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PERFORMANCE ANALYSIS OF ABSORPTION CHILLERS USING DATA RECONCILIATION

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ABSTRACT

Performance data obtained from measurements of process variables usually do not obey material and energy conservation laws. This is why a data reconciliation process, that is, the adjustment of measured data to obey the conservation laws and other constraints is necessary in order to characterize the real performance of equipment, processes, or the whole plant. The information on the partial load and off-design operation performance of absorption chillers is scarce. Real operation of these units do not always coincides with the expected performance according to the data provided by the manufacturer due to site specific conditions. On the other hand the data reconciliation procedure has been extensively applied mainly only for open cycles with a moderate number of recycle streams. The objective of this work is the development and application of the data reconciliation technique to analyse the performance of absorption chillers using rigorous thermodynamic properties for the calculation of the P-V-T equilibrium properties and enthalpies. We present in this paper the preliminary test results for one of the absorption chiller components, the evaporator.

NOMENCLATURE

COP, absorption chiller coefficient of performance
Cp, specific heat capacity at constant pressure (kJ/kg-K)
h, specific enthalpy (kJ/kg)
m, mass flow rate (kg/s)
P, pressure (kPa)
q, vapor quality
Q, heat duty (kW)
T, absolute temperature (K)
t, temperature (ºC)
x, ammonia mass fraction
w, ammonia mole fraction

Subscripts
a, absorber
c, condenser
cw, chilled water
e, evaporator
g, generator
in, mass or energy flow entering a component
l, liquid phase
out, mass or energy flow exiting a component
ps, poor (in ammonia) solution
r, rectifier
rs, rich (in ammonia) solution
to, thermal oil
v, vapor phase
0, reference value

Superscripts
L, liquid phase
V, vapour phase

INTRODUCTION

During recent years the interest on absorption chillers to produce cooling by using waste heat or solar thermal energy for small scale applications has increased. However, in many cases these units have a non negligible consumption of electricity for some auxiliary components such as the cooling tower or pumps and require certain operation ranges for optimal operation. It is therefore important that these systems are both well-designed and later operated close to an optimum, also for changing conditions.

Finding ways to improve the efficiency of absorption and other thermally driven cooling systems has recently become a high research and commercial development priority. In this sense some new and efficient absorption chillers for small scale applications have appeared in the market but their market presence is still very low compared to electrically driven chillers. One of the ways to improve the commercialization of these chillers is to increase the number of successful plant references to promote the trust of the potential users.

Performance data obtained from measurements of variables in equipment or processes usually do not respect the laws of mass and energy conservation. This is why a Data Reconciliation method, adjusting measured data to obey the conservation laws and other constraints, is necessary in order to characterize the real performance of equipment, processes, or the whole plant. Regarding the performance of absorption chillers, information about partial load and off-design operation is scarce. Real operation of these units do not always coincides with the expected performance according to the data provided by the manufacturer that not necessarily can include all the installation specific conditions. The determination of the causes of these mismatches is important for the development of solar cooling technologies, where great efforts are being made in order to build demonstration installations to give a definitive impulse to these technologies, among other cases.

To contribute to these objectives it is necessary to develop a methodology for the proper calculation and monitoring of the plant performance. This methodology should be adequate to determine the minimum set of operational data to be measured and also to obtain a set of validated data to calculate the performance of absorption chillers. So far, the application of the Data Reconciliation procedure has been mainly restricted to open chemical process, but not to closed cycles with complex connectivity and recycle loops involving not only mass flow rates and temperature measurements but also with pressure and chemical equilibrium constraints. Therefore, the introduction of reliable thermodynamic property models to predict temperature-pressure-concentration and enthalpy in several aggregation states is required, which introduces additional complexity and convergence difficulties that have not been treated extensively in the literature. A previous attempt of Data Reconciliation including rigorous calculation of thermodynamic properties in complex absorption refrigeration cycles using the Aspen Plus process simulator revealed that the use of the reconciliation features in that process simulator for this application requires a lot of expertise in their use and the tracking of convergence errors was not easy [1]. This paper is a first step in the direction of addressing the problem: we use new tailored made solution approach instead.

In the next section a brief review on Data Reconciliation fundamentals and applications is given including the aspects of this technique covered in this paper. Later the fundamentals of absorption cooling are presented followed by an example of application of a specific Data Reconciliation model for absorption chillers.

DATA VALIDATION AND RECONCILIATION

The raw data obtained from experimental or field measurements can not be used directly to perform mass and energy balances because these balances may be violated mainly due to the following facts:

1) Errors due to measuring devices that for any reason fail (calibration, location ...).
2) Deviation from steady-state plant operation.
3) Data redundancy. The redundancy appears when the number of measured variables is larger than the number of degrees of freedom of the model used.

To handle this problem Data Validation is used. The Data Validation approach uses measurement redundant information and conservation laws to correct the measurements to:

1) Detect gross errors (biases) in measured variables.
2) Obtain a set of consistent adjusted measured variables
3) Estimate the value of non-measured variables.

