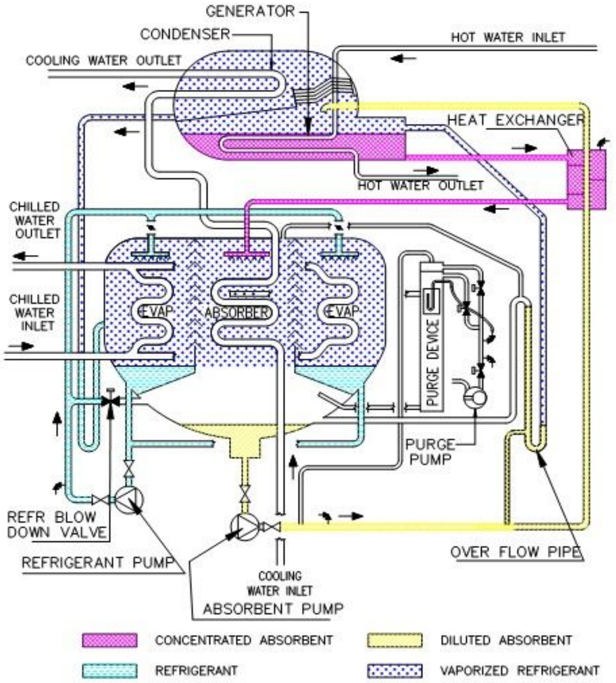


Figure 1. Absorption chiller schematic (Thermax, 2006)

The absorber also has distribution trays and an absorbent collection sump. Concentrated absorbent solution from the low temperature generator is fed into distribution trays. This solution falls on the absorber tubes.

The desorber and condenser tube bundles are enclosed in a shell and are separated by an insulation plate. The driving hot water flows into the generator tubes. It heats the absorbent, flowing outside the tubes (Thermax, 2006).

An important technical feature is the 10-100 % modulation for cooling loads variation. During partial load operation, a 3-way diverting valve automatically varies hot water flow in order to maintain the temperature of chilled water leaving the chiller. This ensures better partial load performance.

An important safety issue is the crystallization protection. If the concentrated absorption solution, while returning to the absorber from the generator is excessively cooled, it crystallizes in the heat exchanger. The crystallization either occurs when the concentration of the absorbent (related to its temperature) becomes too high or when its temperature drops excessively. When one of these two situations occurs the machine goes into the dilution cycle. This dilution cycle reduces the generator temperature or the cooling water temperature.

The chilled water produced by the single effect absorption chiller, shown in Fig. 1, which is installed in NEST/IEM laboratories of the Federal University of Itajubá (UNIFEI) is directed to a reservoir where electrical heaters are installed. The control of the power of these resistors allows its variation from zero to full power (35 kW).

This control mechanism allows the simulation of a thermal load, for example, it's able to simulate the load profile of an air conditioning system for thermal comfort.

2.1. Experimental procedure

The tests were performed, maintaining a constant temperature of the hot water supplied to the chiller. The hot water is supplied at the temperature required to initiate the evaporation process of the water in the absorption chiller desorber.

When the chiller started to produce water at 7 ºC the process of applying heat load on the system, through the electrical resistances, was initiated. For each hot water temperature, the power of the electrical resistance was changed from zero to 35 kW, at increments of 5 kW.

In each of these load steps data were collected during the operation, such as: temperature, flow rates and pressures of the points of entry and exit of chilled, cooling and hot water.

2.2. Performance parameters

The experimental research carried out focused on the behavior of refrigeration absorption system operating at partial load. Among the analyzed parameters, are included the cooling capacity, the heat supplied to the chiller desorber and the coefficient of performance.

These performance parameters were calculated based on physical quantities acquired by measurement instruments, such as, thermoresistances Pt-100 to measure temperature in the chilled, cooling and hot water circuits, turbine type flowmeter to measure the volumetric flow and Bourdon Manometers to measure water pressures in all circuits. A schematic of the measurement instruments location in the experimental set are represented in the Fig. 2.

