Models and Indicators for Energy and CO_2 Emission Assessment of Electric Chillers and Direct-Fired Absorption Chillers

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Abstract: - In this paper a comprehensive approach to energy and CO_2 emission assessment of electric and direct-fired absorption chillers is presented. This approach is based upon black-box energy and emission models of the various components involved in the analysis. Specific indicators are introduced for assessing the effectiveness of the different cooling generation solutions, and break-even analyses are run to highlight some numerical aspects relevant to equipment currently available on the market. Finally, the effectiveness of adopting different alternatives within different power system frameworks is evaluated.

Key-Words: - Absorption cooling, Electric cooling, Emission reduction, Energy saving, Environmental assessment.

A. Acronym list

CEC	Compression Electric Chiller
COP	Coefficient Of Performance
GAC	Gas Absorption Chiller
LHV	Lower Heating Value
CO2ER	CO_2 Emission Reduction
PES	Primary Energy Saving

B. Symbols

Subscripts represent energy sources or end use (*c*=cooling, *e*=electricity, *t*=thermal) and specify the measuring units. Superscripts indicate energy vectors or equipment. η denotes efficiencies, μ denotes dispatch factors. For energy vectors, W is electricity [kWh_e], F is *LHV*-based fuel thermal energy content [kWh_t], R is cooling energy [kWh_c].

1 Introduction

The issues related to energy generation efficiency and CO_2 emission reduction are driving the development of new technologies. In particular, updated equipment is nowadays available for cooling power generation, as an alternative to widespread Compression Electric Chillers (CEC). Among this equipment, gas-fed *direct-fired* absorption chillers (in the sequel indicated as GAC, Gas Absorption Chillers) [1-3] are the most widespread. Absorption chillers have been traditionally adopted as *indirect-fired*, above all for exploiting waste heat available from industrial processes or from cogeneration systems. However, GAC are more and more frequently adopted as an alternative to CEC, above all for relatively high electricity-to-gas rate ratios [1,3]. The growing interest towards direct-fired chillers is also due to power grid vulnerability issues. In fact, the increasing demand of air conditioning worldwide has brought about higher and higher power flows in the electrical grid, up to causing congestions and black-outs [4]. In this respect, cooling generation from GAC occurs *locally*, on the user's site, so that it avoids a certain amount of electricity flowing in the grid, reducing the risk of congestions and black-outs, as well as transmission and distribution losses. In addition, further economic benefits may take place if cooling power is generated through GAC, since air conditioning is mostly needed in the electricity peak hours (central hours of summertime days).

Besides electrical load relief and potentially economic benefits, GAC can exhibit good primary energy performance. In particular, triple-effect absorption chillers are recently being developed and commercialized, allowing for better performance than double-effect chillers [1,3]. High-performance GAC can also bring CO_2 emission reduction with respect to CEC, also owing to the relatively low carbon content of natural gas with respect to other fossil fuels [1,5]. However, this strongly depends on the fuel and power plant typology used for electrical generation.

On these premises, in this paper a comprehensive approach for assessing the energy and CO_2 emission performance of GAC as opposed to CEC is presented. More specifically, the approach proposed is based upon *black-box* energy and emission models of the various equipment involved in the analysis. Equivalent energy and emission indicators are formulated so as to highlight the identical formal structure of the energy and emission model introduced. In particular, it is underlined how, besides energy performance characteristics of the chillers, the emission factor for electricity generation [5] plays a key role in the analysis. In this respect, specific case study applications based upon energy and emission break-even analyses are run in order to comparatively assess the effectiveness of adopting CEC or GAC with various performance characteristics. In particular, the suitability of adopting different cooling generation solutions for CO_2 emission reduction is considered for different countries.

2 Energy and emission performance modeling and evaluation for electric and direct-fired absorption chillers

2.1 Black-box energy characteristics of GAC and CEC

The energy performance of cooling generation equipment is described by means of the relevant *COP* (Coefficient Of Performance), ratio of the desired output (cooling energy) R to the input (electrical energy W_c for electric chillers, *LHV*-based fuel thermal energy [5] F_c for direct-fired absorption chillers):

$$COP^{CEC} = \frac{R}{W_c} \tag{1}$$

$$COP^{GAC} = \frac{R}{F_c} \tag{2}$$

where the subscript c points out that the final use of the relevant input is *cooling* production.