Without gross error detection and elimination the procedure is called Data Reconciliation. In the general case, measured values are only available for some variables, because for reasons of cost or technical complexity not all the variables are measured. Measured variables are classified as redundant or non-redundant and non-measured variables are classified as observable and non-observable variables.

The data reconciliation problem for a non simplified process is mathematically expressed as a constrained non-linear minimisation problem where the estimator of each variable is as close as possible to the measured value (weighted by the standard deviation). The general formulation is the following:

$$\mathrm{Min} \sum_{i=1}^{n} \frac{\left(x_i - x_i^*\right)^2}{\left(\sigma_i\right)^2} \qquad (1)$$

subjected to:

$$f\left(x, y\right) = 0 \qquad (2)$$

$$x_{min} \le x \le x_{max} \qquad (3)$$

$$y_{min} \le y \le y_{max} \qquad (4)$$

where:

$x \in R^n$	is the set of reconciled values of variable i
$x^* \in R^n$	is the set of measured values of variable i
$y \in R^{nn}$	is the set of estimated non-measured variables
$\sigma \in R^n$	is the set of standard deviations corresponding to each measured variable
$f \in R^m$	is the set of non-linear equations that describes the system

As it is in fact an optimisation problem, for each variable consistent guess values as well as lower and upper bounds are needed. Redundancy is an essential concept of data reconciliation. The degree of redundancy of each variable is defined as the number of measurements in the system that have to be removed to make that variable non-redundant (a non-redundant variable is one that when removed the variable is unobservable).

Because reconciled data are consistent with conservation laws, they are of high interest for many important applications: process or equipment off-line and on-line monitoring and performance calculation, model parameter estimation, operational optimization, control, plant fault diagnosis, design of sensor networks, detection of faulty sensors, soft-sensors, etc.

A question to solve in data validation is to determine whether the discrepancy between measured and adjusted values is due to normal measurement errors, which are random, or to gross errors caused by malfunctioning instruments. If gross errors are present, it is necessary to identify and correct them; smaller errors can be reconciled by the reconciliation procedure.

Many methods have been developed to perform data reconciliation and gross error or outlier detection, and one major type are Statistical Test methods (global test, measurement test, nodal test, generalized likelihood ratio and the principal component test) where the reconciliation needs to be applied again after removing gross errors each time. Several methods for this exist: serial elimination [2], serial identification and collective compensation [3] or simultaneous use of supported vector machines [4]. All the statistical test methods can strictly be applied only to linear systems. For nonlinear processes, a linear approximation of the constraints has to be used before the tests can be applied although some modifications for nonlinear problems have been proposed, for example in [5]. Some other new methods have been introduced using robust statistics [4, 6]. Also some approaches have been developed for Data Reconciliation of dynamic processes but will not be reviewed here because we are just interested in the proper determination of steady-state operation performance using Data Reconciliation. The technique is reviewed in several books in detail [7-10].

The complete data reconciliation process consists of a series of steps: performance data acquisition, steady-state detection, data analysis, and the resolution of the reconciliation problem. In this paper we will focus in this last step and assume there are no gross errors.

ABSORPTION COOLING

Absorption chillers driven by waste heat from efficient cogeneration systems or renewable energy sources such as thermal solar energy are in many cases an interesting technology option over the more conventional electric driven chillers for both air conditioning and refrigeration applications in order to save primary energy. Their application includes not only industrial plants but also small scale facilities in building that can benefit on the increased recovery of heat from cogeneration systems or the extended use of solar plants during the summer period when there is no demand for heating and the domestic hot water demand is very low. Commercially available absorption chillers mainly use two types of working fluids: water/LiBr (water as refrigerant and LiBr as absorbent) and ammonia/water (ammonia as refrigerant and water as absorbent). The latter needs a rectifier to remove the vapor water produced in the generator because of the high volatility of water. Water/LiBr chillers, however, cannot operate at temperatures below zero because of the water freezing point limit.

In absorption refrigeration cycles the compressor of vapor compression systems is substituted by an absorber where the vapor refrigerant is absorbed by another fluid, a pump that pressurizes the mixture, and a generator that separates the refrigerant from the absorbent. It's important to note that the energy required for pressurizing a liquid is much less than the energy needed to pressurize a gas. The condenser and evaporator have the same functions in vapor compression as in absorption systems: in the condenser, the high pressure vapor refrigerant rejects heat changing to liquid phase, and in the evaporator the low pressure liquid refrigerant absorbs heat producing the cooling effect, and changing to vapor phase again.