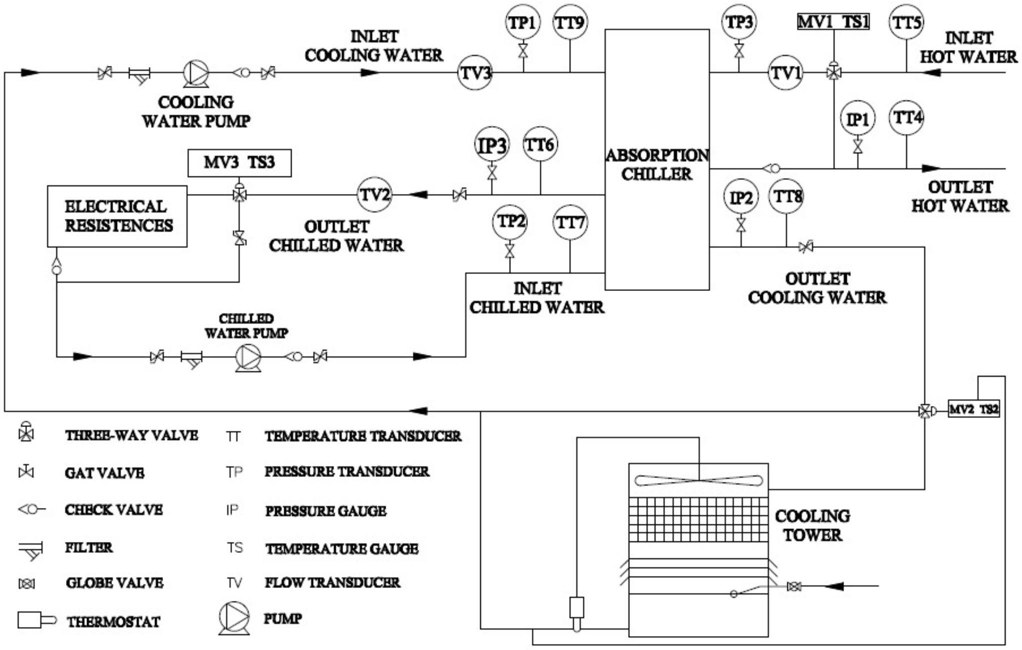
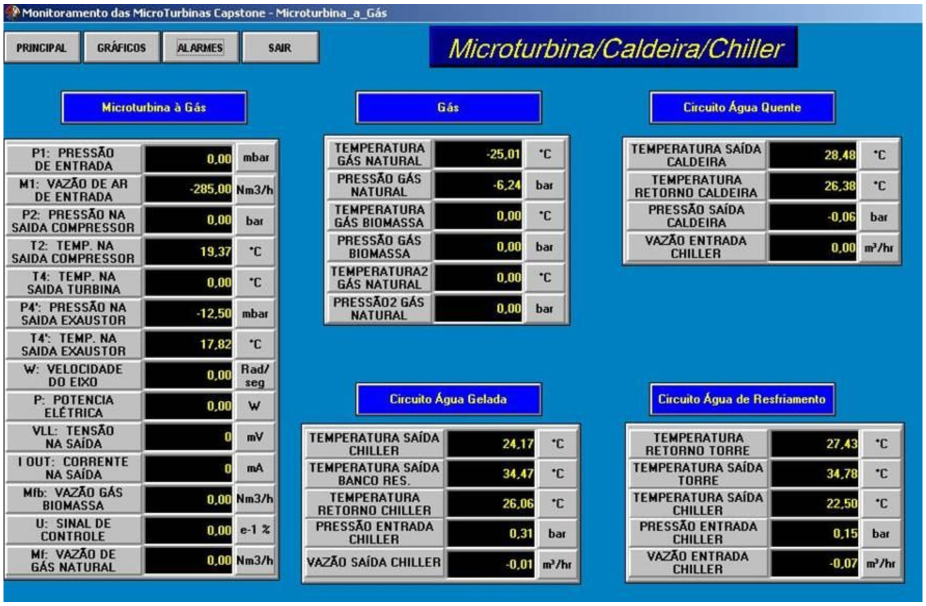


Figure 2. Absorption refrigeration system schematic

All measured quantities are converted into electric signals and directed to a data acquisition system. The software, Elipse Scada, allows to visualize and to memorize all the necessary physical quantities to evaluate the performance of the refrigeration absorption system. The Fig. 3 shows one of the screens of the data acquisition system developed in the Elipse Scada.