In general, the chiller performance depends upon the technology, the condenser typology, the outdoor conditions, the temperature of the ambient to keep cooled, and the loading level [1,6]. The expressions (1) and (2) apparently refer to different energy typology inputs. However, for energy analysis it is more suitable to refer the relevant output (cooling energy, typically in the form of chilled water) to a common input, that in the specific case can be represented by the energy content in the fuel. In this respect, the various chiller typologies can be seen as *input-output black-boxes* characterized by the relevant *COP*, in case considering off-design models. While for a GAC the relevant input is already primary energy delivered when burning gas, for a CEC an intermediate step is needed, represented by the back-tracking conversion model of electricity into fuel energy. Hence, it is possible to introduce an input-output black-box model also for the equivalent power turning fuel input into electrical output, characterized by a classical electrical efficiency η_e [5]. In particular, this equivalent power plant could represent a black-box model of the average power system in a given country. In this case, the numerical value of η_e should also take into account average electrical transmission and distribution losses due to the fact that electricity is usually generated far from the cooling user.

With reference to the black-box models for a GAC (Fig. 1) and a CEC (Fig. 2), it is therefore straightforward to formulate a common-ground energy comparison between the two different typologies. In fact, considering the CEC black-box together with the equivalent power plant black-box can be aggregated together to set up a further black-box model, with fuel as overall input and cooling as final output. Hence, it is possible to compare GAC and CEC by introducing the Cooling Heat Rate (*CHR*) [7], defined as the primary energy-to-cooling energy ratio:

$$CHR^{CEC} = \frac{W_c / \eta_e}{R} = \frac{1}{\eta_e \cdot COP^{CEC}} \quad \text{(CEC)} \tag{3}$$

$$CHR^{GAC} = \frac{F_c}{R} = \frac{1}{COP^{GAC}} \quad \text{(GAC)} \tag{4}$$

The expressions (3) and (4) characterize the fuel-cooling black-box models for GAC and CEC, and can be evaluated on the basis of the relevant performance indicator for the specific components. In particular, the above formulation allows for unbiased estimation of the primary energy needed to produce a certain amount of cooling energy by means of the two different chiller typologies.

2.2 The emission factor approach for environmental assessment

A suitable approach to model and characterize the emissions of a given pollutant (and in particular CO_2) from generic combustion devices is represented by the output-related *emission factor*, defined according to [5]:

$$m^X = \mu^X \cdot X \tag{5}$$

In (5), m^X is the mass of CO_2 emitted while generating the useful energy output X, and μ^X is the relevant *emission factor*, that is, the *specific mass emissions* of CO_2 per unit of X, in [g/kWh]. The emission factor model is usually applied for assessing power plants or heat generators. However, it can be readily extended also to assess the environmental performance of different cooling generation equipment. More specifically, it is possible to follow a black-box approach coherent with the *CHR* definitions in Section 2.1. Hence, the CO_2 emissions from a GAC can be estimated passing by the specific emissions μ^F related to the fuel thermal energy F_c, input to the absorption chiller. This input-related emission factor can be estimated with good approximation as a function of the characteristics of the chemical reaction, and thus of the fuel only [5]. Hence, it is possible to assume μ^F for a given fuel constant for different operational conditions. Therefore, taking into account (2) and (5), the energy output-related specific emissions (mass of CO_2 emitted per unit of cooling energy R produced) for a GAC can be evaluated as

$$\mu^R = \frac{\mu_c^F}{COP^{GAC}} = \mu_c^F \cdot CHR^{GAC} \tag{6}$$

in case accounting for off-design models for COP^{GAC}.