According to Fig. 1, that corresponds to an ammonia/water absorption chiller, the global energy balance, Eqn. (5), accounts for the heat rejected in the condenser, absorber and rectifier, the heat input to the generator, and the heat absorbed in the evaporator. The work input from the solution pump usually is neglected because it is too small compared to the other energy duties.

$$Q_r + Q_c + Q_a = Q_g + Q_e \qquad (5)$$

The efficiency of the cycle is defined by the coefficient of performance, COP, which is the ratio between the cooling capacity produced in the evaporator and the heat input to the generator.

$$COP = \frac{Q_e}{Q_g} \qquad (6)$$

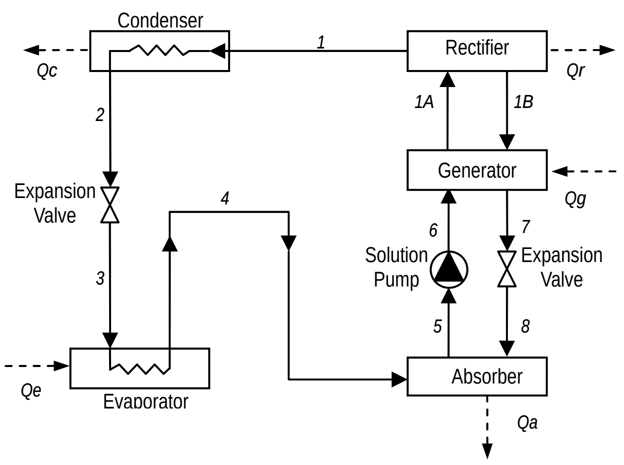

Figure 1. SCHEMATIC DIAGRAM OF A TYPICAL AMMONIA/WATER ABSORPTION CHILLER.

APPLICATION TO AN AMMONIA/WATER ABSORPTION CHILLER

The Data Reconciliation methodology was applied to a section of the cycle of an 18 kW ammonia/water air-condensed absorption chiller driven by thermal oil and connected to a test bench to characterize its performance.

Plant description

The absorption chiller was installed in a test bench as part of a trigeneration system based on simultaneous production of electricity, heat, and cooling, using a single source of primary energy and tested in the CREVER-URV pilot plant. The trigeneration system (Fig. 2) consisted of the following components:

- Micro gas turbine Capstone C30 with a nominal capacity of 28 kWe, fed with low pressure natural gas.
- Cross flow exhaust gas/thermal oil heat exchanger
- Cross flow exhaust gas/hot water heat exchanger
- Ammonia/water single effect air-cooled absorption chiller, Robur model ACF60-00 TK, with a nominal cooling power of 18 kW.

The absorption chiller was placed inside an environmental chamber to keep the temperature of the air that is used for the heat rejection of the chiller's condenser and absorber constant.

Natural gas and air are fed to the micro gas turbine where they react increasing the temperature, velocity and volume of the gases, which are then directed to the turbine's blades producing electricity by means of an alternator. The exhaust gas of the turbine is used in a heat exchanger to generate thermal oil at high temperature (between 190 and 220 °C). This thermal oil is used to activate the absorption system by transferring heat to the chiller's generator. Then, the exhaust gas is used to produce hot water between 70 and 90 °C in a heat exchanger. Finally, the exhaust gas is sent to the atmosphere.

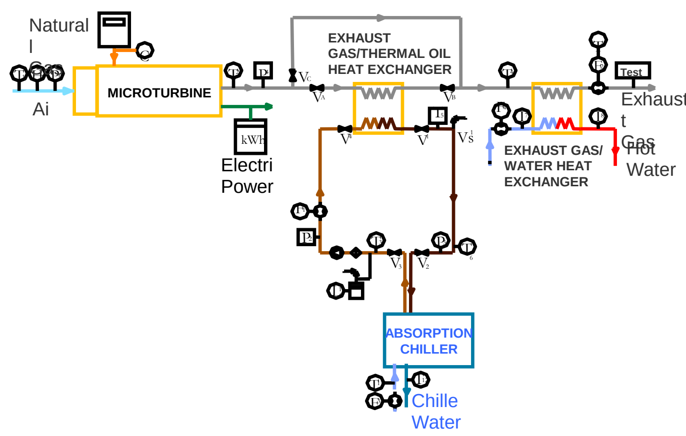

Figure 2. DIAGRAM OF THE TRIGENERATION SYSTEM.

Measurements of the flow rate and temperature of the thermal oil and chilled water at the inlet and outlet of the absorption chiller were taken. These measurements provide enough information to calculate the cooling capacity produced Q_e and the heat input to the generator Q_g as follows:

$$Q_e = m_{cw} \cdot Cp_{cw} \cdot (t_{cw,in} - t_{cw,out}) \qquad (7)$$

$$Q_g = m_{to} \cdot Cp_{to} \cdot (t_{to,in} - t_{to,out}) \qquad (8)$$

With these values, the coefficient of performance (COP), of the absorption chiller can be calculated. However, from a data validation point of view, this information is not enough to obtain an unbiased value of the performance of the chiller because there is no way to know that the measurements are free of biases. Because there isn't information of the internal conditions of the absorption cycle and therefore the degree of redundancy is zero.