Microturbina à Gás

P1: PRESSÃO DE ENTRADA	0,00	mbar
M1: VAZÃO DE AR DE ENTRADA	-285,00	Nm3/h
P2: PRESSÃO NA SAIDA COMPRESSOR	0,00	bar
T2: TEMP. NA SAIDA COMPRESSOR	19,37	°C
T4: TEMP. NA SAIDA TURBINA	0,00	°C
P4': PRESSÃO NA SAIDA EXAUSTOR	-12,50	mbar
T4': TEMP. NA SAIDA EXAUSTOR	17,82	°C
W: VELOCIDADE DO EIXO	0,00	Rad/seg
P: POTENCIA ELÉTRICA	0,00	W
VLL: TENSÃO NA SAÍDA	0	mV
I OUT: CORRENTE NA SAÍDA	0	mA
Mfb: VAZÃO GÁS BIOMASSA	0,00	Nm3/h
U: SINAL DE CONTROLE	0,00	e-1 %
Mf: VAZÃO DE GÁS NATURAL	0,00	Nm3/h

Gás

TEMPERATURA GÁS NATURAL	-25,01	°C
PRESSÃO GÁS NATURAL	-6,24	bar
TEMPERATURA GÁS BIOMASSA	0,00	°C
PRESSÃO GÁS BIOMASSA	0,00	bar
TEMPERATURA2 GÁS NATURAL	0,00	°C
PRESSÃO2 GÁS NATURAL	0,00	bar

Circuito Água Quente

TEMPERATURA SAÍDA CALDEIRA	28,48	°C
TEMPERATURA RETORNO CALDEIRA	26,38	°C
PRESSÃO SAÍDA CALDEIRA	-0,06	bar
VAZÃO ENTRADA CHILLER	0,00	m³/hr

Circuito Água Gelada

TEMPERATURA SAÍDA CHILLER	24,17	°C
TEMPERATURA SAÍDA BANCO RES.	34,47	°C
TEMPERATURA RETORNO CHILLER	26,06	°C
PRESSÃO ENTRADA CHILLER	0,31	bar
VAZÃO SAÍDA CHILLER	-0,01	m³/hr

Circuito Água de Resfriamento

TEMPERATURA RETORNO TORRE	27,43	°C
TEMPERATURA SAÍDA TORRE	34,78	°C
TEMPERATURA SAÍDA CHILLER	22,50	°C
PRESSÃO ENTRADA CHILLER	0,15	bar
VAZÃO ENTRADA CHILLER	-0,07	m³/hr

Figure 3. Elipse acquisition data software screen

A list of physical quantities acquired by the data acquisition systems is showed in the Tab. 2:

Table 2. Parameters acquired by the system in real time.

$T_{in,h}$	Inlet hot water temperature	$\dot{m}_{h,w}$	Hot water flow rate
$T_{out,h}$	Outlet hot water temperature	$\dot{m}_{ch,w}$	Chilled water flow rate
$T_{in,c}$	Inlet cooling water temperature	$\dot{m}_{c,w}$	Cooling water flow rate
$T_{out,c}$	Outlet cooling water temperature		
$T_{in,ch}$	Inlet chilled water temperature		
$T_{out,ch}$	Outlet chilled water temperature		

The cooling capacity (Q_e) is calculated using Eq. (1):

$$\dot{Q}_e = \dot{m}_{ch,w} . c_{p,w} . (T_{in,ch} - T_{out,ch}) \tag{1}$$

The heat supplied by the hot water in the absorption chiller desorber (Q_g) and the coefficient of performance (*COP*) are calculated by Eq. (2) and (3), respectively. The water specific heat ($c_{p,w}$) is considered constant and equals to 4.187 (kJ/kg °C).

$$\dot{Q}_g = \dot{m}_{h,w} . c_{p,w} . (T_{in,h} - T_{out,h}) \tag{2}$$

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g} \tag{3}$$

All measurement instruments, such as, flowmeter and thermoresistances, present a measurement error. This kind of error, denominated direct measure error, is transmitted to other data's which depends on measured parameters. The error propagation of the indirect measures is calculated through partial derivative of each parameters of the equation, and they are represented as errors bars in the figures below.

