2014

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Baojie Mu
University of Texas at Dallas, United States of America, Baojie.Mu@utdallas.edu

Yaoyu Li
University of Texas at Dallas, United States of America, yaoyu.li@utdallas.edu

John E. Seem
High Altitude Trading Inc., United States of America, john.seem@gmail.com

Experimental Study on Extremum Seeking Control for Efficient Operation of Air-side Economizer

Baojie Mu[1]*, Yaoyu Li[2], John E. Seem[3]

[1]The University of Texas at Dallas, Department of Electrical Engineering,
Richardson, TX, USA
Email: Baojie.Mu@utdallas.edu

[2]The University of Texas at Dallas, Department of Mechanical Engineering,
Richardson, TX, USA
Email: yaoyu.li@utdalals.edu

[3]High Altitude Trading, Inc.
Jackson, WY 83001, USA
Email: john.seem@gmail.com

*Corresponding Author

ABSTRACT

The air-side economizers have been developed as a major class of energy-saving equipment to enhance the energy efficiency of central air-conditioning systems by taking advantage of outdoor air during cool or cold weather. In current practice, the outdoor air damper is controlled to maintain either the maximum or minimum opening by comparing the outdoor air temperature/enthalpy with the setpoint temperature/enthalpy or return-air temperature/enthalpy. However, in practice many economizers do not behave as expected or even waste more energy due to the erroneous damper actions because of the inaccurate or failed temperature and/or relative humidity (RH) sensors. Recently, a self-optimizing controller based on extremum seeking control (ESC) has been proposed in an earlier study by Li et al. (2010) for efficient operation of an air-side economizer. This paper presents two experimental studies of the ESC air-side economizer control: one is a laboratory setup with a direct-expansion air conditioning unit, and the other is a chilled-water based air handling unit (AHU) facility at Iowa Energy Center. Experimental results from both studies validate the effectiveness of the ESC scheme as a model free optimal control strategy for air-side economizer operation.

1. INTRODUCTION

Commercial and institutional buildings commonly require year-round cooling regardless of their geographic location (Mumma, 2005; Seem et al. 2010). Beside the mechanical cooling by vapor compression equipment, the air-side economizers have been widely used in air handling unit (AHU) for central air-conditioning systems to improve the energy efficiency by taking advantage of outdoor air during cool or cold weather. An air-side economizer is based on combined use of three dampers (outdoor, relief and return air) , sensors (i.e. temperature, relative humidity), actuators and controls that work together to determine how much outdoor air to bring into buildings when the outdoor air are favorable and cool enough to be considered as a cooling medium. Fig. 1 shows the schematic of a typical single-duct air-side AHU (Li et al. 2010). In current practice, the air-side economizers control the AHU dampers to allow 100% outdoor air when it cool but not extremely cold to reduce or eliminate the need for mechanical cooling. When it is hot or humid outside, the dampers are controlled to provide minimum amount of outdoor air to satisfy the requirement for ventilation.

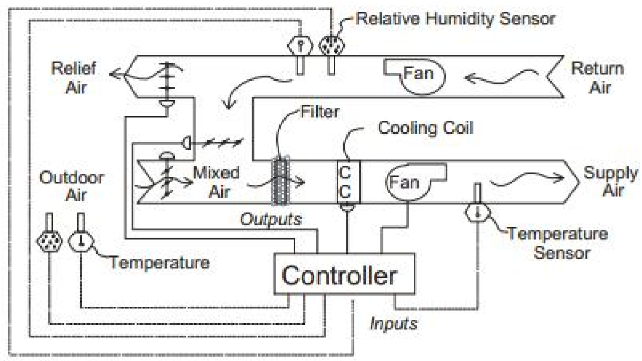


Figure 1: Single-duct of air-handling unit

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) specifies requirements for the use of economizers based on the cooling capacity of an individual air handling unit (AHU) and weather characteristics of the building location (ASHRAE, 2004). The existing control strategies described by ASHRAE are:

- ***Fixed dry-bulb temperature control*** compares the outdoor air temperature with a transition temperature. If the outdoor air temperature is greater than the transition temperature, the dampers are controlled for minimum outdoor air.
- ***Differential dry-bulb temperature control*** compares the outdoor air temperature with return air temperature. If the outdoor air temperature is greater than return air temperature, the dampers are controlled for minimum outdoor air.
- ***Fixed enthalpy control*** compares the outdoor air enthalpy with a transition enthalpy. If the outdoor air enthalpy is greater than the transition enthalpy, the dampers are controlled for minimum outdoor air.
- ***Differential enthalpy control*** compares the outdoor air enthalpy with return air enthalpy. If the outdoor air enthalpy is greater than return air enthalpy, the dampers are controlled for minimum outdoor air.

