Efficient Integration of advanced absorption heat pumps and chillers in District Heating and Cooling networks

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Abstract:

The design and analysis of District Heating and Cooling (DHC) networks using local renewable energy sources such as thermal energy from solar collectors is one of the most interesting tools to fight against greenhouse gas emissions. The development and viability of these networks will be facilitated by the parallel development of new highly efficient absorption systems to efficiently produce not only chilled water but also heating and/or cooling and working as booster absorption heat pumps for the fifth generation of DHC networks using very low temperatures. These new absorption units are already commercialized and ready to be integrated as central units or distributed as substations with other energy conversion technologies. The new absorption systems considered include the following: a) double-lift chillers to improve the recovery of waste heat by producing a very high temperature glide in the driving heat, b) double-lift absorption units, or very low-temperature driven systems. This paper examines the technical assessment of solar thermal based cooling networks using advanced absorption chillers and taking as a reference conventional DHC networks. The indicators used include the saving in energy and greenhouse gas emissions and a prospect of the economic benefit. The results show the role that the new advanced absorption chillers could play for the development of future net zero-emissions DHC networks.

Keywords:

Absorption chillers and Heat pumps; Thermal solar energy; District networks; Energy integration.

1. Introduction and objectives

There is a great interest to fulfil the increasing energy demand for refrigeration and air conditioning using renewable energies. Encouraged by the Renewable Energy Directive (EU) 2018/2001 [1], it is projected that by 2030, 40% of heating and cooling sector in Europe will come from renewable energy sources. If we compared this goal with the current situation, there is still a long way for renewable heating and cooling to fulfil the projected vision of the directive. One of the technological options could be the development of large-scale solar cooling plants to benefit from the scale economic factor in conjunction with the use of advanced absorption chillers.

In the project Task 55 of the International Energy Agency [2] (IEA SHC, 2016-20) was conducted a comprehensive study on the modelling, analysis, and real case study survey for the integration of large solar heating and cooling systems into District Heating and Cooling (DHC) Networks. The main conclusion was that in the selected case studies mainly in Denmark and Austria the main solar technologies used Flat Plate collectors and hot water as working fluid, and only a few of them used parabolic collectors. Using renewable energies for air conditioning applications, the preferred working fluid for absorption chillers is Water/LiBr instead of Ammonia/water because of its higher efficiency, although direct fired units using ammonia/water of could be considered for certain small capacity applications such as when air heat rejection is needed.

The objective of this paper is to provide a brief review of novel features incorporated in the current absorption chillers and their integration into DHC networks. It is presented a preliminary assessment of technologies using low-temperature flat plate solar collectors and the current state-of-the-art hot water driven absorption chillers in comparison with alternative and much more extended compression chillers using electricity grid. The idea is to compare different thermal solar cooling technologies by measuring its performance using key parameters with respect to an equivalent electric compression chiller but not to design cooling alternatives for a certain specific case study.

This paper is organized as follows. After the introduction to justify the research interest and to set the objectives in the second section are presented the current trends in the technology of absorption heat pumps and chillers followed in section 3 with a short review of how these units could be integrated in District networks. Finally, in

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section 4 and 5 is presented a modelling and analysis to compare the performance of selected hot water driven absorption chillers being the conclusions summarized in section 6.

2. High efficiency absorption heat pumps and chillers

Some of the main new features related with the current high-efficiency absorption chillers could be classified as:

1. Improvement on the system components and internal arrangements such as:

   1.1. Double section components. This two-step evaporator and absorber technology has two pressure levels but the overall pressure is reduced. The absorption process is also divided in two steps reducing the solution concentration values but increasing the overall concentration different between the rich and poor solution [3]. This arrangement enhances absorption of the refrigerant into the concentrated solution, making the unit more efficient and reliable than conventional absorption chillers. The result is that quite simple cycles such as single effect units can reach COP values higher than 0.8 or up to 1.48 for double-effect steam driven configuration, the highest of its class. Moreover, the cost of the chiller benefits of lower solution concentrations due to the cost of the LiBr.

