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Designing state estimator for multi-stage MED desalination systems in the presence of noise

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Abstract. According to a reduction in available water resources such as rainfall and groundwater; today, the supply of drinking water has become one of the main problems of the worldwide countries. Seawater desalination methods are one of the alternatives to deal with this problem, among which the employment of distillation units by means of solar radiation can be a suitable and cost effective alternative. Multi-effect distillation is one of the thermal desalination systems that have received great attention today due to energy efficiency and high performance. In this paper, a PDE and non-linear model from MED desalination systems has been initially presented. To understand how these systems work, one is required to have a sound understanding of the behavior of the system variables while access to the exact value of these variables is not possible due to the presence of noise in the system model. Thus, *due to the nonlinearity of the model of the system, extended Kalman filter* (EKF) was proposed to provide a desired approximation of the system variables in addition to reducing the noise in the system. The simulations conducted in MATLAB software show that the employed algorithm has been largely successful.

Keyword: Desalination systems, multi-stage distillation, Gaussian white noise, extended Kalman filter

1. INTRODUCTION

Man has been dependent upon energy to spend their lives since the origin of life, but they have always encountered the shortage of these resources in some areas. Nowadays, this shortage is viewed as a crisis due to the increasing growth of population and limited access to these resources. In addition, the increase in human activities, the use of fossil energy and environmentally pollutant fuels, and also the contamination of surface and ground waters have caused environmental crisis to be considered as a new challenge. Thus, the technology of desalination systems has been moving forward in a more accelerated fashion in recent decades [1]. Today, the desalination of seawaters and ocean waters has been considered by most countries. About 71% of the Earth's surface is covered with water. When it comes to human's need to water, it is not only meant drinking water since there are many industries that need water with low level of salts, such as steam power plants. Lack of fresh water for life, agriculture, and industry has created problematic issues for countries. Oceans and seas are large water resources in the world; however, the high weighting percentage of impurities has made it difficult to use these waters for different purposes. Groundwater is a major source of water, but this water also contains impurities. It should be noted that the amount of these impurities is related to the geographical location of the region. These days, there is the possibility of the production of large volumes of fresh water by means of different desalination methods while the selection of the best desalination method depends on the situation, the geographical location of the region, initial cost, and other factors [2].

Desalination usually refers to a process in which the concentration of solid minerals in the water or the water salinity gets reduced. It is evident that seawater is very salty and the direct use of it in industrial and domestic situations (such as boilers, steam turbines, and distillation and wash

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towers) is not possible. However, the sweetening of water makes it ready to be used for this purpose.

Common desalination water methods, which are used more for high-capacity items include multi-stage flash (MSF), multi-effect distillation (ME), vapor compression (VC), and reverse osmosis (RO) [3].

With the development of the instruments to measure pressure and temperature as well as the discovery of the properties of fluids, fresh water production in the early 1950s became an important issue. The increase of oil explorations in the Gulf countries, America, and other countries that are facing a shortage of drinking water influenced the development of fresh water. The first commercial desalination unit was installed in Jeddah by Autamanz Company. This was a boiler unit which was working under atmospheric pressure but suffered acute problems in terms of corrosion and deposition. With the promotion the technology of float tubes, the first unit was built with the capacity of 45,000 cubic meters per day in Kuwait in the early 1950s [4]. As long as a multi-stage flash method had not been devised by Professor Robert Silver [5] in the 1950s, water desalination was not regarded as a practical solution to resolve the shortage of drinking water. The turning point in the history of desalination returns to the use of multi-stage flash in Kuwait in 1957. Department of Electricity and Water of Kuwait ordered the Westinghouse Company to construct four units with the capacity of 0.5 MGD, each with four stages. This achievement caused the encouragement and development of the units towards higher efficiency and higher capacities and led to the acceptance of an offer by Weir Company to develop a new design concept in desalination systems which is known as multi-stage flash.