However, temperature and relative humidity (RH) sensors have a crucial impact on the energy savings for existing economizers. The economizers may do not operate as expected and even waste more energy than before installation due to the wrong decision by on-off controllers because of the sensor errors. The National Building Controls Information Program (NBCIP) performed long term performance tests on 20 RH sensors for six manufactures (NBCIP, 2004). Nine of them failed during the tests, and the remaining had many measurements outside the specifications with largest mean error of 10%RH, and largest standard deviation error of 10.2%.

Modeling of air-handling units has been well investigated to improve the performance of the economizers in the past. Zajic (2011) proposed a Hammertein-bilinear model for subsequent control optimization of the system. A model based on step response was presented by Brath et al. (1998) for modeling and control of the inlet temperature of an air handling unit. A neural network assisted cascade control system was proposed for temperature control of an AHU by Guo et al. (2007). Seem and House (2010) described a cooling coil model based on which different control regions on the psychrometric chart as shown in Fig. 2 are investigated. The regions indicate the outdoor air fraction that will produce minimum mechanical cooling load at a given outdoor air and return air condition. Three major regions are: A (red) minimum outdoor air; B (purple) 100% outdoor air; C (gradient) fraction between minimum and 100%. The outcome indicates that for some certain indoor/outdoor air conditions, there exists a convex map between damper position and energy consumption of an air handling unit (AHU). Two model based control strategies were then described to investigate the energy performance in comparison with traditional economizer control strategies. These model-based control strategies achieved modest energy savings over traditional strategies for perfect sensors. However they still suffered when sensor errors were introduced. It is thus great beneficial to develop sensor-free controls for air-side economizer in the view of energy saving.

Different from model predictive control and other nonlinear control techniques dealing with the problem of stabilization of a system with a known reference, the extremum seeking control (ESC) deals with the on-line optimization problem of finding an optimum input to maintain the output at extremum has drawn significant attention in recent years (Krstić, 2000; Rotea, 2000; Ghaffari, 2012). Its applications to HVAC systems have been widely studied by HVAC research community recently (Li, 2013; Li, 2010; Burns, 2012; Mu, 2013, Mu, 2014). The convex characteristic from outdoor air fraction to energy consumption for optimizing of an AHU was investigated by Li et al. (2010). An ESC controller was applied to a model-based air-side economizer where the chilled water flow rate of the cooling coil (equivalently the energy consumption) is minimized by automatically discovering an optimal damper opening. The approach does not depend on the use of temperature and RH sensors and accurate model of the air-side economizer and thus provides a reliable way for economizer optimization.

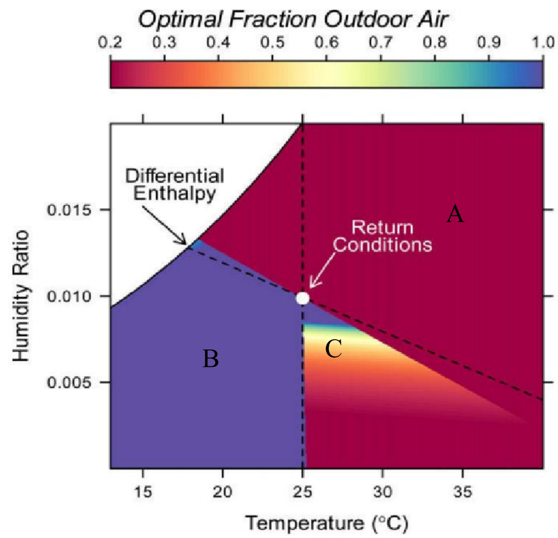


Figure 2: Optimal outdoor air fraction obtained with optimization-based control for a bypass factor of 0.1, and return air conditions of 25ºC and 50% RH (Seem et al. 2010)

