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Experimental heat transformer monitoring based on linear modelling and statistical control process

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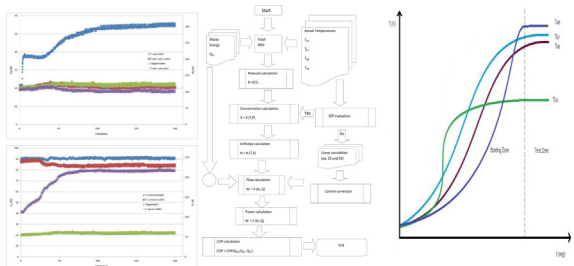
HIGHLIGHTS

- This paper proposes a new way to monitoring absorption heat transformer components.
- Potential and actual capacity values indicate an AHT capable process.
- Waste heat at evaporator makes the recover absorber temperatures tend to 92.8 °C.
- Condensation process was under statistic control at 24.7 °C in normal distribution.
- Analysed steady state shows variations lower than 2% in each temperature component.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper the Statistical Process Control (SPC) methodology is used for first time to analyse the data obtained from an Absorption Heat Transformer (AHT), the aim in here is to define if the system was operated under statistical control using a Carnot Coefficient of Performance (COP) equal to 0.7 as an established specification. Data of a 10 kW prototype *Single Stage Heat Transformer* (SSHT) were analysed. Carrol/water mixture was used as a working pair in the thermodynamic cycle. The operating conditions of the SSHT under steady stated conditions show an energy recovery between 352.9 and 366.0 K, while waste energy is added from 339.1 to 361.9 K. Condenser temperature shows a process under statistical control; its *Process Capability Ratio* (C_p) is 1.15 dimensionless, and the *Actual Process Capability Index* (C_{pk}) is 1.11 dimensionless, as well. A linear modelling technique was used to control the SSHT. Finally, the COP variation is expressed as the absorber and generator linear functions, and evaporator temperatures are shown as techniques for SSHT control. The C_{pk} value indicates that the Condenser process has the ability to perform the specified operation of the SSHT.

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1. Introduction

Absorption heat transformers (AHT) are thermo – mechanical devices in which the main feature is the recovery of waste heat. AHTs are capable of recovering a large amount of energy and increase its temperature, using part of the same energy as power in a thermodynamic cycle. The increased temperature inside any closed thermodynamic system is a consequence of the increment of pressure. The difference of pressure in an AHT is obtained by means of a relatively small (2%) amount of mechanical energy supplied by a mechanical pump to move a fluid; it is a measured value for this AHT [8] for the pumps consumptions of 32 W each.

One of the most important challenges of the AHT technology is the cycle control. AHT devices are affected by environmental conditions (rain or wind) because one of their components interacts with the environment. There are 60 variables interacting in an AHT in order to achieve the desired effect, i.e., revaluing waste energy.

The parameters present in an AHT are Temperature, Absorbent Concentration, Pressure, and Flow. There are two main thermodynamic parameters in the operation of an AHT: the first is the relative recovered amount of energy that is recovered, shown in the Coefficient of Performance (COP) and second the absolute increase of temperature in relation to waste energy (GTL).

2. Analyzed parameters

There are two important parameters for the industrial processes: quantity and quality. In the case of recovery of industrial waste heat, quantity is given by the recovered power (calculated by COP), and quality is given by the thermal level of recovery (calculated by GTL).

In this paper, the Coefficient of Performance (COP) parameters are defined as the relationship between the thermal energy that is recovered and the total inlet of thermal energy. This definition ignores the performance of mechanical pumps, in which are two orders of magnitude lower [17].

$$\mathrm{COP} = \frac{Q_{AB}}{Q_{GE} + Q_{EV}} \tag{1}$$

The absolute increase of temperature is defined as the difference between the temperature of the absorbent and the temperature of the evaporator.

$$\mathrm{GTL} = T_{AB} - T_{EV} \tag{2}$$

In an AHT, the variables that drive great changes in the two parameters defined in the section above are Temperatures, since the changes in Pressure and Concentration do not affect the AHT performance considerably.

3. AHT cycle

The AHT has four basic components: two for energy inlet, and two for heat rejection. The inlet components are the generator and the evaporator. The rejection components are the absorber and the condenser. There is an internal heat recirculation that increases the recovery of waste heat; it is called economizer [15]. The thermodynamic cycle under study starts with a waste heat exchange towards two AHT components simultaneously. There is an exchange of energy with the generator that contains a mixture called aqueous Carrol. The mixture Water/Carrol developed by Carrier Corporation. Carrol is an aqueous LiBr mixture with a crystallization inhibitor (ethylene glycol) in the ratio 1:4.5 by weight [14]. Inside the generator, the water evaporates and is conducted to the upper part, due to density difference. A concentrated solution of aqueous Carrol remains in the bottom of the generator, which is sent to the absorber by means of a micro-pump. The steam created in the generator is sent to a component that is called condenser. In the condenser, the steam exchanges heat with a stream of cold water that is not useful, as its temperature is near the room temperature. Once the steam heat is exchanged, water in liquid phase is sent to the evaporator by means of a second micro-pump. In the evaporator, the exchanged waste energy turns into steam again, but at a relative high pressure. The evaporator drives the steam through a pipe to the absorber. In the absorber, the solution of concentrated aqueous Carrol gets into contact with high-pressure steam, causing high temperature absorption. This heat is the useful heat in the AHT. The solution formed is the diluted aqueous Carrol and is sent to the generator through a pipe. The entire cycle can be seen in Fig. 1. The operating conditions are reported on Table 1 to operate the AHT. The generator, evaporator and absorber are Plate Heat Exchanger and have 7 corrugated plates and 3 channels per pass. The condenser has 4 corrugated plates and 1 channel per pass for working fluid (water) and 2 channels per pass for cooling fluid. The total operating design AHT power is 10 kW at Table 1 operating conditions.

4. AHT's options for control

Statistical process control is a widely used methodology in manufacturing and services; it allows monitoring, controlling and improving the quality of a process [2,12,20,22]. However, it has not been applied in AHT at all. This methodology may provide an option for improving the monitoring of the process.

A recent review [3], shows that there are two options on improvement for heat pumps that are based on lithium bromide: the use of inhibitors, and mechanical designs. On the other hand, in control systems for compression heat pumps, progress has been made in dynamic control based on storage [18] and there is a proposal for the increase of COP based on a control strategy, by means of plate exchangers [10]. A method proposed by Liao & Radermacher [11] consists basically of increasing the set point of the Chiller temperature to prevent the risk of crystallization. Recently, in addition [9], the control of high temperature for the recovery of industrial waste heat has been considered as a challenge. However, in the case of AHT there is only one study, based on the *Statistic Process Control* [4], which conducted a comparison between two designs.

Other studies that refer to some type of control in AHT [6] suggest that maintaining the flow relationship constant is a control strategy; however, the study belongs to exergy and not to control. One correspondent and his team [7] reported an AHT for water purification in which testing showed control problems; in a similar manner, the correspondent and his team [15] had previously reported an AHT control based on pumps with adjustable gears and electric resistors for a study on exergy under steady conditions.

There is an opportunity to improve the quality by statistical analysis in heat transforming process [21] based on function regression. In this paper temperature is the independent variable for capability evaluation, similar to the new methodologies for energy loads in buildings [1].

5. Control by linear approximation model

In the case of AHT, in steady state, a COP value for each GTL value is expected as function of T_{AB} for a constant T_{EV}. These values may be correlated, assuming a model based on the following equation:

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