Following this success, companies around the world, especially in America and England, initiated the conduct of a lot of research to develop large evaporator units in order to achieve lower production costs. Afterwards, Sasakura Japanese Company installed the first MSF units with the capacity of 5 MGD in Shuwaikh Kuwait and, then, some units were established in Shaibiyeh Kuwait. The success of this large unit in this achievement that MSF can generate fresh water more confidently and more economically in comparison with other methods has paved the way for further progress in the 1970s and 1980s [6].

At that time, distillation was the only method and, then, the use of conventional membranes became common in late 1965. In 1953, a research group at the University of Florida proposed a research project to the water management department of Florida. They produced a membrane made of porous acetate which could remove the salt, but the passing flow of water through the compressed membrane was so low that no economic value could be attached to it.

The most important step in the development of membrane technology was taken in a research program at the University of California from 1958 to 1960. This team established the first urban unit of reverse osmosis Calistoga California [7].

In the twentieth century, the use of solar energy to produce fresh water was resumed and several different types of solar systems were studied.

The results of this research revealed that the produced water did not compensate for the external costs and expenses pertaining to the building of the device and, from then on, the conduct of studies on economic estimates of instruments and the enhancement of its operational efficiency continued. In recent years, most of the studies have been conducted on modeling and experimental examination of steep devices where researchers have studied the effect of various parameters [8].

In this paper, a non-linear PDE model from multi-stage desalination systems has been proposed whose input is a Gaussian white noise. This was done with the review of the studies conducted in the last few years in terms of the modeling of desalination systems. Due to the presence of noise in the model structure and the inaccessibility of the exact amount of system variables, this study was aimed at proposing an optimum filtering to provide a desired approximation of the system variables in addition to reducing the noise in the system.

This paper is organized in five sections. In the second part, a non-linear PDE model from *multi* effect desalination systems has been proposed whose input is a Gaussian white noise. Since the purpose of this paper is to provide a method for accurately estimating the system variables, the structure of a non-linear filter, known as extended *Kalman filter,* is presented in the third part. The implementation of the proposed filter on the model of the system in MATLAB software and the presentation of the results obtained from the simulation constitute the theme of the forth chapter. Last but not least, the fifth chapter is dedicated to the conclusion.

2. PDE AND NON-LINEAR MODEL FOR MULTI-EFFECT DESALINATION (MED) SYSTEMS

In this paper, a particular type of multi-effect desalination systems, entitled AQUASOL has been examined. An overview of the system is shown the figure below [9].

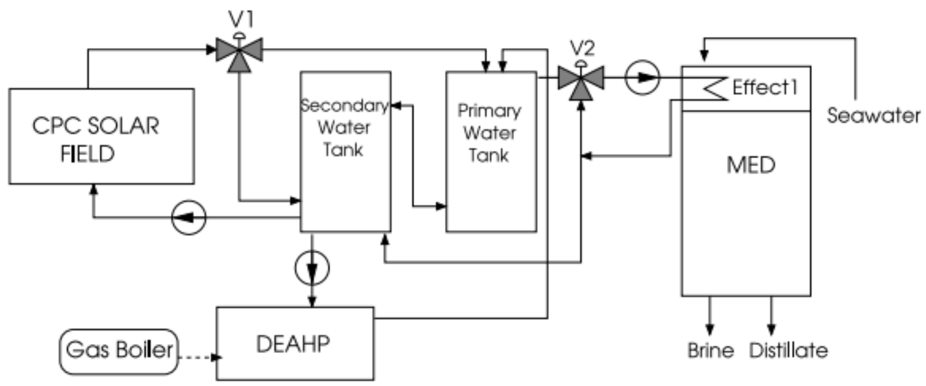

Figure 1. An overview of an AQUASOL process.