Similarly to the approach followed for the emission characterization of a GAC, the specific emissions related to cooling generation from an electric chiller can be assessed, considering (1) and (5), starting from the average emission factor μ^W for electricity generation from a given equivalent power plant:

$$\mu^R = \frac{\mu^W}{COP^{CEC}} \tag{7}$$

Thus, also for a CEC it is possible to assess the CO_2 emission factor passing by the specific *COP* off-design models, in case. In alternative to the expression (7), the cooling-related emission factor for electric chillers can be assessed with reference to the equivalent power plant fuel input, in analogy to (6):

$$\mu^R = \frac{\mu^W}{COP^{CEC}} = \frac{\mu_e^F}{\eta_e \cdot COP^{CEC}} = \mu_e^F \cdot CHR^{CEC} \tag{8}$$

Both expressions (6) and (8) reflect the black-box modeling of Section 2.1, and are represented in Fig. 1 and Fig. 2 for GAC and CEC, respectively.

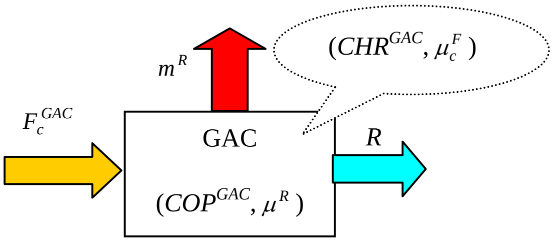

Fig. 1. Black-box model for energy and environmental assessment of direct-fired absorption chillers.

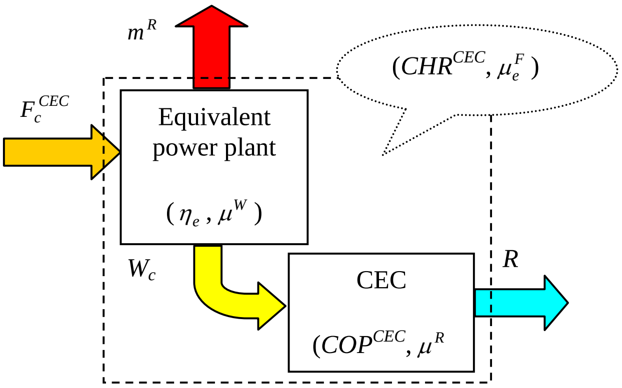

Fig. 2. Black-box model for energy and environmental assessment of electric chillers.

2.3 Energy and emission indicators for GAC and CEC comparison

Let us consider a certain amount of cooling energy R, that can be generated in a GAC from a certain fuel thermal input F_c, or in a conventional CEC from a certain electrical input W_c. Referring the generation of the reference cooling energy R to primary energy, with reference to Fig 1 and Fig. 2 it possible to write

$$F_c^{CEC} = CHR^{CEC} \cdot R \tag{9}$$

$$F_c^{GAC} = CHR^{GAC} \cdot R \tag{10}$$

Therefore, it is possible to define a *Primary Energy Saving* indicator for cooling generation (PES_c), indicating the relative energy saving brought by adopting a GAC with respect to a “classical” CEC, as

$$PES_c = \frac{F_c^{CEC} - F_c^{GAC}}{F_c^{CEC}} = 1 - \frac{\dfrac{1}{COP^{GAC}}}{\dfrac{1}{\eta_e \cdot COP^{CEC}}}$$

$$= 1 - \frac{CHR^{GAC}}{CHR^{CEC}} \tag{11}$$

In particular, positive values of the PES_c (11) indicate higher energy profitability of a GAC for producing cooling energy under specific conditions.

