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On-line COP estimation for waste energy recovery heat transformer by water purification process

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Abstract

On-line COP (coefficient of performance) estimation is carried out for waste energy recovery heat transformer by water purification process using developed different algorithms by bash (information acquisition) and Octave (information training). This variable estimation is very important to an optimum performance in the system. The COP is estimated from observation a filter Kalman. In addition, a thermodynamic model is used to on-line COP prediction to steady-state conditions. The two models consider output measures temperatures for each one of the four components of the heat transformer (absorber, generator-evaporator, and condenser). However to thermodynamic model, two pressures (absorber-evaporator and generator-condenser) and LiBr + H_2O concentrations in the absorber and generator are required in real-time. The pressures and concentrations are calculated from literature. The results are satisfactory for the COP estimation in both models, allowing to optimizer and know the system operation situation in each set measured. In addition this allows to reduce costs of production and a process control can be implemented from this indirect measure.

Keywords: On-line COP estimation; Heat recovery; Thermodynamic model; Absorption heat transformer

1. Introduction

The coefficient of performance (COP) is a variable very important for determiner the performance of an absorption heat transformer [1,2]. This COP is defined as the heat delivered in the absorber per unit of heat load supplied to the generator and evaporator, Eq. (24). Absorption heat transformer is a system that consists of a thermodynamic device capable of producing useful heat at a thermal level superior to the one in the source [3]. The advantage of this absorption heat transformer is that it may be incorporated in any other system that requires a temperature

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greater than the one provided by the source. In this context, a number of works report that it is possible to integrate the absorption heat transformer to a water purification process [1,4,5]. This integration of both systems enables us to increase the temperature of the impure water system, and thus obtain pure water and useful heat. Recently, Siqueiros and Romero [6] developed a portable water purification process integrated to an absorption heat transformer, and obtained pure water with a quality similar to that obtained from a laboratory's electrical distiller. The authors demonstrated that the coefficient of performance, COP can be increased by the incorporation of the waste-heat from the water purification condenser to the evaporator and generator of the absorption heat transformer (see Fig. 1). This allows a fraction of heat obtained by the absorption heat transformer to be recycled, thus obtaining a higher value of COP, when only the evaporator and generator temperatures are slightly increased. In addition, the authors concluded that energy recycling of the water purification process could increase the COP by more than 120%.

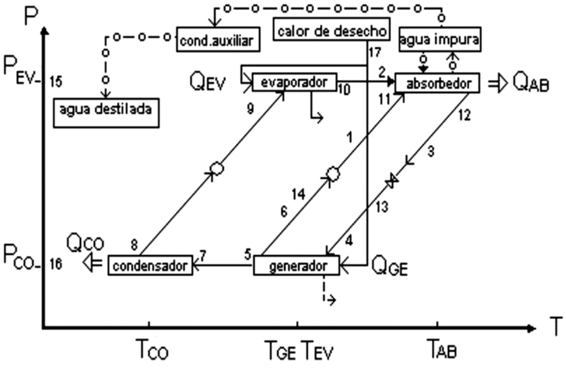

Fig. 1. Water purification process integrated to absorption heat transformer with the incorporation of the waste-heat from the auxiliary condenser to the evaporator and generator of the absorption heat transformer. The continuous line (-) represents the absorption heat transformer, the line (-o-) represents the water purification process and the line (- -) represents the recycle energy.

The aim of the present work is to test the importance and efficiency of the developed algorithms to evaluate on-line the coefficient of performance (COP) for waste energy recovery heat transformer by water purification process. A thermodynamic model is evaluated to the COP prediction and incorporated in the algorithms of estimation. On-line direct measures, such as input and output temperatures of four components (AB, GE, CO and EV), two pressure (EV-AB and CO-GE) are carried out by sensor robust. The software is developed in Linux considering bash and octave.

2. Materials and methods

2.1. Data acquisition of direct measures

The Fig. 2 shows the on-line data acquisition of input and output temperature measure in the water purification integrated to absorption heat transformer. To the data acquisition, we developed an algorithm in bash (Linux GNU-Debian) [7] that allows the communication between computer and data acquisition (Agilent 34970A), from the configuration the port RS-232 and with the command STTY for the input and output signs. The command cat was used to store the information in file, as it appears in the Table 1.

2.2. On line COP measures estimation

The Fig. 3 presents the recurrent architecture for the on-line indirect measures estimation (COP) in the water purification process integrated to absorption heat transformer. This architecture considers the direct measures obtained and the proposed mathematic models (see Thermodynamic

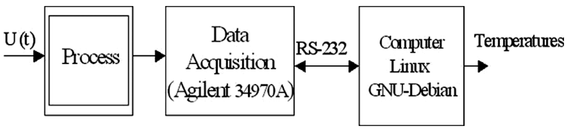

Fig. 2. Acquisition data of direct measures.