3. EXPERIMENTAL DATA AND RESULTS

Among all the data collected, only the ones obtained when the system was operating at steady state were considered in this analysis.

3.1. Inlet chilled water temperature effects

This analyze evaluates the influence of the inlet chilled water temperature on the system performance. The Tab. 3 shows the values of the parameters used to calculate the cooling capacity, heat supplied at the desorber and the coefficient of performance.

For the variation of the inlet chilled water temperature, the inlet cooling water temperature, the inlet hot water temperature and the flow rate of the chilled, cooling and hot water were kept constant, as can be seen in Tab. 3.

Table 3. Flow water rates and inlet temperatures for different values of inlet chilled water temperature

$\dot{m}_{h,w}$ m³/h	$\dot{m}_{ch,w}$ m³/h	$\dot{m}_{c,w}$ m³/h	$T_{out,c}$ °C	$T_{in,c}$ °C	$T_{out,ch}$ °C	$T_{in,ch}$ °C	$T_{out,h}$ °C	$T_{in,h}$ °C
8.0	3.6	9.3	30.7	26.7	7.0	8.9	83.0	87.3
8.1	3.6	9.3	30.7	26.5	7.0	9.3	83.4	87.8
7.7	3.6	9.3	30.9	26.8	7.1	9.4	81.7	86.1
7.9	3.5	9.3	32.3	29.4	7.4	9.7	83.4	87.8
7.9	3.7	9.4	30.7	27.3	7.1	9.7	82.1	86.5
8.0	3.7	9.4	32.3	29.7	7.1	9.9	81.8	86.2
7.9	3.7	9.4	29.9	26.9	7.3	10.1	81.8	86.2
7.9	3.6	9.3	31.5	26.8	7.4	10.9	83.1	87.7
8.0	3.7	9.3	32.9	27.7	7.9	11.6	83.1	87.9

The chiller capacity and the heat supplied to the desorber increases as the inlet chilled water temperature increases. The increase in the inlet chilled water temperature rises the evaporation temperature, this way the evaporator has a higher heat exchange. With more refrigerant vapor absorbed by the solution, the heat exchanged at desorber increases for a constant inlet hot water temperature. These behaviors can be observed in the Fig. 4 below.

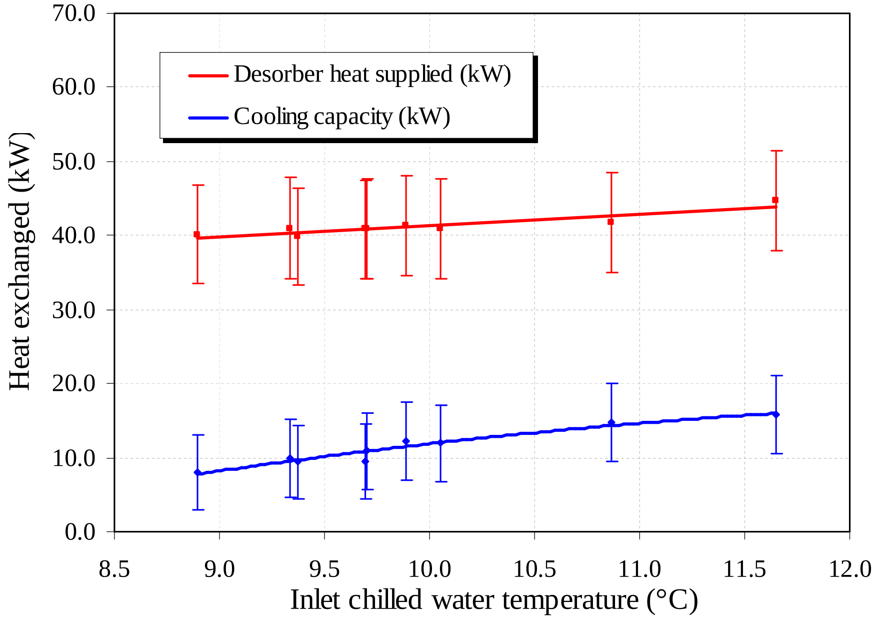


Figure 4. Effects of inlet chilled water temperature on the chiller capacity and heat supplied to the desorber

Figure 5 shows the coefficient of performance as function of inlet chilled water temperature for different inlet hot water temperatures. The COP rises as inlet chilled water temperature increases and for higher inlet hot water temperatures, the coefficient of performance increases. For low inlet hot water temperatures it is needed a higher heat exchanged at the desorber. So, for higher temperatures the heat exchanged at desorber is smaller and the chiller reaches higher capacities cooling, which provides better coefficient of performance.