   1.2. Falling-film generator design provides superior heat transfer compared to a conventional flooded generator. This design also reduces the required amount of solution to be circulated, decreasing start-up time from a cold start [3].

   1.3. Internal heat recovery of the absorption heat. In this case one of the two absorber steps uses part of the absorption heat to reduce the demand for cooling water. This feature is really not new in the absorption field and was proposed in the past but only for ammonia/water systems [4].

   1.4. Some manufacturers produce water/LiBr absorption chillers that use refrigerant mixed with water and lithium bromide solution, so that they can decrease the evaporative temperature of refrigerant to 0℃ or less [5]. Delivering brine at temperatures down to -7℃, which is applicable not only to comfort cooling but also to phase change cold storage with its corresponding volume savings and provide below zero process cooling. Other chiller versions are prepared for onboard ship operation recovering hot water and waste steam from engines to produce cooling using sea water as heat rejection fluid.

2. Improvement of the thermal cooling cycles by the incorporation of additional components in multiple stages arrangements. The result is the development of new chiller types beyond the traditional single and double effect cycles:

   2.1. Single-effect double-lift absorption chillers. This configuration concept was proposed in the literature [6] and now implemented commercially and consist of a three-level pressure cycle (fig. 1) with a high temperature glide of the heat source that enables a higher heat input and consequently a higher cooling capacity for a given heat source. This thermally driven cycle uses the source heat in three generators (high-temperature generator, low-temperature generator and auxiliary generator) to lower temperature more efficiently than a conventional single-effect cycle. Several manufacturers offer this cycle configuration very suitable for district cooling systems that could benefit from its low return temperatures.

   2.2. Half effect absorption chillers use two water/LiBr solution circuits with the aim to recover very low temperature heat sources of about 70ºC to produce cooling. The COP is much lower than single effect cycles but could be an ideal solution for some specific cases such as geothermal energy sources or for the use of waste heat from low temperature fuel cells or electrolyzers.

   2.3. Triple effect absorption chillers are high-temperature chillers that claim a COP as high as 1.8 [7]. The high temperatures to drive double or triple effect chillers using fuel-fired units, steam, pressurized hot water or exhaust gas and certain specific manufacturing limitations, reduce the range of application of these type of chillers to medium or large size applications (starting at a few hundreds of kilowatts). Due to the materials used (stainless steel) and flow circulation, the rate of corrosion is negligible even for triple effect cycles that include also online concentration measurement [7]. Moreover, the variable frequency drives on solution pumps helps to improve the COP during part loads. The stainless-steel plate type solution heat exchangers also helps to increase the COP by offering maximum internal heat recovery.

3. New cycle arrangements to cover applications not fully available commercially until the last years:

3.1. Heat pumps of Type I driven by high-temperature heat to work as amplifiers from low temperature sources close to ambient temperature to medium temperature. The heat source can be steam, hot water, exhaust gas, fuel, geothermal energy, or any combination of these heat sources.

3.2. Heat pumps of Type II known also as heat transformers driven by medium-temperature than in part is degraded to ambient temperature and the other part upgraded to produce high-temperature hot water or steam.

3.3. Simultaneous production of heating and cooling using high-temperature driven systems such as waste steam or direct-fired units. In some case also multi-energy systems recovering hot water and exhaust gases simultaneously to produce cooling and hot water.

3.4. Reversible operation systems to provide cooling in summer and heating in winter or domestic hot water along the year. One of the weaknesses of absorption systems is the lack of reversibility so they operate only during certain periods of the year. However, using certain flow configurations [8] is possible to use the evaporator to increase the temperature glide of the heat-driving source and increase the temperature of the heat rejected at the condenser/absorber for useful heat applications.