This paper presents an ongoing experimental study on the ESC scheme proposed by Li et al. (2010). The algorithm was first realized on the self-built air-side economizer operated by using a direct-expansion unit with variable-speed compressor operation. An adiabatic test chamber is built with internal heat gain and moisture gain emulated. The ESC controller takes the total power of the AC unit as feedback signal and drives the dampers to the position that minimize the cooling load of the system. Later, the algorithm was implemented on an air-handling unit of a chilled-water system for commercial buildings at Energy Resource Station of Iowa Energy center. The ESC takes chilled water position as feedback signal to track the optimal damper positions. The rest of the paper is organized as follows: a general overview of extremum seeking control is presented in Section 2. Section 3 describes the experimental setup of the air-side economizer for a direct-expansion air conditioning unit. The extremum seeking control is then employed for two experiments under tested outdoor air and return air conditions. The experimental study of proposed algorithm for an AHU at Energy Resource Station of Iowa Energy Center is also presented in this section. The experiments results are discussed accordingly. The concluding remarks are given in Section 4.

2. OVERVIEW OF ESC

As a major class of self-optimizing control strategies, ESC has drawn significant attention in recent years. It has demonstrated ability to automatically tune inputs that optimize a convex performance map of a system without requiring *a priori* knowledge of a model of a system, which distinguishes it from other nonlinear control techniques such as feedback linearization or model based predictive control. The objective of extremum seeking control (ESC) is to search for an extremum of the system by automatically tracking an optimal input (Krstić, 2000; Rotea, 2000; Ghaffari et al., 2012, Mu et al., 2013).The underlying on-line optimization problem of finding the optimum input for the unknown performance function can be denoted as:

$$u_{opt}(t) = \arg\min f(u,t) \tag{1}$$

where u is the vector of control inputs, and $f(\cdot): R^n \times R^1 \to R^1$ is the objective function. In this study, the nonlinear system with input-output performance function $y = f(u,t)$ is assumed to have a convex characteristic with a unique global minimum. In the context of energy efficiency, the associated ESC problem aims to find the minimum of the objective function. As shown in Fig. 3, the ESC algorithm composing a scalar high-pass filter, multiplied by a vector-valued signal $M(t) \in R^n$, a multivariable low-pass filter, a bank of integrators, a dynamic compensator *K*, and the addition of the vector-valued dither signal $S(t) \in R^n$.

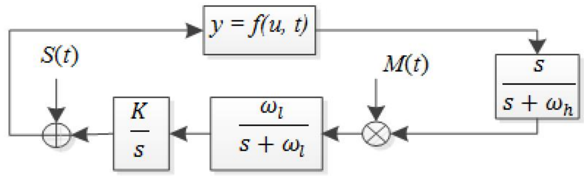


Figure 3: Schematic of Extremum Seeking Control

The mechanism of the single-input ESC is interpreted as follows. Suppose the objective function f is time-invariant and continuous so that u_{opt} is independent of time *t*. The input *u* consists of a slow signal and a sinusoidal dither signal $S(t) = a\sin(\omega t)$ with amplitude *a* and angular frequency , that is:

$$u = u_0 + a\sin(\omega t) \tag{2}$$

The corresponding output is

$$y = f(u_0 + a\sin(\omega t)) \tag{3}$$

Eq. (3) can be approximated by the first terms of Taylor expansion around a given value :

$$\begin{aligned} y &= f(u_0) + \frac{df(u_0)}{du_0} a\sin(\omega t) + \frac{1}{2}\frac{d^2 f(u_0)}{du_0^2} a^2 \sin^2(\omega t) + \cdots \\ &\approx f(u_0) + \frac{df(u_0)}{du_0} a\sin(\omega t) + \frac{1}{4}\frac{d^2 f(u_0)}{du_0^2} a^2 - \frac{1}{4}\frac{d^2 f(u_0)}{du_0^2} a^2 \cos(2\omega t) \end{aligned} \tag{4}$$

If the cut-off frequency of the high-pass filter is carefully selected as , the filtered output would contain the component of the gradient:

$$y_h = \frac{df(u_0)}{du_0} a\sin(\omega t) - \frac{1}{4}\frac{d^2 f(u_0)}{du_0^2} a^2 \cos(2\omega t) \tag{5}$$

Multiplying filtered output by demodulating signal one can obtain:

$$\begin{aligned} y_h \cdot M(t) &= [\frac{df(u_0)}{du_0} a\sin(\omega t) - \frac{1}{4}\frac{d^2 f(u_0)}{du_0^2} a^2 \cos(2\omega t)]\frac{2}{a}\sin(\omega t) \\ &= \frac{df(u_0)}{du_0} - \frac{df(u_0)}{du_0}\cos(2\omega t) - \frac{a}{2}\frac{d^2 f(u_0)}{du_0^2}\sin(3\omega t) + \frac{a}{2}\frac{d^2 f(u_0)}{du_0^2}\sin(\omega t) \end{aligned} \tag{6}$$