For inlet chilled water temperatures higher than 11 °C, considering these operations conditions, the chiller is not able to maintain the outlet chilled water temperature at 7 °C, which is the temperature usually used in air conditioning systems for comfort.

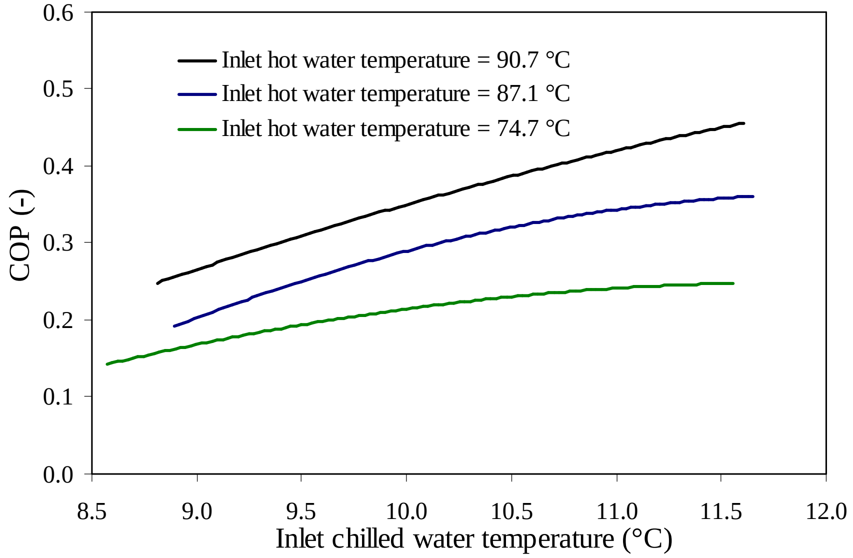


Figure 5. Chiller COP for different inlet hot water temperature

As higher is the inlet hot water temperature, higher is the increase of the coefficient of performance. For an inlet chilled water of 11 °C, and inlet hot water temperature of 75°C the COP increases 17%. For an inlet hot water temperature of 91 °C the COP increase 29%.

3.2. Inlet hot water temperature effects

The cooling capacity of the chiller is influenced by the hot water temperature. If hot water temperature is lower than the rated temperature, cooling capacity of the chiller tends to reduce.

Table 4 shows measures of inlet and outlet temperatures of the external streams and the water flow rate. With these values the cooling capacity and the heat supplied at the desorber are calculated and shown in Fig. 6.

Table 4. Flow water rates and inlet temperatures for different values of inlet hot water temperature

$\dot{m}_{h,w}$	$\dot{m}_{ch,w}$	$\dot{m}_{c,w}$	$T_{out,c}$	$T_{in,c}$	$T_{out,ch}$	$T_{in,ch}$	$T_{out,h}$	$T_{in,h}$
m³/h	m³/h	m³/h	°C	°C	°C	°C	°C	°C
7.8	3.6	9.3	30.9	26.8	7.3	9.5	80.6	85.0
7.9	3.7	9.4	30.7	27.3	7.1	9.7	82.1	86.5
7.9	3.6	9.3	31.5	26.8	7.4	10.9	83.1	87.7
7.9	3.7	9.4	31.5	28.1	7.1	10.7	84.2	88.7
7.9	3.6	9.4	32.6	27.6	7.8	10.7	84.3	89.1
8.1	3.7	9.3	30.9	26.3	7.1	9.8	84.9	89.5
8.0	3.7	9.4	33.1	29.9	7.4	10.6	85.2	89.9
8.0	3.7	9.3	33.5	30.1	7.4	10.8	85.9	90.5
8.0	3.8	9.3	30.7	27.3	6.6	9.9	87.4	91.7

As can be seen in the Fig. 6 the cooling capacity increases as the inlet temperature at the desorber increase. In the same way, the other two temperatures of the external streams and the flow water rate were constant, which values are showed in the Tab. 4.