Absorption chiller modeling and Data Reconciliation approach

Figure 3 shows a schematic of the absorption chiller tested. The solution pump moves the ammonia/water rich solution to the high pressure side (10). From there the ammonia-rich solution flows through the rectifier (11) and then into the solution cooled absorber. After being preheated in the rectifier and solution cooled absorber, the ammonia-rich solution enters the generator (12). The generator is fired through a heat transfer fluid, in this case thermal oil, exchanging heat with the rich solution. The poor solution is picked up by a tube (13) and sent to the solution cooled absorber after passing through an expansion valve (14). In the solution cooled absorber, the ammonia depleted solution drips over the tube coil while absorbing vapor refrigerant and is collected in the bottom of the tank. It continues to flow along with the vapor that was not yet absorbed through the air-cooled absorber (8), which is the parallel tube system in the lower half of the device. Here the absorption process is completed and the heat is rejected to the surroundings. The outlet of the air-cooled absorber is connected to the solution pump receiver (9).

The ammonia vapor leaves the generator (1A) and is forced across the rectifier where the heat of rectification is rejected to the rich solution and proceeds to the condenser (1). The condenser is the tube system located in the upper half of the device. The heat of condensation is rejected to the surroundings, in our case inside the environmental chamber. The liquid refrigerant (2) passes through a throttling device reducing its pressure to an intermediate value (between the high and low pressure levels) and lowering its temperature (3), and circulates through the refrigerant precooler, which is a refrigerant-refrigerant heat exchanger. After the precooler (4), the liquid refrigerant passes through another throttling device, and then refrigerant enters into the evaporator (5). The refrigerant evaporates inside the coil while the water to be chilled flows across the outside of the coil. The refrigerant vapor enters in the cold side of the precooler (6) and returns to the solution-cooled absorber (7).

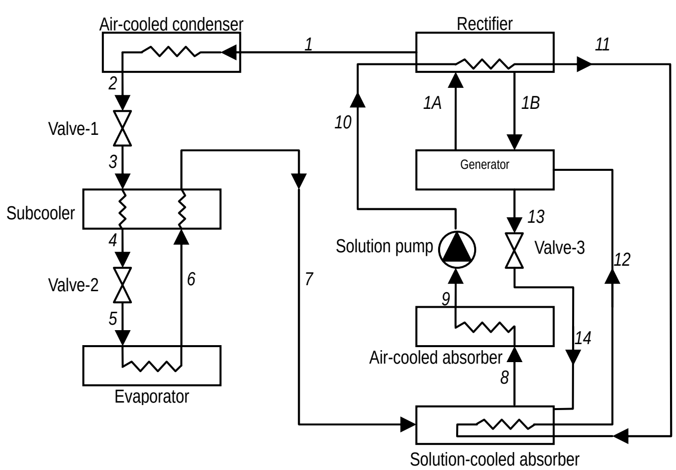

Figure 3. SCHEMATIC OF THE ABSORPTION CHILLER TESTED.

In [11], a detailed modeling of this absorption chiller driven by natural gas using a process simulator is presented. The results obtained in [11] are compared with some performance data available in [12, 13].

In [14] some examples for the systematic calculation of the degrees of freedom for compression refrigeration chillers are presented, but the case of absorption chillers is not included. We now concentrate on the model.

Consider that each of the internal streams of the cycle are characterized by the following variables: mass flow rate (m), ammonia mass fraction (x), temperature (t), pressure (P), specific enthalpy (h) and vapor quality (q).

The model is described by the mass and energy balance in all components of the absorption cycle. These are the balances that are used for the reconciliation problem as the constraints that the reconciled measurements are subjected to:

Global mass balances:

$$\sum m_{in} - \sum m_{out} = 0 \tag{9}$$

Ammonia mass balances:

$$\sum (m_{in} \cdot x_{in}) - \sum (m_{in} \cdot x_{out}) = 0 \tag{10}$$

Energy balances:

$$\sum (m_{in} \cdot h_{in}) - \sum (m_{in} \cdot h_{out}) + \sum Q_{in} - \sum Q_{out} = 0 \tag{11}$$

According to these balances the absorption chiller is described by 55 equations and 66 variables.