The comparative energy analysis between GAC and CEC is related to the relevant efficiencies involved, that is, to the *CHR* for a GAC and a CEC, as apparent from (11). In the same light, the comparative CO_2 emission assessment is firstly related to the electricity-related emission factor μ^W of the equivalent power plant for electricity generation (input to the CEC) (Fig. 2) and to the fuel-related emission factor μ_c^F for the input to the GAC (Fig. 1). In fact, given the same amount R of cooling energy produced by a GAC or a CEC, on the basis of (1) and (2), and taking into account the general definition (5), it is possible to write for a GAC (Fig. 1)

$$\left(m^R\right)^{GAC} = \left(\mu^R\right)^{GAC} \cdot R = \frac{\mu_c^F}{COP^{GAC}} \cdot R \qquad (12)$$

and for a CEC (Fig. 2)

$$\left(m^R\right)^{CEC} = \left(\mu^R\right)^{CEC} \cdot R = \frac{\mu^W}{COP^{CEC}} \cdot R \qquad (13)$$

Hence, in analogy to the PES_c indicator (11), it is possible to introduce an indicator for assessing the *CO_2 Emission Reduction* for cooling generation (*$CO2ER_c$*) as

$$\begin{aligned} CO2ER_c &= \frac{\left(m^R\right)^{CEC} - \left(m^R\right)^{GAC}}{\left(m^R\right)^{CEC}} = 1 - \frac{\left(\mu^R\right)^{GAC}}{\left(\mu^R\right)^{CEC}} \\ &= 1 - \frac{\mu_c^F \cdot COP^{CEC}}{\mu^W \cdot COP^{GAC}} \qquad (14) \end{aligned}$$

The expression (14) is formally similar to (11), with the emission factors substituting the cooling heat rates. In addition, the electricity-related emission factor can be explicitly considered in (14), yielding

$$\begin{aligned} CO2ER_c &= 1 - \frac{\mu_c^F \cdot COP^{CEC}}{\mu_e^F \cdot \eta_e \cdot COP^{GAC}} \\ &= 1 - \frac{\mu_c^F \cdot CHR^{GAC}}{\mu_e^F \cdot CHR^{CEC}} \qquad (15) \end{aligned}$$

The expression (15) highlights the role of the fuel typology used as input for electricity generation and for firing the absorption chiller. In fact, with respect to (11) in which only the primary energy is relevant, in (15) the emission factors appear as weight to the cooling heat rates. In particular, if the same fuel (natural gas, in this specific case) is used as input to the equivalent power plant and to the direct-fired chiller, the expression (15) coincides with the expression (11). Indeed, according to the emission model discussed in Section 2.2, energy saving and emission reduction expressed in relative terms bring the same numerical value.

3 Energy and CO_2 emission assessment case study applications

3.1 Energy break-even analysis

On the basis of the expression (11), the energy break-even condition is given by

$$\hat{COP}^{GAC} = \eta_e \cdot COP^{CEC} \qquad (16)$$

and there will be energy saving brought by adopting a GAC for COP^{GAC} values higher than (16), that is, for:

$$COP^{GAC} > \hat{COP}^{GAC} \qquad (17)$$

On the basis of (16) and (17) it is possible to run parametric analyses in order to assess the potential energy profitability from adopting a GAC, once given the characteristics of the electrically-based cooling generation means. For instance, Fig. 3 shows different energy break-even curves with $\hat{COP}^{GAC}$ (16) in function of the electric chiller *COP*, with the equivalent power plant electrical efficiency as the curve parameter. In addition, for the sake of comparison, also typical *COP* values for single-effect (rarely used as direct-fired), double-effect and triple-effect (on the way of commercialization) absorption chillers are shown.

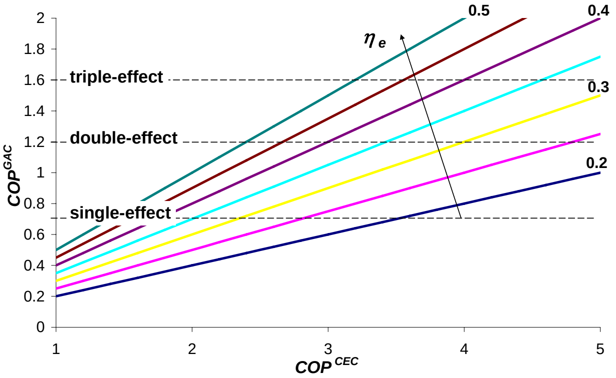

Fig. 3. Energy break-even characteristics.