Table 1
Algorithm used to the on-line direct measures and information store

```
cat < ./conf > /dev/ttyS0
stty [–F DEVICE]
do
m=‘date +%H%M%S’
echo –n “$m,” >> <file>
sleep 0.01
cat /dev/ttyS0 >> <file>&
echo read? > /dev/ttyS0
sleep 4.45 #time necessary to unload the information to
the file done
```

model), which it is integrated with help of an algorithm developed wrote in Octave [8].

2.2.1. Thermodynamic model and assumptions

The thermodynamic model that intends for the simulation of single stage absorption heat transformer is based on the pattern published previously [9]. The following assumptions have been made in the development of the mathematical model for a refined system with reference to Fig. 1 [6].

(i) the entire system is in thermodynamic equilibrium,
(ii) the analysis is made under steady-state conditions,
(iii) a rectifier is not required since the absorbent does not evaporate under the operating temperature range of the system,

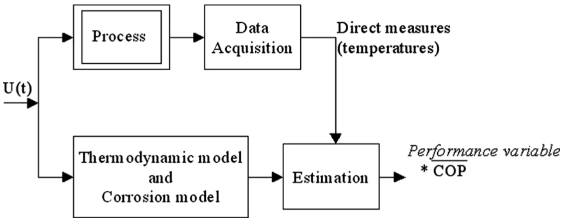

Fig. 3. Architecture used for the on-line indirect measures estimation (COP).

(iv) the solution that leaves the generator and the absorber is saturated; similarly, the working fluid leaving the condenser and the evaporator is also saturated.
(v) heat losses and pressure drops in the tubing and into the components are considered negligible,
(vi) the flow through the valves is isenthalpic,
(vii) temperatures at the output of the main components T_5, T_8, T_{10} and T_3 and the heat load in the evaporator Q_{EV} are known,
(viii) a heat supply is delivered by industrial waste heat.

(1) From assumption (i),

$$T_5 = T_6 \tag{1}$$

(2) Since the working flows is considered saturated leaving the condenser and evaporator, then the pressure at state points may be obtained by the following equations:

$$P_8 = P(T_8) \tag{2}$$

$$P_{10} = P(T_{10}) \tag{3}$$

(3) Since the pressure drops in the tubing and the components are consider negligible,

$$P_7 = P_8 = P_4 = P_6 \tag{4}$$

$$P_9 = P_{10} = P_3 = P_1 \tag{5}$$

(4) From assumption (iv) the concentration of the LiBr concentrated solution leaving the generator can be estimated as follows

$$X_6 = X(P_8, T_6) \tag{6}$$

(5) In the same way, the concentration of the LiBr diluted solution leaving the absorber can be estimated

$$X_3 = X(P_{10}, T_3). \tag{7}$$

(6) Cause there is not mass transfer between generator and absorber

$$X_6 = X_1 \tag{8}$$

$$X_3 = X_4. \tag{9}$$

(7) From assumption (iii), the concentration of the absorbent in the vapor leaving the generator is zero, then

$$X_5 = X_8 = X_9 = X_{10} = 0 \tag{10}$$

(8) The enthalpies at the exit of absorber and generator can be estimated by

$$H_3 = H(T_3, X_3) \tag{11}$$

$$H_6 = H(T_6, X_6) \tag{12}$$

(9) From consideration (iv), the enthalpies at the output of the condenser and the evaporator can be estimated as follows

$$H_8 = H(T_8) \tag{13}$$

$$H_{10} = H(T_{10}). \tag{14}$$

(10) Considering that the vapour upon leaving the generator is superheated

$$H_5 = \mathrm{H}(P_8, T_5) \tag{15}$$

(11) Cause the absorbent does not evaporate in the temperature range under operating conditions, from mass balance in generator and absorber, the flow ratio (RF) can be rewritten for this system by

$$\mathrm{FR} = \frac{M_{\mathrm{AB}}}{M_{\mathrm{WF}}} = \frac{X_6}{X_6 - X_4} \tag{16}$$

(12) Carrying out mass and energy balances in the to absorb and using FR definition, the mass flow rate of the working flows can be calculated by the following equation:

$$M_{\mathrm{WF}} = \frac{Q_{\mathrm{AB}}}{H_{10} - H_1 + FR(H_1 - H_3)} \tag{17}$$