In order to calculate the specific enthalpy for each internal chiller stream, the thermodynamic properties correlations from [15] are used in this paper:

– Temperature in terms of the pressure and the ammonia mole fraction in the liquid phase:

$$T(P, w^L) = T_0 \sum_i a_i (1 - w^L)^{m_i} \left[\ln\left(\frac{P_0}{P} \right) \right]^{n_i} \tag{12}$$

– Temperature in terms of the pressure and the ammonia mole fraction in the vapor phase:

$$T(P, w^V) = T_0 \sum_i a_i (1 - w^V)^{\frac{m_i}{4}} \left[\ln\left(\frac{P_0}{P} \right) \right]^{n_i} \tag{13}$$

– Ammonia mole fraction in terms of the pressure and the ammonia mole fraction in the liquid phase:

$$w^V (P, w^L) = 1 - \exp\left[\ln(1 - w^L) \sum_i a_i \left(\frac{P}{P_0} \right)^{m_i} w^{L \frac{n_i}{3}} \right] \tag{14}$$

– Specific enthalpy of the liquid in terms of the absolute temperature and the ammonia mole fraction in the liquid phase:

$$h_l(T, w^L) = h_0 \sum_i a_i \left(\frac{T}{T_0} - 1 \right)^{m_i} w^{L n_i} \tag{15}$$

– Specific enthalpy of the vapor in terms of the absolute temperature and the ammonia mole fraction in the vapor phase:

$$h_g(T, w^V) = h_0 \sum_i a_i \left(1 - \frac{T}{T_0}\right)^{m_i} (1 - w^V)^{\frac{n_i}{4}} \qquad (16)$$

Where *a*, *m*, and *n* are the experimental coefficients and exponents obtained from the data fitting. These coefficients are given in [15].

These thermodynamics relations used in the simulation model are accurate enough to evaluate later the chiller performance accurately.

In this model pressure drop across the cycle components is neglected, hence, there are three pressure levels: high pressure, determined by the condenser pressure, low pressure, determined by the air-cooled absorber, and an intermediate pressure at streams 3 and 4.

The model consists of 84 equations and 98 variables, which corresponds to 14 degrees of freedom including the thermodynamic correlations for the calculation of the enthalpy and the assumed three pressure levels. Adding models of the heat exchanger performance parameters like UA (heat transfer coefficient times the heat transfer area), effectiveness, or the saturation conditions at the outlet stream, could reduce the degrees of freedom of the problem. Other way to reduce the degrees of freedom is adding more sensors in order to have enough measurements to perform data reconciliation.

A major issue when trying to simulate a complex process like this absorption cycle, using a data validation framework, is the high non-linearity of the model, particularly when dealing with energy balances. Some of the properties have to be calculated using iterative methods, adding this to the complexity of the cycle because its recirculation loops, and equilibrium involved in the fluid properties, the modeling and simulation including data reconciliation becomes a very complex task.

That's why in this work the focus was put into analyzing the evaporator as an example of what would be the impact of the data reconciliation technique in the performance study of the chiller. The evaporator was chosen since is the absorption chiller's component where more information is available, and also where the calculation of the cooling capacity is made, hence affecting the calculation of the COP. Figure 4 shows a schematic of the evaporator with the streams and variables involved in the analysis.

When studying the cooling capacity and the performance of an absorption chiller usually only the measurement of the temperature difference of the chilled water and its flow rate are considered. With these measurements the cooling capacity produced by the chiller is calculated, for example, by means of Eqn. (7). In this case, in a data validation scheme, the measured variables in Fig. 4 are $T_{cw,in}$, $T_{cw,out}$ and m_{cw}; leaving the rest of the variables unmeasured and non calculable, and without redundancy.

To achieve redundancy is necessary to obtain information on the refrigerant side of the evaporator. Thermocouples attached to streams 5 and 6 give information about the refrigerant temperature at the inlet and outlet of the evaporator.

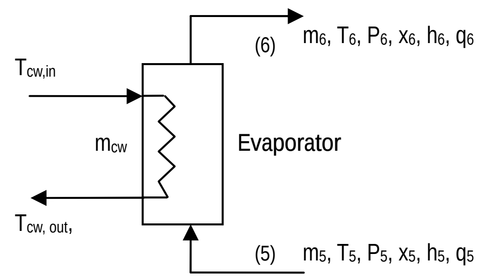

Figure 4. DIAGRAM OF THE ABSORPTION CHILLER'S EVAPORATOR INCLUDING THE VARIABLES INVOLVED IN THE RECONCILIATION PROBLEM.

The refrigerant mass flow and compositions were not measured, but they can be calculated from balances in other cycle components. In this work, due the complexity of solving this system with data reconciliation the refrigerant mass flow rate and concentration were not calculated.

In order to demonstrate the usefulness of data reconciliation, the values of the refrigerant flow rate were taken from the ASPEN simulations presented in [16], and composition from average values reported in [11-13], for three cases at different steady-state operating conditions of the trigeneration system (Tab. 1).

Table 1. REFRIGERANT FLOW RATES AND COMPOSITIONS USED IN THE EVAPORATOR RECONCILIATION PROBLEM FOR THREE DIFFERENT CASES OF THE SYSTEM OPERATING CONDITIONS.

Variable	Case A	Case B	Case C
m_5, m_6 (kg/h)	31.77	33.74	35.12
x_5, x_6	0.984	0.984	0.984
T_{air} (ºC)	37.0	30.5	28.0
Q_g (kW)	14.76	15.33	16.11

Table 2 presents the variable classification of the absorption chiller evaporator studied in this work. There are a total of 15 variables involved, of which 5 are measured ($T_{cw,in}$, $T_{cw,out}$, m_{cw}, T_5 *and* T_6), 4 variables values are taken from the simulations (Tab. 1) which in this example are supposed to be provided by the data reconciliation method applied to the other components of the cycle (m_5, m_6, x_5 and x_6), and the rest are observable.