The increase of the inlet hot water temperature provides a higher amount of refrigerant vapor at the condenser and, consequently, at the evaporator. This increase of refrigerant flow elevates the cooling capacity, considering the parameters of the chilled and cooling water circuit constants.

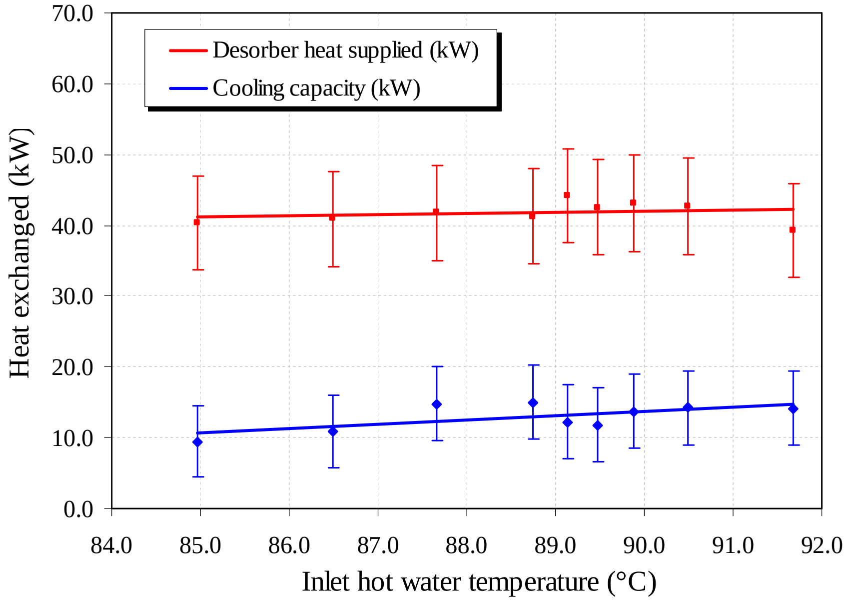


Figure 6. Effects of inlet hot water temperature on the chiller capacity and heat supplied at desorber

The effects of the inlet hot water temperatures on the COP are shown in Fig. 7. The chiller COP rises with an increase in the hot water temperature. The curves of the Fig. 7 represent the influence of the inlet hot water temperature for three different inlet chilled water temperature.

The amount of refrigerant vapor produced at the desorber provides an increase in the cooling capacity, which elevate the chiller performance as higher the inlet chilled water temperature. However, the inlet hot water temperature doesn't have a significant effect on the chiller performance as the inlet chilled water has. Even supplies hot water with a temperature higher than the nominal temperature, the chiller performance is limited by the possibility of occurs the solution crystallization.