According to Figure 1, multi-effect desalination systems are designed in such a way that hot high-pressure steam enters into the system from the boiler with a state close to saturation. Then, this steam suctions some part of the dead vapor remaining from the final stage while passage through the thermo compressor and its pressure drops to the incoming pressure of the first stage after the occurrence of the shock. With the spraying of water into the desuper heater, this steam changes into saturation vapor and enters the horizontal tubes (with bundle tube) of the first stage. The steam passing through the tubes gets distilled and becomes saturated while the film flow falling on tubes evaporates. The creation of vacuum in each stage is the requirement for evaporation at low temperatures which has been previously done by ejectors. The mathematical model describing the structure of Figure 1 is as follows:

$$\rho.C_p.A.\frac{\partial T'(t)}{\partial t} = \beta.I(t) - \frac{H}{L_{eq}}.\left(\bar{T}(t) - T_a(t)\right) - C_p.\dot{m}_{eq}(t).\frac{T'(t) - T_{in}(t - d_{tin})}{L_{eq}} + \gamma.w(t) \quad (1)$$

$$\bar{T}(t) = \frac{T'(t) + T_{in}(t - d_{tin})}{2}$$

Model (1) is a non-linear and PDE model whose parameters are shown in the table below:

Table 1. Parameters of the model (1).

unit	Symbol	parameter
$kg\ m^{-3}$	The density of water at a temperature of 65°C	ρ
$J\ kg^{-1}\ °C^{-1}$	Specific heat capacity of water at a temperature of 65°C	C_p
m^2	Solar ray absorption cross section	A
m	Parameter in the model, exposure to the sun	β
$J\ s^{-1}\ K^{-1}$	Heat loss coefficient	H
m	The length of the tubes in the desalination	L_{eq}
$kg/_s$	The current through each of the tubes in the desalination	$\dot{m}_{eq}$
°C	Temperature of incoming water desalination system	T_{in}
°C	The temperature of the water trapped inside the machine desalination	T_a
$W\ m^{-2}$	The amount of solar radiation	I
$-$	Gaussian white noise in the desalination	w

3. NONLINEAR STATE ESTIMATOR FILTER

the models presented in (1) have some significant features. for example, it is nonlinear and its input is considered as Gaussian white noise. Based on these assumptions, an optimum nonlinear filter like extended Kalman filter is proposed to estimate the states of the system[10]. The structure of the filter is as follows:

1) consider the following nonlinear system

$$\begin{cases} X_{k+1} = f_k(X_k) + g_k(X_k).W_k \\ Z_k = h_k(X_k) + V_k \end{cases} \quad)1($$

2) we assume the following definitions for system linearization

$$F_k \triangleq \frac{\partial f_k(x)}{\partial x}|x = \hat{X}_{(k|k)}$$

$$H_k^T \triangleq \frac{\partial h_k(x)}{\partial x}|x = \hat{X}_{(k|k-1)} \qquad)2($$

$$G_k \triangleq g_k(\hat{X}_{(k|k)})$$

3) regarding to equation (3), the literalized system for equation (2) can be written as:

$$\begin{cases} X_{k+1} = F_k.X_k + G_k.W_k \\ Z_k = H_k^T.X_k + V_k \end{cases} \qquad)3($$

4) where the extended Kalman filter algorithm for linearized system (4) can be regarded as:

$$L_k = \Sigma_{(k|k-1)}.H_k.\left(H_k^T.\Sigma_{(k|k-1)}.H_k + R_k\right)^{-1}$$

$$\hat{X}_{(k|k)} = \hat{X}_{(k|k-1)} + L_k.\left[Z_k - h_k\left(\hat{X}_{(k|k-1)}\right)\right] \qquad)4($$

$$\Sigma_{(k|k)} = \Sigma_{(k|k-1)} - \Sigma_{(k|k-1)}.H_k.\left(H_k^T.\Sigma_{(k|k-1)}.H_k + R_k\right)^{-1}.H_k^T.\Sigma_{(k|k-1)}$$

Finally, with respect to (5), the quantities estimated by EKF will be as follows:

$$\hat{X}_{(k+1|k)} = f_k\left(\hat{X}_{(k|k)}\right)$$

$$\Sigma_{(k+1|k)} = F_k.\Sigma_{(k|k)}.F_k^T + G_k.Q_k.G_k^T \qquad)5($$

That

$$\hat{X}_{(k_0|k_0-1)} = \bar{X}_{k_0}$$

$$\Sigma_{(k_0|k_0-1)} \triangleq P_{k_0} \qquad)6($$

4. SIMULATION RESULTS

Due to the inaccessibility of system states and the presence of measurement and state noise in multi-effect desalination systems, proposing an optimum filtering that can provide a desired approximation of the system variables via the weakening of the existing noises is required to design control law. The current simulations in this research have been performed using the data available in [11]. In this reference, one multi-effect desalination system has been kept under examination for 16 consecutive days and the model of the system has been identified using the acquired data. In the figure below, the performance of extended Kalman filter for the variables of this model has been shown.