Table 2. ABSORPTION CHILLER'S EVAPORATOR VARIABLE CLASSIFICATION.

Variable	*Type of variable*
$T_{cw,in}$	Measured/redundant
$T_{cw,out}$	Measured/redundant
m_{cw}	Measured/redundant
T_5 , T_6	Measured/redundant
P_5 , P_6	Not measured/calculable
x_5 , x_6	Not measured/calculable
h_5 , h_6	Not measured/calculable
q_5 , q_6	Not measured/calculable
m_5 , m_6	Not measured/calculable

Using correlations (12) to (16) in explicit form or through an iterative process, like the secant method, the model is able to calculate q_5, q_6, h_5, h_6, P_5 and P_6. Aside from Eqn. (7), the set of equations that describe the evaporator is the following:

Cooling capacity calculation on the refrigerant side,

$$m_6 \cdot h_6 - m_5 \cdot h_5 = Q_e \quad (17)$$

Specific enthalpy in stream 5,

$$h_5 = h_{l5} \cdot (1 - q_5) + h_{v5} \cdot q_5 \quad (18)$$

Specific enthalpy in stream 6,

$$h_6 = h_{l6} \cdot (1 - q_6) + h_{v6} \cdot q_6 \quad (19)$$

No pressure drop across the evaporator,

$$P_5 = P_6 \quad (20)$$

Vapor quality in stream 5,

$$q_5 = \frac{x_5 - x_5^L}{x_5^V - x_5^L} \quad (21)$$

Vapor quality in stream 6,

$$q_6 = \frac{x_6 - x_6^L}{x_6^V - x_6^L} \quad (22)$$

The evaporator's model has 15 variables, of which 9 are known ($T_{cw,in}$, $T_{cw,out}$, m_{cw}, T_5, T_6, m_5, m_6, x_5, x_6) and 8 equations (Eqn. (7), Eqn. (12), and Eqns. (17) to (22)). There are 2 more equations than unknown variables, meaning that there is redundancy in the system.

This example intends to demonstrate that when evaluating the cooling capacity produced in an absorption chiller, different results can be obtained when the calculations are performed taking in account the chilled water side or the refrigerant side of the evaporator, and that data reconciliation is a useful technique capable of correcting these differences through the adjustment of measurements satisfying the mass and energy balances.

The reconciliation problem presented above was solved using MATLAB. This modeling environment uses toolboxes that extend its capacity in order to integrate the data acquisition, data analysis, optimization (required to solve the reconciliation problem), and write the model's equations including the working fluid properties in the same programming environment.

The MATLAB solver used to solve the optimization problem is FMINCON that is part of the integrated Optimization Toolbox. This solver finds a constrained minimum of a function of various variables.

RESULTS

Tables 3A, 3B and 3C show the values of the measured variables and its reconciled value for the three different system operating conditions (cases A, B and C).

Table 3A. EVAPORATOR'S MEASURED AND RECONCILED DATA (CASE A).

	$T_{cw,in}$	$T_{cw,out}$	m_{cw}	T_5	T_6
Measured Value	12.36	9.96	3.40	7.60	9.52
Standard deviation	0.24	0.25	0.10	0.30	0.27
Reconciled Value	12.29	10.03	3.38	7.58	9.54

Table 3B. EVAPORATOR'S MEASURED AND RECONCILED DATA (CASE B).

	$T_{cw,in}$	$T_{cw,out}$	m_{cw}	T_5	T_6
Measured Value	12.70	10.05	3.50	2.91	7.52
Standard deviation	0.08	0.10	0.05	0.21	0.15
Reconciled Value	12.77	9.96	3.57	2.94	7.50

Table 3C. EVAPORATOR'S MEASURED AND RECONCILED DATA (CASE C).

	$T_{cw,in}$	$T_{cw,out}$	m_{cw}	T_5	T_6
Measured Value	12.86	9.99	3.5	0.24	4.34
Standard deviation	0.20	0.22	0.1	0.19	0.20
Reconciled Value	12.92	9.93	3.52	0.25	4.33

It can be seen that all the measurements were slightly adjusted, in order to satisfy the energy balances. In consequence the cooling capacity (and therefore the COP) calculated with the reconciled data also changes. Since measurements were adjusted, the values of calculated variables from the measurements also vary as shown in Tabs. 4A, 4B and 4C.

Table 4A. CALCULATED VARIABLES FROM MEASUREMENTS (CASE A).

	P_5, P_6	h_5	h_6	q_5	q_6
non-reconciled values	561.95	12.00	1091.1	0	0.7940
reconciled values	561.48	18.03	1023.0	0	0.7983

Table 4B. CALCULATED VARIABLES FROM MEASUREMENTS (CASE B).