(13) From FR definition:

$$M_{\mathrm{AB}} = M_{\mathrm{WF}}\mathrm{FR} \tag{18}$$

(14) From to mass balance in the absorber or generator side

$$M_{\mathrm{GE}} = M_{\mathrm{AB}} - M_{\mathrm{WF}} \tag{19}$$

(15) Considering that the process though the expansion valve is isenthalpic (vi)

$$H_3 = H_4 \tag{20}$$

(16) From mass and energy balances in the main components, the amount of heat supplied or delivered can be estimated from the following equations:

$$Q_{\mathrm{CO}} = M_{\mathrm{WF}}(H_5 - H_8) \tag{21}$$

$$Q_{\mathrm{EV}} = M_{\mathrm{WF}}(H_{10} - H_9) \tag{22}$$

$$Q_{\mathrm{GE}} = M_{\mathrm{WF}}H_5 + M_{\mathrm{GE}}H_6 - M_{\mathrm{AB}}H_4 \tag{23}$$

(17) Then the coefficient of performance for single stage heat transformer is defined by following Eq. (24):

$$\mathrm{COP} = \frac{Q_{\mathrm{AB}}}{Q_{\mathrm{GE}} + Q_{\mathrm{EV}}} \tag{24}$$

2.2.2. COP estimation

A filter Kalman is employed for state estimation (COP). This filter is based on the linearization of the process model around the sub-optimal COP estimate by the thermodynamic model. The filter has the function as work as an estimator, which consider the covariance of the system variable function time.

2.2.3. Time-varying Kalman filter

The time-varying Kalman filter is a generalization of Kalman filter for steady state. A time-varying Kalman filter is able to perform well even when the noise covariance is not stationary. In order to the Kalman filter, the equations used for the system model are the following [MatLab®, Control System Toolbox]:

$$x[n+1] = \mathrm{Ax}[n] + \mathrm{Bu}[n] + \mathrm{Gw}[n] \tag{25}$$

$$\mathrm{yv}[n] = \mathrm{Cx}[n] + v[n] \tag{26}$$

where $[n] \geq 0$ is the successive moments of time, yv is the noisy measurements, *w* and *v* are modelled as white noise.

The time varying Kalman filter has the following update equations:

$$x[n+1 \mid n] = \mathrm{Ax}[n \mid n] + \mathrm{Bu}[n] \tag{27}$$

$$P[n+1 \mid n] = \mathrm{AP}[n \mid n]A^{\mathrm{T}} + B \times Q[n] \times B^{\mathrm{T}} \tag{28}$$

Measurement update:

$$x[n \mid n] = x[n \mid n-1] + M[n]\left(\mathrm{yv}[n] - \mathrm{Cx}[n \mid n-1]\right) \tag{29}$$

$$M[n] = P[n \mid n-1]C^{\mathrm{T}}\left(\mathrm{CP}[n \mid n-1]C^{\mathrm{T}} + R[n]\right)^{-1} \tag{30}$$

$$P[n \mid n] = \left(I - M[n]C\right) \cdot P[n \mid n-1] \tag{31}$$

where *P* is the covariance matrix, the $x[n|n-1]$ and $x[n|n]$ as defined in Discrete Kalman Filter [MatLab®, Control System Toolbox], and $Q[n]$, $R[n]$, $P[n|n]$ and $P[n|n-1]$ are obtained as the proposed MatLab®, Control System Toolbox and *u* is function of input variable.

In order to estimate the COP from Kalman filter is necessary to linear the system, the order first differential equation is used to obtained $y(t)$:

$$\tau \frac{\mathrm{d}y}{\mathrm{d}t} + y = \mathrm{Ku}(t) \tag{32}$$

where *K* is the filter gain and τ is the time constant. The solution of this Eq. (32) can be resolute by the domain of Laplace. The constants (*K* and τ) are evaluated from information of the system (output temperature measured of the condenser, evaporator-generator, and absorber) or of the proposed model. The resulting equations system (25–32) were solved using *tf, ssdata* and *ss* (MatLab®, Control System Toolbox).

3. Results and discussion

3.1. Direct measured

According to developed algorithms in bash and octave in Linux, the output temperatures (absorber, generator, evaporator, condenser) are presented in Fig. 4.

The on-line obtained temperatures values are between 30.88 and 31.43°C for the condenser, 81.67 and 83.49°C for the evaporator, 84.030 and 90.94°C for the generator and 94.84 and 97.01°C for the absorber. These temperatures values are acquired with interval of time between each acquisition and these are on function of the requests of sampling. The algorithm was stopped voluntarily in two occasion, and consequently, this perturbation had not effect negative, since this algorithm have vantage of salving the file and starting the algorithm in all the times it is necessary.