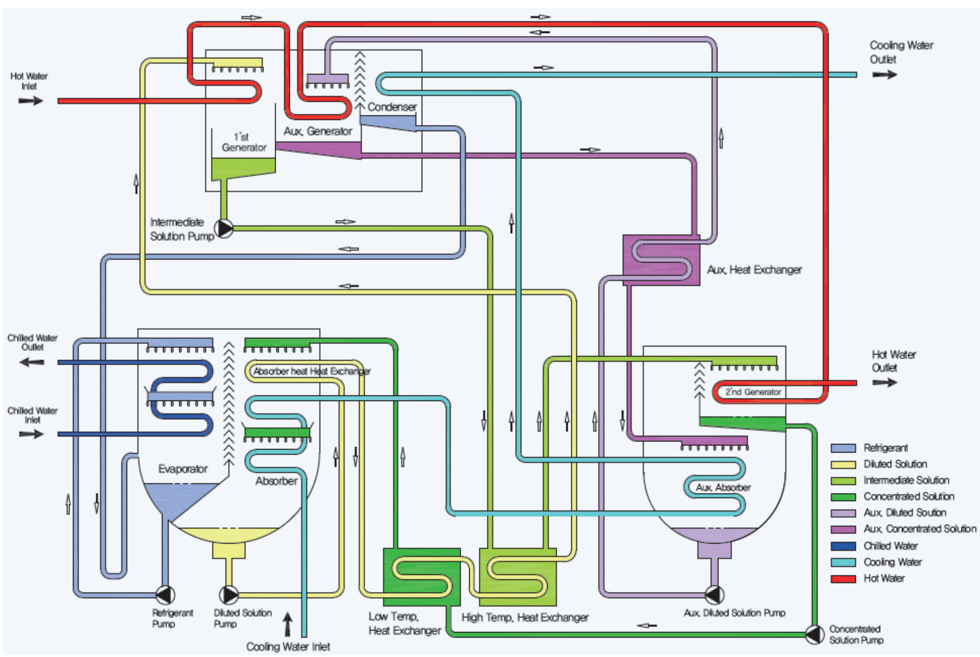

Figure 1. Single-effect Double Lift hot water driven absorption chiller (World Energy 2ABH). Source: [5].

3. Integration of absorption systems in DHC networks

District energy systems have been successfully implemented in many countries around the world and will play an important role in future sustainable cities. The current heating network technology, usually classified as 3rd generation district heating uses hot water between 70-100ºC. But other lower temperature networks are in development in order to reduce heat losses because of its lower operation temperature, the 4th generation working at around 55ºC and even a 5th generation using temperatures around the ambient temperature. The integration of compression heat pumps for their integration in this kind of networks has been started to be studied in the literature [9, 10] but not yet using absorption heat pumps. Nevertheless, the use of absorption systems in District heating networks has been used quite extensively to produce cooling using heat from a heating network [11]. One almost unexplored application is the use of absorption heat pumps and chillers as substations close to each user using smaller capacity units [8]. In that case, the absorption unit could also be configurated to provide heating and cooling in a reversible way (fig. 2) as shown in Ayou et al. [8].

The integration of some of the new advanced low-temperature absorption chillers mentioned in section 2 will be studied here for its integration in District cooling networks. The modelling for a preliminary assessment of these chillers for that kind of applications is given in the next section.

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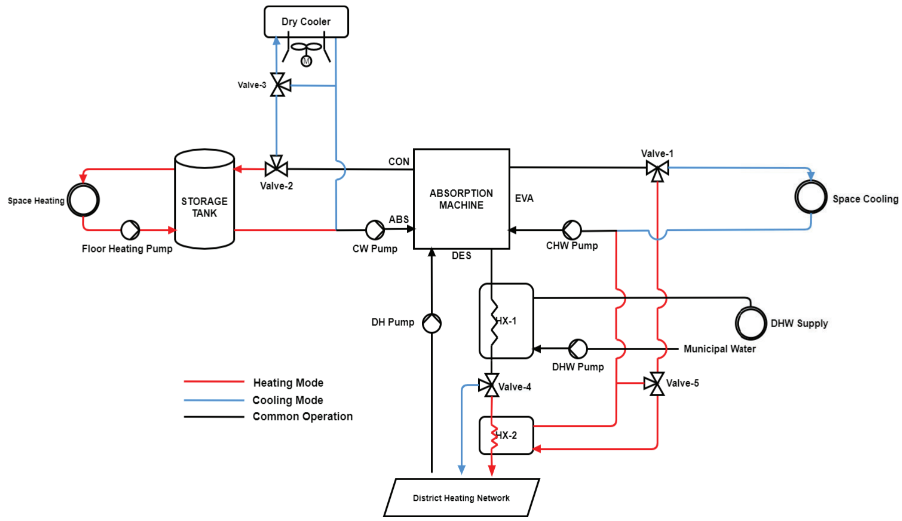