If the cut-off frequency of the low-pass filter is carefully selected as , the filtered output would be an unbiased estimator of gradient:

$$g = \left.\frac{df(u)}{du}\right|_{u=u_0} \tag{7}$$

By closing the control loop after integrating the gradient signal, asymptotic stability of the closed loop system will make the gradient vanish, i.e., achieving the optimality.

Actuator saturation should be always considered for air-side economizer optimization. The actuator saturation might happen when the outdoor air is too cool or hot. For instance, when the outdoor air is around 53°F, the outdoor air damper would be positioned as fully open to bring 100% outdoor air to the AHU. When the outdoor air is warmer than 100°F, the dampers are forced to a minimum opening to allow minimum amount of outdoor for indoor ventilation requirement (ASHRAE, 2001). In other words, the optimal amount of outdoor air is not inside the saturation limit, but rather at either limit point. Since the ESC algorithm can be deemed as a linear system by regulating the gradient with a PI controller at a larger time scale (Rotea, 2000), the integrator windup is unavoidable when the saturation is happened during ESC operation. In this study, the back-calculation based anti-windup ESC was adopted from (Li, 2010) to avoid actuator saturation for air-side economizer operation as depicted in Fig. 4. The proposed anti-windup ESC algorithm employs the back-calculation method, where the difference between the input and output of the saturator is fed back to the input end of the integrator through a gain factor.

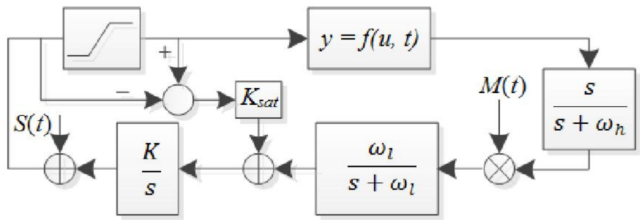


Figure 4: Anti-windup ESC

3. EXPERIMENTAL STUDY

In order to validate the anti-windup ESC for operation of an air-side economizer, two sets of experimental studies have been conducted. One study utilizes an air-side economizer built with a direct expansion air conditioning system. The other study is conducted on the air-handling unit facility at Energy Resource Station of Iowa Energy Center, which is essentially a chilled-water based system.

3.1 Testing with Direct Expansion Air-side Economizer

In order to validate the anti-windup ESC for operation of an air-side economizer, a variable speed air conditioner unit (Lennox, XC25) is instrumented. The indoor air handler unit with self-built air-side economizer as shown in Fig. 5 (a) is installed to an adiabatic test chamber (16' • 8' • 8' . Four Electrical heaters (Lasko, 751320, with rated power 1500 W), are used for the heating load, and humidifiers (Honeywell, HCM-890) and dehumidifiers (Soleus Air, SG-DEH-70EIP-6) are used to regulate the indoor air humidity. Data acquiring system (National Instruments, NI CompactRIO-9024) is configured to record temperature, RH and other measurements. The electric power consumption of the total system is measured at the AC unit connection to the external power supply using an electric power meter (Watt Node Pulse, WNB-3D-240-P). Temperature sensors (Omega, P-L-1/10-1/8-6-0-T-3) and RH sensors (Veris Industries, HN3XVSX) are installed to monitor the change of indoor and outdoor air conditions. The fan speed sensors (Omega, HHT13) and the motor current sensors (Fluke, 80i-110s) are installed to monitor the change of indoor/outdoor blower speed and compressor speed, respectively. The readers should note that the ESC controller does not need these measurements. Fig. 5 (b) shows an overview of the system.