Considering a "classical" double-effect GAC with *COP* of about 1.2, if the equivalent power plant electrical efficiency is set to 0.4 (about the average efficiency from thermal power plant production in Italy, considering about 7% of transmission and distribution losses), the GAC can compete with an electric chiller if COP^{CEC} is lower than 3. This is a value normally reached by small-scale (below 1 MW_c) chillers for centralized air conditioning, while household-size air conditioning units usually do not reach this performance level. However, even the performance of a centralized chiller depends on various conditions, and in particular on the outdoor temperature, above all if air-cooled [1,6], as often occurs in urban areas. Hence, double-effect GAC can also be competitive for centralized applications in case the chiller is constrained to operate under severe outdoor conditions. In this case, in fact, it could be profitable to adopt a double-effect absorption chiller instead of an electric one. The convenience in this sense might as well occur in the presence of lower-efficiency equivalent power plants, such as centralized coal or oil or gas turbine-based plants, as well as small-scale distributed generation [8] prime movers, with efficiency normally lower than 0.4. Instead, if adopting a combined cycle (η_e about 0.5, with also allowance for transmission and distribution losses) for electricity production, a double-effect chiller could be competitive only with respect to a CEC with *COP* lower than 2.5. Adopting a triple-effect GAC, with a *COP* higher than 1.5, would allow for higher profitability. For instance, considering again η_e = 0.4, there would be energy convenience for a GAC with respect to a CEC with COP^{CEC} as high as about 4. Single-effect chillers, instead, can barely be energy-competitive in correspondence of average values for COP^{CEC} and electrical efficiencies in most of countries worldwide. Besides economic reasons, then, also from an energy standpoint their utilization should be related to waste heat recovery, for instance from cogeneration systems to set up trigeneration systems [7,9].

3.2 CO_2 emission break-even analysis

In analogy to the energy analyses run in Section 3.1, it is possible to carry out a CO_2 emission break-even assessment based on the expressions (14) and (15). More specifically, it is possible to formulate some relevant indicators that make the analysis straightforward and point out the major variables involved. In particular, as apparent from the models developed in Section 2.3, on the one hand the CO_2 emission source in the GAC is directly represented by the fuel input. On the other hand, with the aim of comparing the chiller alternatives with respect to the *status quo* or possible scenarios of electricity generation in a certain region (as for instance done in [10] for co- and tri-generation systems), the key driver in the analysis turns out to be the CO_2 average emission from electricity generation. On these premises, from (14), it is possible to express the CO_2 emission *break-even* condition ($CO2ER_c = 0$) between the production in GAC and CEC as

$$\overline{COP}^{GAC} = COP^{CEC}\frac{\mu_c^F}{\mu^W} \tag{18}$$

and the condition for obtaining positive CO_2 emission reduction from a GAC is

$$COP^{GAC} > \overline{COP}^{GAC} \tag{19}$$

Given the symmetry highlighted above with the energy saving problem, this approach allows for carrying out analyses formally identical to the ones shown in Section 3.1. In particular, the relevant break-even emission problem is formulated in terms of an equivalent *COP* that, fixed the fuel adopted for firing the GAC (natural gas), is a function of only the COP^{CEC} and μ^W. Therefore, it is possible to run parametric analyses that estimate the profitability of adopting different cooling generation equipment within different power systems with different values of μ^W. In this respect, Fig. 4 shows different emission break-even $\overline{COP}^{GAC}$ (18) curves as a function of the electric chiller *COP*, with the electricity-related emission factor for the equivalent power plant (in g/kWh$_e$) as the curve parameter. The CO_2 emission factor for natural gas, with reference to the *LHV*, is assumed equal to 200 g/kWh$_t$ [5]. In addition, as for Fig. 3, for the sake of comparison also typical *COP* values for single-effect, double-effect and triple-effect GAC are shown in Fig. 4.