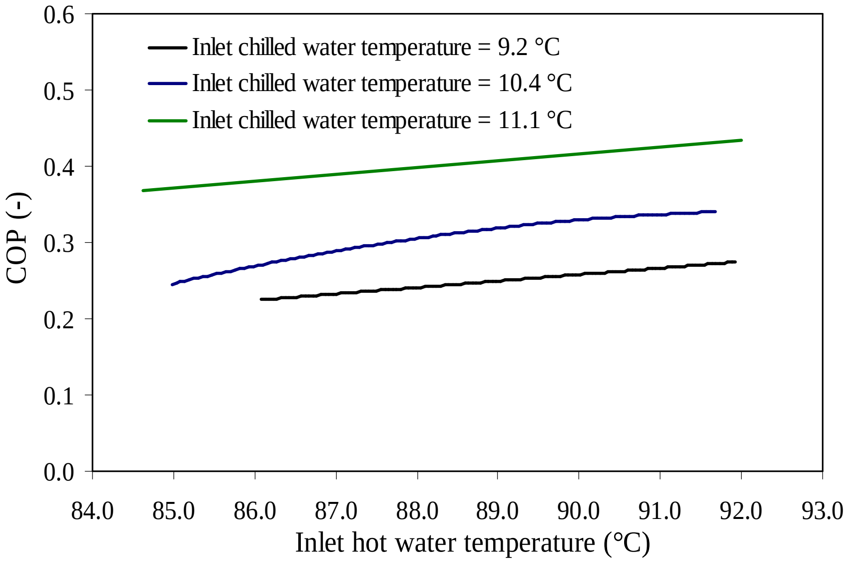


Figure 7. Chiller COP for different inlet chilled water temperature

For an inlet hot water temperature of 90 °C, its can be observed for a elevation of 2° C of the inlet chilled water that the performance of the chiller rises 20%, while for an inlet chilled water of 11°C, the rise of 5°C in the inlet hot water provides an increase of 8%.

3.3. Inlet cooling water temperature effects

The condensation temperature decreases as the cooling water temperature decreases. With the condensation pressure reducing, the boiling temperature of the LiBr solution in the generator is lowered. Hence the quantity of heat required in the generator is reduced, resulting in lower energy consumption.

The Tab. 5 below has the values of the water flow rate and temperature measured. In this analyze the inlet cooling water temperature variety, the flow rate and the inlet temperature of the chilled and hot water circuits were kept constant.

Table 5. Water flow rates and inlet temperatures for different values of inlet cooling water temperature

$\dot{m}_{h,w}$ m³/h	$\dot{m}_{ch,w}$ m³/h	$\dot{m}_{c,w}$ m³/h	$T_{out,c}$ °C	$T_{in,c}$ °C	$T_{out,ch}$ °C	$T_{in,ch}$ °C	$T_{out,h}$ °C	$T_{in,h}$ °C
7.9	3.7	9.2	31.3	26.2	7.2	11.4	84.2	88.8
7.9	3.6	9.3	31.5	26.5	7.4	11.4	83.9	88.6
7.9	3.6	9.3	31.5	26.8	7.4	10.9	83.1	87.7
8.0	3.8	9.3	30.7	27.3	6.6	9.9	87.4	91.7
8.0	3.7	9.4	31.2	27.4	7.0	10.8	84.4	88.9
7.9	3.7	9.4	31.5	28.1	7.1	10.7	84.2	88.7
8.0	3.6	9.3	31.8	28.3	6.8	10.9	87.2	91.6
7.9	3.5	9.3	32.3	29.4	7.4	9.7	83.4	87.8
8.0	3.7	9.3	33.5	30.1	7.4	10.8	85.9	90.5

In the absorber, the temperature of the diluted solution increases as it absorbs vaporized refrigerant. As the LiBr solution temperature increases, its absorption capacity decreases. So, it is necessary to provide cooling water flow to remove heat from the solution in the absorber for ensure maximum absorption of the refrigerant.

This behavior can be observed in the Fig. 8, which shows the desorber heat supplied as function of the cooling water temperature supplied to the chiller.

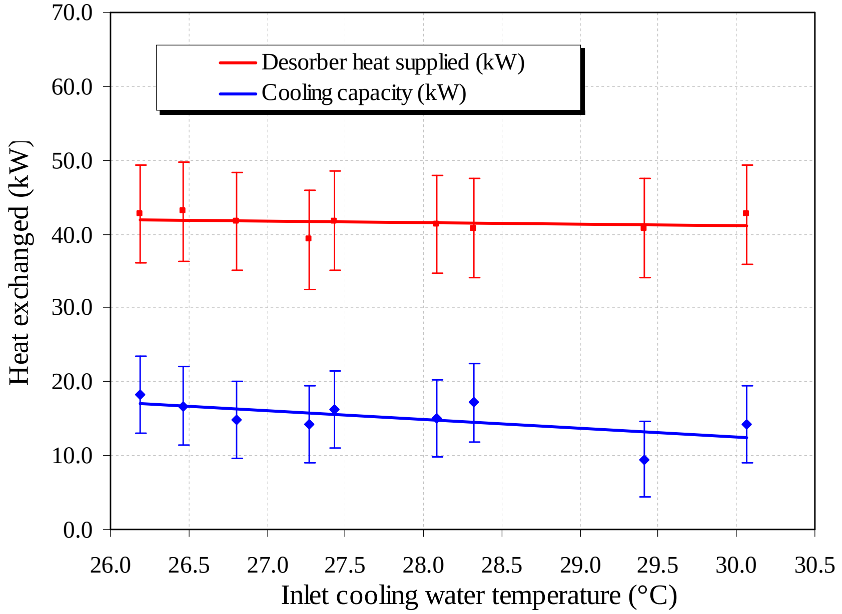


Figure 8. Effects of inlet cooling water temperature on the chiller capacity and heat supplied at desorber