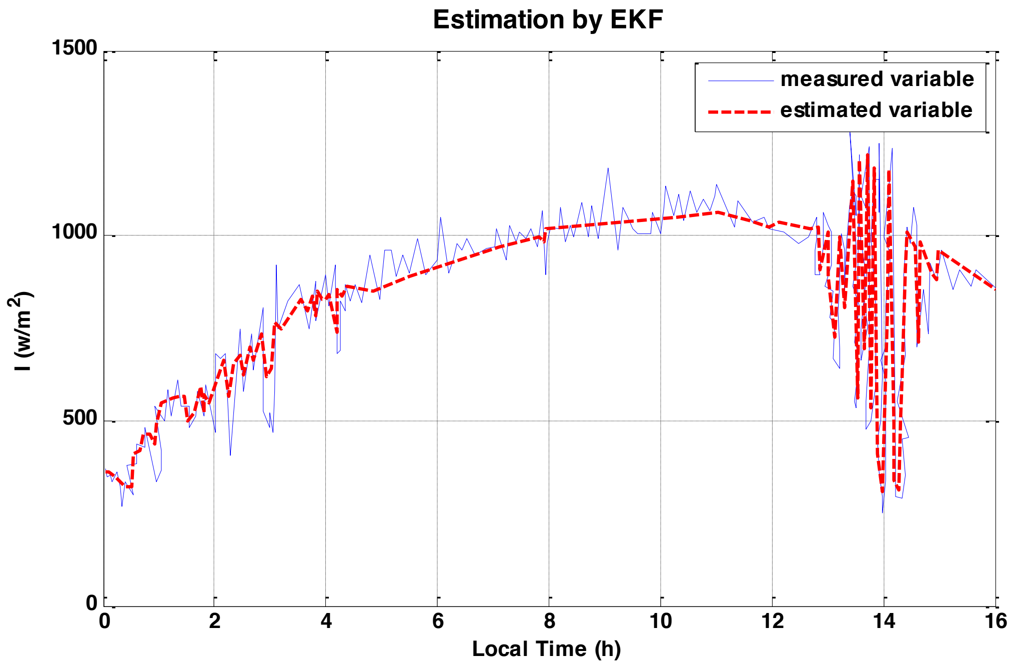

Figure 2. The measured values (blue figure- continuous line) and estimated values (red figure-wavy line) for the variable entitled the amount of solar radiation.