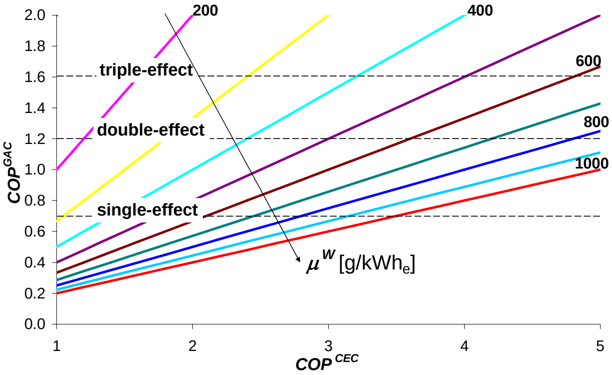

Fig. 4. CO_2 emission break-even characteristics.

As a term of comparison, it is possible to consider that the average emission factor for electricity produced from thermal power plants in Italy is about 700 g/kWh$_e$ (also entailing transmission and distribution electrical losses). In this case, a double-effect GAC would be competitive, in terms of CO_2 emissions, if compared to a CEC with COP^{CEC} lower than about 4.2; a triple-effect chiller would bring about emission reduction for COP^{CEC} lower than about 4.8. Hence, absorption chillers could be emission-efficient for a wide range of applications and conditions, in comparison with CEC fed by electricity produced in thermal power plants. However, if considering that a share of the overall electricity generation comes from renewable sources, that are virtually emission-free (excluding from the analysis the emissions embedded in the plant building process), the average emission factor for electricity production in Italy drops to about 525 g/kWh$_e$. With this emission factor, double-effect chillers would be competitive only for COP^{CEC} below about 3.1, while triple effect chillers would be emission-efficient for COP^{CEC} values below about 4.2. Direct-fired single-effect chillers could be effective only for relatively high values of μ^W and relatively low values of $COP^{CEC,}$, thus confirming that they should be mostly exploited for waste heat recovery applications.

For a further general comparison between GAC and CEC, Table 1 reports the maximum COP^{CEC} values for which, in correspondence of the overall electricity-related emission factors in some countries (data referred to 2003 [11]), adoption of typical double-effect and triple-effect GAC would bring emission saving with respect to the CEC.

Table 1. Maximum COP^{CEC} for having positive CO_2 emission reduction from GAC in different power systems

Country	μ^{W} [g/kWhe]	double-effect GAC (COP=1.2)	triple-effect GAC (COP=1.6)
Norway	3	0.02	0.02
France	78	0.47	0.62
EU15	362	2.17	2.90
Japan	389	2.33	3.11
Italy	525	3.15	4.20
USA	610	3.66	4.88

From the results in Table 1, absorption chillers could exhibit a certain emission reduction potential in countries such as Italy or USA, with relatively “polluting” power systems, mostly based on thermal power plants. However, only triple-effect chillers could be competitive in countries such as Japan or aggregation such as the 15 European Union Countries at the year 2003 (EU15). Finally, in power systems based upon renewable sources (Norway) or nuclear energy (France), with very low CO_2 specific emissions per kWh_e, basically GAC could play no role to bring CO_2 emission reduction.

4 Concluding remarks

In this paper, CEC and GAC have been compared from the energy and CO_2 emission standpoint by means of a comprehensive approach based upon black-box energy and emission models and by exploiting specific indicators introduced here. Break-even analyses have been carried out to highlight some numerical aspects of the energy and environmental performance of various cooling generation solutions within different power systems. As a general result, double-effect GAC can be competitive from an environmental outlook above all in those countries where the power system is characterized by a high share of thermal generation units fuelled by coal or oil, with also a relatively low average conversion efficiency. In addition, the development of high-efficiency triple-effect chillers represent a promising alternative both primary energy saving and CO_2 emission reduction, particularly for cases with average power system emissions higher than $\mu^{W} \cong 500 \div 600$ g/kWh_e, for typical values of COP^{CEC}.

Besides energy and environmental performance, the potential economic benefits from adopting GAC as opposed to CEC should be thoroughly evaluated, with the aim of developing sustainable as well as economical solutions. In this respect, works in progress are aimed at formulating a comprehensive model for energy, environmental and economic assessment of different cooling alternatives within various energy and market frameworks.

Acknowledgments

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