	P_5, P_6	h_5	h_6	q_5	q_6
non-reconciled values	475.38	-4.00	1244.6	0	0.9767
reconciled values	475.94	-3.56	1241.1	0	0.9740

Table 4C. CALCULATED VARIABLES FROM MEASUREMENTS (CASE C).

	P_5, P_6	h_5	h_6	q_5	q_6
non-reconciled values	430.92	-16.04	1242.9	0	0.9784
reconciled values	431.11	-16.00	1237.6	0	0.9770

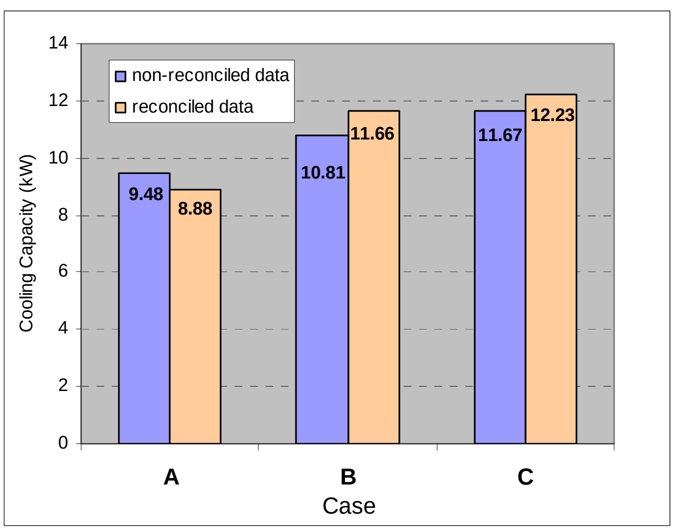

Figure 5. ABSORPTION CHILLER'S COOLING CAPACITY COMPARISON BETWEEN THE NON-RECONCILED AND RECONCILED DATA FOR THE THREE CASES: A, B, AND C.

Figure 5 shows a comparison between cooling capacity calculated with reconciled and non-reconciled data. According to the results showed in this figure the performance of the chiller was underestimated in cases B (-7.89 %) and C (-4.78 %), while in case A was overestimated (+6.39 %). These differences are an important factor when optimizing the chiller's performance. Table 5 shows the same information of Fig. 5 in terms of the COP.

Table 5. ABSORPTION CHILLER COP CALCULATED BEFORE AND AFTER DATA RECONCILIATION.

Case	COP without reconciliation	COP with reconciliation
A	0.64	0.60
B	0.70	0.76
C	0.72	0.76

Table 6 shows the difference in the cooling capacity when calculated using the raw measurements for the chilled water side and the refrigerant side of the evaporator. It can be seen that the energy balance is not satisfied in the three cases, and that the mismatches between both calculations are in the order of 5 and 8%.

Table 6. EVAPORATOR'S COOLING CAPACITY DIFFERENCE WHEN CALCULATED FROM THE CHILLED WATER AND REFRIGERANT SIDE.

Case	$Q_{e,\ \text{chilled water side}}$ (kW)	$Q_{e,\ \text{refrigerant side}}$ (kW)	Diff (kW)	Diff (%)
A	9.48	8.89	0.59	6.22
B	10.81	11.70	0.89	8.23
C	11.67	12.28	0.61	5.23

While in this work a small unit with just a few kW was tested and analyzed, when dealing with a higher capacity absorption cooling plants the reconciliation and validation would become more important in order to accurate estimate and optimize the performance of the system.

FUTURE WORK

More tests will be done with the same chiller working in continuous regime and located in a trigeneration demonstration plant in Barcelona.

A sensor network upgrade analysis must be done previous to the location of the sensors to monitor the chiller performance (see [10, 17]). This kind of analysis is a key element for the data validation framework. With an optimum sensor network design, all the information required to perform data reconciliation could be obtained.

Since there is no information about the internal conditions of the absorption chiller, and in order of not to add intrusive instrumentation that could damage the absorption equipment, thermocouples will be attached to the chiller's pipes in some streams in order to obtain the corresponding stream temperature. With these temperatures the model should allow to calculate pressures and compositions and stream enthalpies to perform the energy balances around the key components of the absorption cycle. It will be treated also the question if redundancy in all the cycle components is necessary or not, or if it is just needed in some key components according to their impact on the calculated cycle performance.

Prior to reconcile measured values, a gross error detection module will be implemented. This will allow the identification and correction of possible biases in measurements due to sensor malfunction, leaks, or other reasons.

Also, the concept of Software Accuracy and Stochastic Accuracy, which is an extension of the classical definition of measurement accuracy through data reconciliation [18, 19], will be used in order to have a more adequate definition of the measurement accuracy, including the instrument systematic error, and the model's capacity to find gross errors.