Figure 2. Connection as substation of district heating driven absorption heat pump for space heating and cooling. Source: [8].

4. Modelling of absorption chillers for District Solar Cooling

The electric efficiency factor for the rejection of heat at the condenser for compression chillers and condenser and absorber for absorption chillers is defined as:

$$f_{rej} = \frac{E_{rej}}{Q_{rej}} \tag{1}$$

The solar thermal collector efficiency is modelled using equation (2). The solar collector's area can be also calculated using this same equation.

$$\eta = \frac{Q_D}{I\,A_c} = c_0 - c_1 x - c_2\, I\, x^2 \tag{2}$$

Where x is given by:

$$x = \frac{(T_{av} - T_a)}{I} \tag{3}$$

The rejection of heat is higher for absorption chillers than in compression chillers. The additional heat that has to be rejected with respect to an electric chiller can be computed as:

$$\Delta Q_{rej} = Q_{rej,TDC} - Q_{rej,EC} = Q_D \cdot (1 + COP_{TDC}) - \dot{W}_e \cdot (1 + COP_{EC}) \tag{4}$$

The pump work required to provide the specified hot water flow rate to drive the absorption chiller has been estimated as:

$$\dot{E}_{sol} = \frac{\dot{V} \cdot \Delta P}{\mu_{pump}} \tag{5}$$

The internal electrical efficiency factor for the absorption chiller is defined as the ratio between the electricity consumed internally by the absorption chiller per unit of cooling capacity:

$$f_{el,int} = \frac{E_{TDC}}{Q_c} \tag{6}$$

Similarly, the electrical efficiency factor for the solar plant can be defined as:

$$f_{el,int} = \frac{E_{sol}}{Q_D} \tag{7}$$

Absorption systems are usually known by being bulky and heavy. To compare these characteristics among the considered chillers, it is defined the cooling density per unit of volume and weight as follows:

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$$C_v = \frac{Q_c}{V_{chiller}} \tag{8}$$

$$C_w = \frac{Q_c}{W_{chiller}} \tag{9}$$

Thus, the total electricity consumption to run the absorption chiller will be mainly given by the electricity to run the absorption chiller itself, the electricity to be used for the additional heat rejected with respect to the electric chiller and the electricity used in the solar plant to pump the hot water from the solar collectors to the absorption chiller:

$$E_{tot} = E_{TDC} + E_{rej} + E_{sol} \tag{10}$$

The electricity to drive the compression chiller of reference can be easily estimated from its COP and used to compute the electricity savings provided by the absorption chiller:

$$\Delta E = \frac{E_{EC} - E_{tot}}{E_{EC}} \cdot 100\ \% \tag{11}$$

The saving in emissions is deduced from the considered emissions associated with the electricity mix. With respect to the economics comparison, the Levelized Cost of Cooling (LCOC) is selected to compare the three selected low-temperature absorption chillers. This LCOC is calculated using the following definitions and equations.

$$LCOC = \frac{I \cdot CRF + I \cdot f_{O\&M} \cdot n \cdot CRF}{Q_c \cdot N} \tag{12}$$

Where:

$$CRF = \frac{i}{1-(1+i)^{-n}} \tag{13}$$

5. Preliminary analysis of high-efficiency low-temperature absorption chillers

The most common Solar District Cooling networks consist of Flat plate collectors and hot water driven chillers. Even that parabolic solar collectors producing directly steam could be an option to produce high COP cooling using double-effect chillers, it would be difficult to justify its selection unless process steam could be required in the case studying specific small industrial applications.