(a) air-side economizer configuration **(b)** distant view of the setup

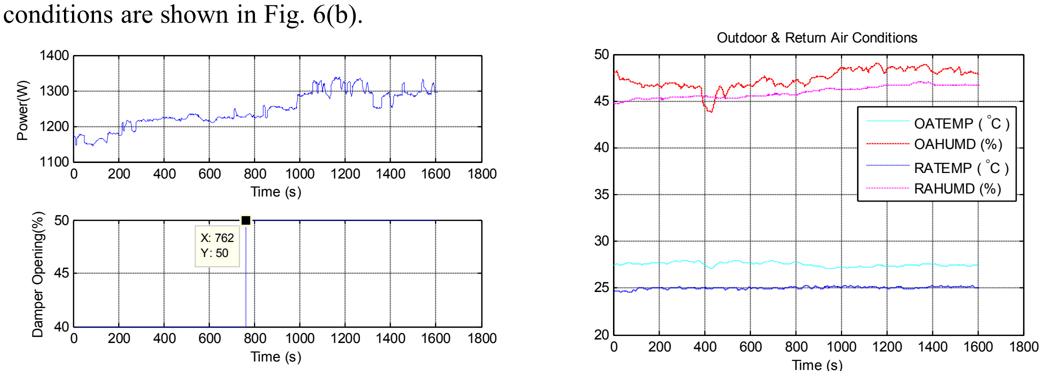
Figure 5: Experimental setup for air-side economizer

The anti-windup ESC algorithm described in Section 3 is then implemented for the test. As the ESC is to search for the optimum performance index (i.e. steady-state extreumum) at a 'slow' time scale, an easy way to determine the choice of dither signal S(t) follows (Li, 2010; Mu, 2014):

1) Choose dither frequency well within the corresponding plant bandwidth, while also avoiding possible peak in the spectrum of measurement noise.

2) Dither amplitude large enough to overcome the estimated noise effect and small enough to reduce the steady-state oscillation.
3) It is better to choose dither phase angle to compensate for the delay due to the input and output dynamics and the high-pass filter.

A step test is applied to determine the dynamic of the Lennox AC unit from damper position to total electricity power consumption under outdoor conditions around 27.5°C and 48% RH and return air conditions of 25°C and 27.5% RH. The step change was applied at 762 sec with amplitude change of 10% for outdoor air damper opening. The result is shown in Fig. 6 (a). It reveals that the settling time for AC unit power consumption is about 340 sec. A dither signal with amplitude of 10% and frequency of 0.001Hz is then selected. The variations of the outdoor air and return air conditions are shown in Fig. 6(b).

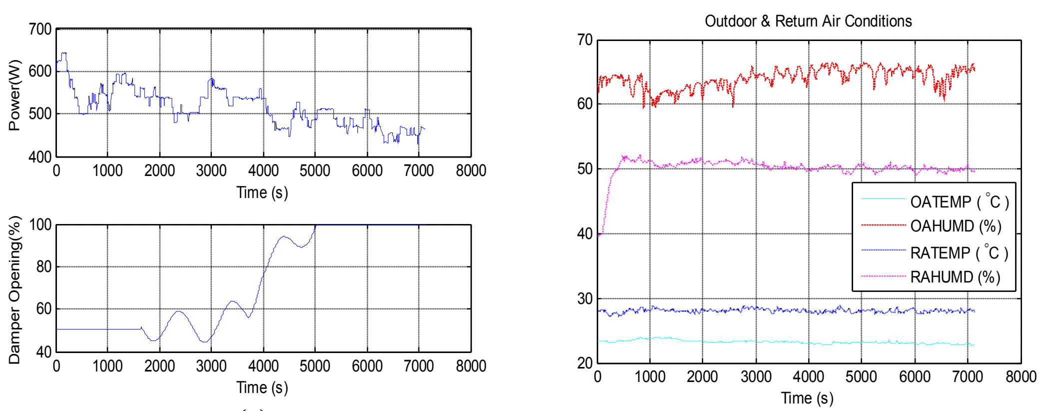


(a) **(b)**

Figure 6: (a) Step test from damper opening to power consumption **(b)** outdoor air conditions and return air conditions

Two experiments are then performed to investigate the performance of proposed ESC controller under different outdoor air and return air conditions. Initially, a 6,000 W heat load is applied to the test chamber. The room temperature and relative humidity are allowed to be maintained at pre-specified setpoints by the controls of Lennox AC unit and humidifiers and dehumidifiers. After that, the ESC controller was turned on to test its performance of energy saving.