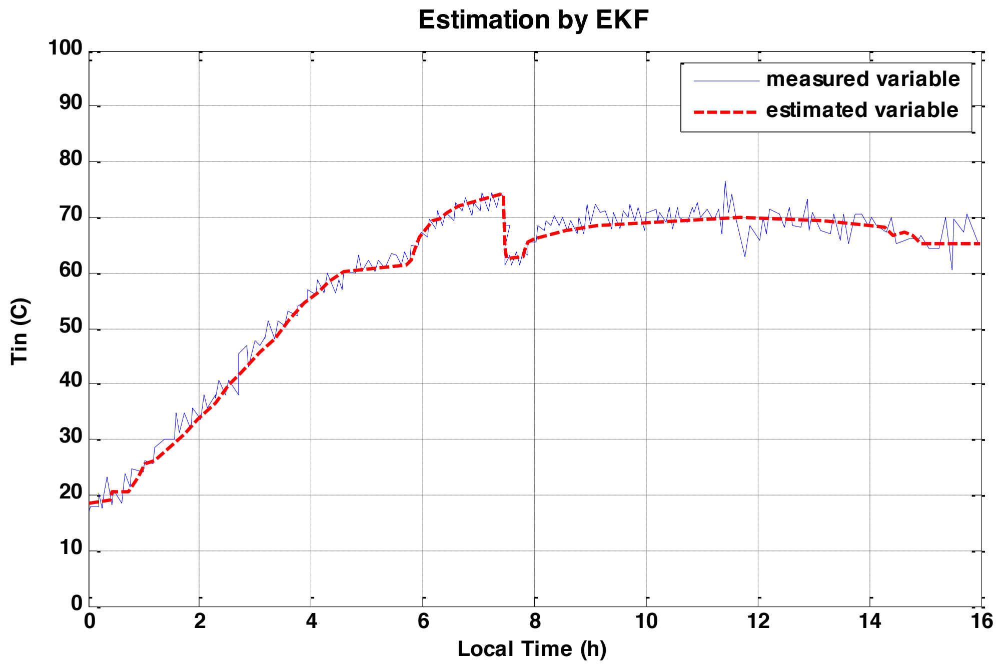

Figure 3. The measured values (blue figure- continuous line) and estimated values (red figure-wavy line) for the variable entitled water temperature when entering the desalination system.

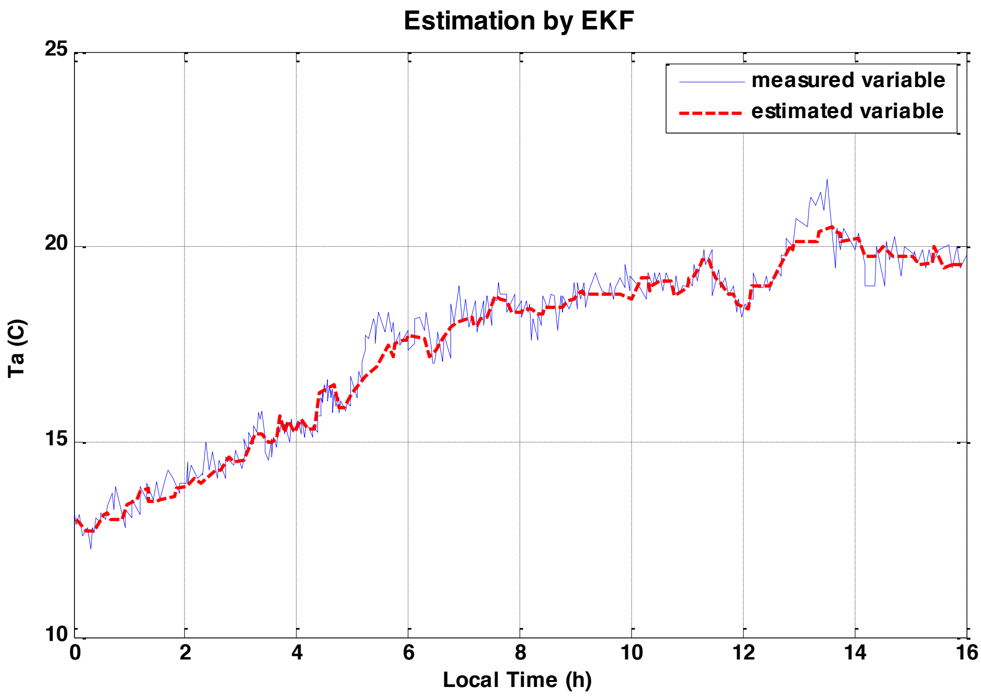

Figure 4. The measured values (blue figure- continuous) and estimated values (red figure-wavy line) for the variable entitled the temperature of the water available in the desalination system.

5. CONCLUSION

In this study, the design of extended Kalman filter was studied to estimate the variables in the model of the system. To this end, a non-linear and PDE model was selected whose input is a Gaussian white noise. The first step is to identify a system is access to the exact value of its variables which is not possible for multi-effect desalination systems due to the presence of noise in its structure. The solution presented in this paper is to use extended Kalman filter. After selecting the model and applying the estimator of extended Kalman on it in MATLAB software, it was observed that this filter could estimate the system variables with the weakening of noise. In the end, it was observed that the estimated error, i.e. the difference between the measured state and the estimated state of the system was obtained at an acceptable level.

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