The main objective of the present analysis is to compare the performance of three different types of absorption chillers using as a reference an electric compression chiller and the simple model described in the previous section 4. The selected chillers are: High-efficiency Single-effect (SE chiller), Single-effect Double-Lift (SE DL chiller) and Half-effect (HE chiller). The main technical data for these chillers is given in Tables 1, 2 and 3. These data is taken from the public catalogue data provided by the Korean company World Energy Co. Ltd [5]. The selected thermal solar collector is a large size double glazed flat plate collector used for District Heating applications manufactured by GreenOneTec. Table 4 shows technical data of these solar collectors and additional information used for the energy, environmental and economic assessment.

The results of the economic and environmental analysis are summarized in Table 5. At a first glance, the low driving temperature as the main advantage of the HE Chiller is not enough to produce an improvement in the solar collector efficiency that could compensate its lower COP. Therefore, it would not be a good idea to use an HE chiller in large scale solar cooling plants. Instead, the HE chiller is clearly a good candidate to be used as bottoming cycle of another cycle such as other higher driving temperature absorption chiller or Organic Rankine Cycle or any other cycle producing an outlet stream of at least 70ºC or used in smaller scale thermal solar plants working at those temperatures.

The main benefit provided by the SE DL chiller is the high temperature difference of the driving hot water. As a result, the hot water flowrate is reduced for a given cooling capacity. Two advantages are derived from this feature: the power required to pump the hot water is considerably reduced and the average temperature of the solar collector is also lower increasing the collector efficiency both with respect to the high efficiency SE chiller. The results show that even with a lower COP than the SE chiller the energy and emissions savings with respect to the compression chiller are similar (Table 5). However, the increased temperature glide is not enough to compensate for the lower COP and the economic indicators are favourable to the SE chiller (Table 6).

The SE chiller is simpler, thus it is not surprising that for the same capacity the other units are larger and more heavy as it is shown using the cooling density parameter (Table 5) and exhibits also the lowest internal electricity consumption. The increase of rejected heat in comparison with a compression chiller of similar size is also the lowest for the case of the SE chiller. Even that the solar collector efficiency is the worst, the required

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size of the solar plant is the smallest. It is also true that for the case of an specific application, the heat at the outlet would not return to the solar collector plant but integrated into other applications such as the production of heating of domestic hot water because of its still high temperature, 80ºC. From the economics, the SE chiller is the one that exhibits the lowest Capex and best LCOC. Considering a CAPEX for the compression chiller of 250 €/kW and an average electricity cost of 30 c€/kWh, the payback for a solar thermal plant driven high-efficiency single-effect chiller would be slightly below 5 years.

Table 1. Technical data of the single-effect hot water driven absorption chiller.

Characteristics		**Unit**	**Data**
Cooling Capacity		kW	1055
Chilled Water	Inlet Temp	^{0}C	12
	Outlet Temp	^{0}C	7
	Flow Rate	m^3/h	181.4
Cooling Water	Inlet Temp	^{0}C	30
	Outlet Temp	^{0}C	35
	Flow Rate	m^3/h	401.4
Hot Water	Inlet Temp	^{0}C	95
	Outlet Temp	^{0}C	80
	Flow Rate	t/h	73.3
	Flow Rate	m^3/h	76.2
Electricity		kW	2.4
COP			0.825
Volume (LxWxH)		m	4.86x1.451x2.736
Weight in operation		kg	10100

Table 2. Technical data of the single-effect double-lift hot water driven absorption chiller.

Characteristics		**Unit**	**Data**
Cooling Capacity		kW	1055
Chilled Water	Inlet Temp	^{0}C	13
	Outlet Temp	^{0}C	8
	Flow Rate	m^3/h	181
Cooling Water	Inlet Temp	^{0}C	31
	Outlet Temp	^{0}C	36.5
	Flow Rate	m^3/h	400
Hot Water	Inlet Temp	^{0}C	95
	Outlet Temp	^{0}C	55
	Flow Rate	t/h	32.3
	Flow Rate	m^3/h	33.6
Electricity		kW	3.1
COP			0.702
Volume (LxWxH)		m	4.96x1.966x2.845
Weight in operation		kg	15300

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Table 3. Technical data of the half-effect hot water absorption chiller.