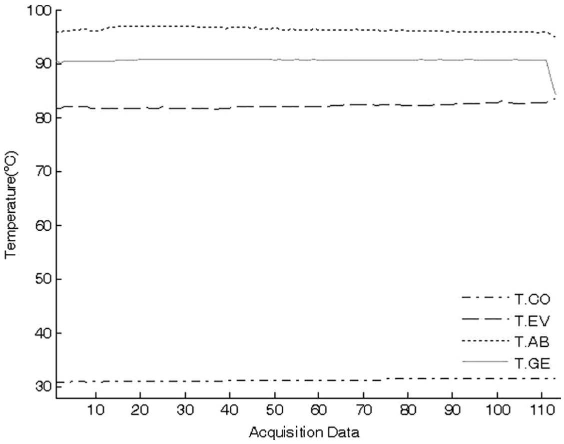

Fig. 4. On-line output temperature measured of the four heat transfer components (condenser, evaporator, absorber and generator) versus the update acquisition.

3.2. On-line COP prediction by thermodynamic model (indirect measure)

From on-line direct measure (temperatures and pressures, obtained of the same acquisitor with help of thermocouples) and considering the thermodynamic model, it is possible to on-line COP values predict. Fig. 5 show the predict COP values function of the generator output temperature during the process of purification of water integrated to absorber heat transformer. The obtained COP values are between 0.32 and 0.37. These COP values are similar to reported by Siqueiros and Romero [6].

3.3. On-line COP estimation with filtro Kalman

The Fig. 6 shows the COP estimated values by the filter Kalman and the COP predict values by the thermodynamic model. This figure present that the COP estimated values by Kalman are similar for the COP predict values by the Thermodynamic model. This confirms that the COP estimation can be carried out considering filter Kalman. In addition, Kalman have as objective the process supervision, detection of flaws of the process and control of process of the water purification from absorption heat transformer. Consequently, this algorithm will offer a major mastery of the process to the operator.

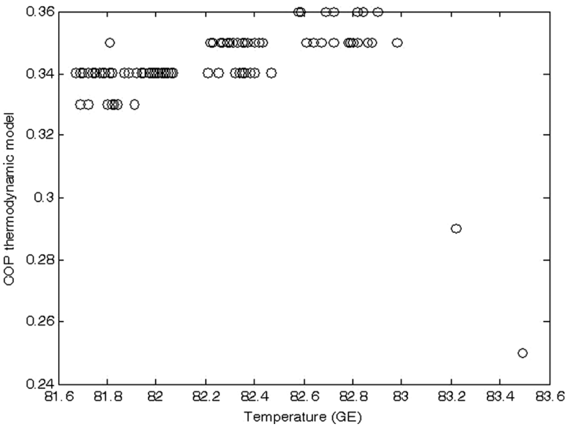

Fig. 5. On-line COP prediction versus temperature of GE considering the thermodynamic model.

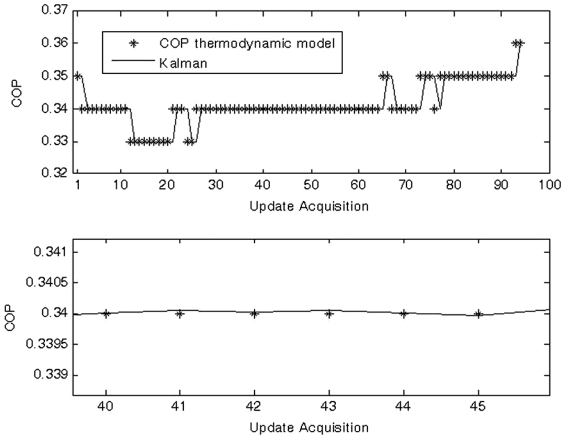

Fig. 6. On-line COP values estimation with filter Kalman.

4. Conclusion

It is important to mention that this work propose algorithms to indirect measured on-line estimate (COP) to know the process state. These on-line indirect measure will allow to optimizer the system. The STTY of Linux allows to do the communication between computer and instrument acquisition without resorting to VISA® library. The developed algorithms are validated (acquisition information and treatment of the information) with experimental system. The applied thermodynamic model is considering satisfactory to COP predict, naturally with the assumptions considered. There are that notice, the developed algorithms allow carried out changes in the software for the progress of the system without any additional cost of software license. In addition, Kalman filter is capable of estimating the states of the process on-line when perturbations exist in the process. This Kalman algorithm can be used as supervision in the process.

Nomenclature

COP	coefficient of performance, dimensionless
FR	flow ratio, dimensionless
P	pressure, in Hg
Q	heat flow, W
RMSE	root mean square error
T	temperature, °C
X	concentration, % w/w

Subscripts

AB	absorber
CO	condenser
EV	evaporator
GE	generator

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