CONCLUSIONS

The results of this paper set the basis to obtain a methodology flexible enough for its application in several types of absorption chillers ranging from just a few kW to various MW of cooling power and using different working pairs.

In this work only the evaporator of an ammonia/water absorption chiller was analyzed using data reconciliation because of the complexity of solving the reconciliation problem due the high non-linearity of the equations involved in the model. When the evaporator energy balance is calculated using the measured data for the chilled water side and measured data for the refrigerant side, it is seen that there are mismatches between both calculations. In this case, for the three operating conditions presented as examples, these differences are between 5-8%.

The differences in the calculation of the cooling capacity and the COP using reconciled and non-reconciled measurements are 6.39% for case A, for case 7.89% B and 4.78% for case C.

These examples are applied to a small capacity chiller, but the importance of these differences could become a major issue when dealing with large capacity cooling plants. The optimum operation of these plants relies on the accuracy and reliability of its measurements, therefore a robust methodology that improves the accuracy of the information obtained through sensors should be implemented when monitoring the plant performance.

It is desirable to extend the use of data validation should be from linear mass and energy balances as it is the usual practice to advanced energy systems. This work demonstrates that the application of this technique can provide a good contribution in the performance evaluation of complex systems an absorption chiller.

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REFERENCES

[1] Bruno, J.C., Romera, S., Figueredo, G., Coronas, A., Hybrid solar/gas single/double effect absorption chiller: operational results using Data Reconciliation, 2nd International Conference on Solar Air-Conditioning, pp. 244-249, Tarragona (Spain), 2007.

[2] Ripps, D.L. "*Adjustment of Experimental Data.*" Chem. Eng. Progr. Symp. Ser., 1965, No. 55, 61, pp. 8-13.

[3] Jiang Q. and M. Bagajewicz. *On a Strategy of Serial Identification with Collective Compensation for Multiple Gross Error Estimation in Linear Data Reconciliation*. Ind. & Eng. Chem. Research, 1999, 38, 5, 2119-2128.

[4] Miao, Y., Su, H., Xu, Ouguan, Chu, J., Support vector regression approach for simultaneous Data Reconciliation and gross error or outlier detection, Industrial Engineering Chemistry Research, 2009, 48, 10903–10911.

[5] Renganathan, T., Narasimhan, S., A strategy for detection of gross errors in nonlinear processes, Industrial Engineering Chemistry Research, 1999, 38, 2391-2399.

[6] Wang, D., Romagnoli, J.A., A framework for robust Data Reconciliation based on a generalized objective function, Industrial Engineering Chemistry Research, 2003, 42, 3075-3084.

[7] Madron F. *Process Plant Performance.* Ellis Horwood, Chichester, England, 1992.

[8] Sánchez M. and J. Romagnoli. Data Processing and Reconciliation for Chemical Process Operations. Academic Press, 2000.

[9] Narasimhan S. and C. Jordache. Data Reconciliation and Gross Error Detection. An Intelligent Use of Process Data. Gulf Publishing Company, 2000.

[10] Bagajewicz M. *Smart Process Plants: Software and Hardware for Accurate Data and Profitable Operations.* McGraw Hill, 2010.

[11] Darwish, N. A.; Al-hashimi, S. H.; Al-Mansoori, A. S., 2008, Performance analysis and evaluation of a commercial absorption-refrigeration water-ammonia (ARWA) system, International Journal of Refrigeration 31, 1214-1223.

[12] Lazzarin, R. M.; Gasparella, A.; Longo, G. A. 1996, Ammonia-water absorption machines for refrigeration:

theoretical and real performances, International Journal of Refrigeration 19, 239-246.

[13] Horuz, I.; Callander, T. M. S., 2004, Experimental investigation of a vapor absorption refrigeration system, International Journal of Refrigeration 1, 10-16.

[14] Jensen, J.B., Skogestad, S., Steady-state operational degrees of freedom with application to refrigeration cycles, Industrial Engineering Chemistry Research, 2009, 48, 6652-6659.

[15] Pátek, J., Klomfar, J., Simple functions for fast calculations of selected thermodynamic properties of the ammonia-water system, International Journal or Refrigeration – Revue Internationale du Froid, 1995, 18, 228-234.

[16] Martínez, D. E., Modeling and simulation of an air-cooled ammonia/water absorption chiller driven by the exhaust gas of a micro gas turbine, Master Thesis, University Rovira i Virgili, June 2009.

[17] Bagajewicz, M. Design and Upgrade of Process Plant Instrumentation. Technomic, 2000.

[18] Bagajewicz, M., On the definition of software accuracy in redundant measurement systems, AIChE Journal, 2005, 51, 1201-1206.

[19] Bagajewicz M. and DuyQuang Nguyen. *Stochastic-Based Accuracy of Data Reconciliation Estimators for Linear Systems.* Computers and Chemical Engineering, 2008, Vol. 32, 6, 1257–1269.