Characteristics		Unit	Data
Cooling Capacity		kW	1055
Chilled Water	Inlet Temp	^0C	13
	Outlet Temp	^0C	8
	Flow Rate	m^3/h	181
Cooling Water	Inlet Temp	^0C	31
	Outlet Temp	^0C	36
	Flow Rate	m^3/h	622
Hot Water	Inlet Temp	^0C	70
	Outlet Temp	^0C	60
	Flow Rate	t/h	220
	Flow Rate	m^3/h	225
Electricity		kW	3.9
COP			0.412
Volume (LxWxH)		m	5.266x2.36x2.853
Weight in operation		kg	15700

Table 4. Additional information for the energy, environmental and economic assessment.

Characteristics		Unit	Data
Ambient conditions	Temperature	^0C	25
	Solar Radiation		36.5
Compression Chiller	COP		5
Emissions	Grid CO_{2eq} emissions	kg/kWh	0.14
Solar collector	Coef. C_0		0.814
	Coef. C_1		2.102
	Coef. C_2		0.016
Economic data	Cost solar district heating	€/m^2	500
	Cost SE Chiller	€/kW	400
	Cost Comp. Chiller	€/kW	250
	Main. & Oper. cost		0.02
	Operation time	h/year	3000
	Plant life time	year	25
	Interest rate		0.07

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Table 5. Energy and environmental results.

Characteristics	Unit	SE	SE DL	HE
Cooling density by volume	kW/m^3	54.7	38	29,8
Cooling density by weight	kW/kg	0.104	0,069	0.067
Heat input (Q_D)	kW	1278	1502	2557
Increase heat rejected	kW	1067	1291	2346
Elec. solar plant	kW	24.2	10.7	71.4
Elec. chiller	kW	2.4	3.1	3.9
Elec. add. rejection system	kW	32	38.7	70.4
Total elec. consumption	kW	58.6	52.5	145.7
Elec. savings	kW	152	159	65
Elec. savings	%	72.2	75.1	30.9
Average solar collector temp.	ºC	87.5	75	65
Efficiency of solar collector	%	49.1	57.2	63.1
Required solar col. area	m^2	1045	1432	2690
Solar plant Elec. Eff. Factor		0.0189	0.0071	0.0279
Chiller Elec. Eff. Factor		0.0023	0.0029	0.0037
Rejec. Syst. Elec. Eff. Factor		0.03	0.03	0.03
Emissions saving	kg/h	21	22	9

Table 6. Economic results.

Characteristics	Unit	SE	SE DL	HE
Solar plant cost	€	522700	715900	1345000
Chiller cost	€	422000	464200	464200
Total cost	€	944700	1180100	1809200
LCOC	€/MWh	38.4	48.0	73.6

6. Conclusions

The integration of the most efficient low-temperature absorption chillers is essential for the deployment of District heating and cooling renewable networks and particularly using thermal solar cooling to contribute to the abatement of greenhouse emissions. Many new features have been added to absorption systems beyond the typical single or double effect configurations. The result are higher efficiencies and a broader field of applications not only restricted to cooling but also different types of heat pumps and combined cooling and heating applications.

To compete with traditional compression electric chillers characterized for a continuous decrease in cost, the simple flat plate collectors driving low-temperature absorption chillers could be an interesting alternative. Due to the low driving temperature required by half effect absorption cycles, they provide the best collectors efficiency, but this is not enough to compensate its lower efficiency. Single effect double lift chillers have a very interesting low electricity consumption because of its characteristic high temperature glide of the driving heat. Nevertheless, the highly efficient single effect cycle incorporating the latest advance cycle improvements provide a good energy efficiency and the lowest levelized cost for the produced cooling. It is true also that despite this preliminary comparison among available low-temperature hot water alternatives, the real selection should be made for specific applications.

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