Increasing the inlet cooling water temperature also increases the diluted solution temperature in the absorber, resulting in a reduction of the solution absorption potential. As the absorption potential decreases, the evaporation pressure increases leading to a cooling capacity reduction, as can be seen in the Fig. 8. To prevent this, it is essential to maintain low cooling water temperature.

Figure 9 shows the behavior of the coefficient of performance as function of the inlet cooling temperature variation. As can be seen, the coefficient of performance decreases for higher inlet cooling water temperatures.

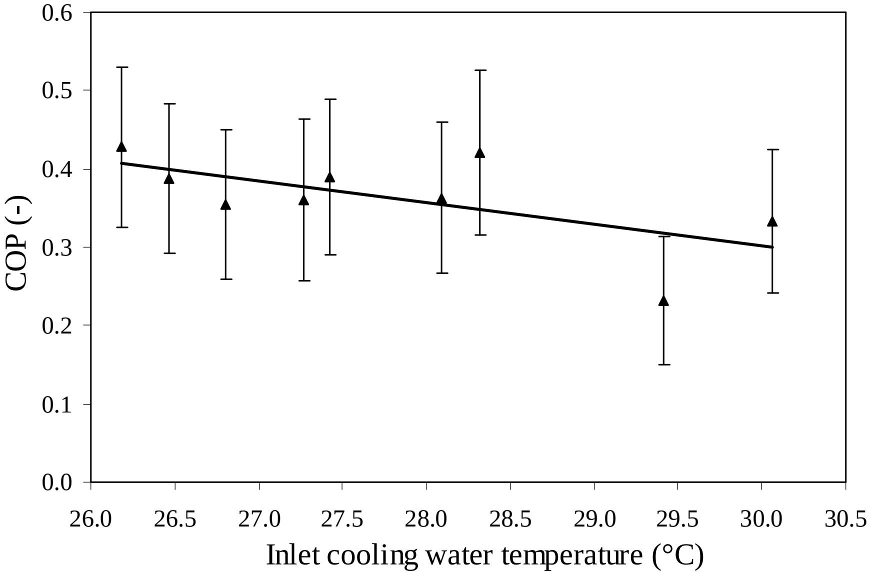


Figure 9. Effects of inlet cooling water temperature on the chiller COP

4. CONCLUSIONS

According to the behavior presented on this study the inlet chilled water temperature has a higher effect on the chiller capacity than inlet hot water temperature. The elevation of 16 °C of the inlet hot water temperature provides an increase of 21% in the chiller capacity and 31% in the COP while the increase of 2°C in the inlet chilled water rises 20% of the chiller performance.

The results also shows that the absorption chiller can’t keep the outlet chilled water temperature at 7 °C for inlet hot water temperature below, approximately, 85 °C, which can compromise the ability of the chiller to fulfill the expected cooling load demand.

The absorption chiller didn’t reached the nominal operating conditions due the heat supplied at desorber wasn’t enough for this chiller capacity. For the analyzed data the cooling capacity reached only 55 % (19.2 kW) of its nominal capacity that resulted in a COP of 0.45.

For an inlet hot water temperature of 75 °C the absorption chiller reaches an outlet chilled water temperature of 7 °C with a capacity of approximately 10kW.

In some operation conditions, even when the inlet hot water temperature reaches the nominal desorber temperature, the chiller didn’t reach the nominal capacity. This occurs due to the fact that the chilled water flow rate was below from the nominal condition and the chiller was operating with elevate inlet cooling water temperature, which reduces the capacity of the chiller.

The partial load conditions obtained from the tests were not compared with the ones provided by the manufacturer as it wasn’t possible to know the manufacturer parameters for partial load.

5. ACKNOWLEDGEMENTS

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