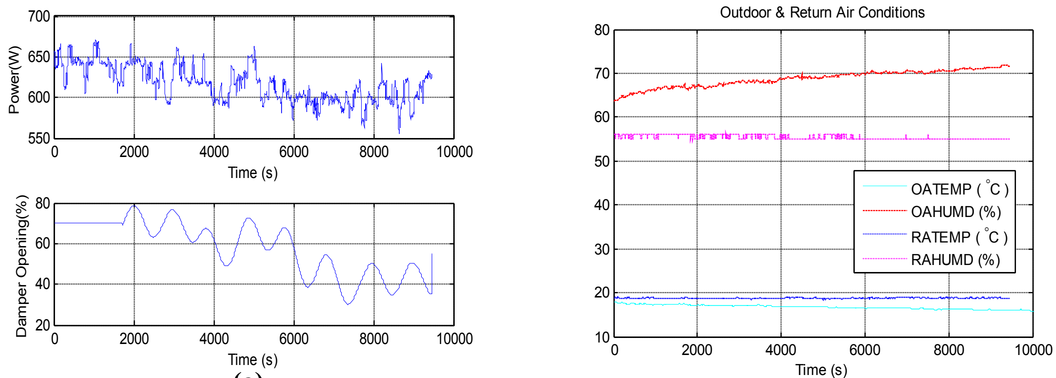
In experiment **#1**, the room temperature setpoint is 80°F (26.7°C) and the ESC controller is turned on at 1594 sec with initial outdoor air damper opening of 50%. As shown in Fig. 7 (a), the outdoor air damper was automatically turned on to allow maximum outdoor air with outdoor air conditions of 23.2°C and RH 64% and return air conditions of 28°C and RH 50% as shown in Fig 7(b). The electric power consumption of the AC unit was reduced from 540 W to 450 W with an energy efficiency increase of 16.67%.



(a) **(b)**

Figure 7: Experiment # **1: (a)** Profiles of power and damper opening **(b)** Profiles of outdoor air conditions and return air conditions

In experiment **#2**, the room temperature setpoint is 65°F (18.3°C) and the ESC controller is turned on at 1712 sec with initial outdoor air damper opening of 70%. As shown in Fig. 8 (a), the outdoor air damper was automatically moved to 42% to allow partial amount of outdoor air to be introduced to the test chamber. During the experiment, the outdoor air conditions are 18°C-15.8°C and 65%-71% RH and the return air conditions are around 18.7°C and 54%-58% RH, as shown in Fig 8(b). The power consumption of the AC unit was reduced from 640 W to 610 W with an energy efficiency increase of 4.69%.



(a) **(b)**

Figure 8: Experiment # **2: (a)** Profiles of power and damper opening **(b)** Profiles of outdoor and return air conditions

3.2 Testing with Chilled-water Based AHU

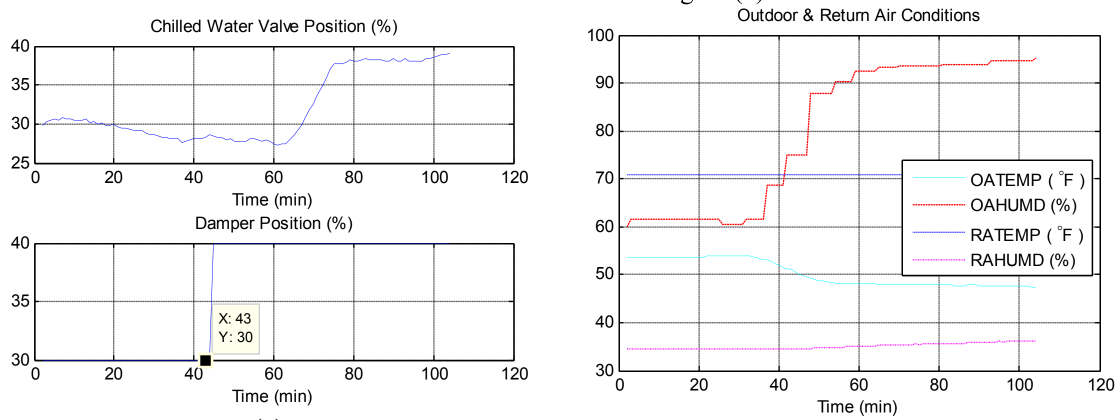
The proposed ESC algorithm was later implemented on an air-handling unit of a chilled-water system for commercial buildings at Energy Resource Station of Iowa Energy center. The air-handling unit and chiller are shown on Fig 9(a), 9(b), respectively. The Iowa Energy Center building is equipped with two identical air-handling units (A & B), each with its own dedicated and identical chiller. One air-handling unit serves four test rooms designated as A rooms for AHU-A, and B rooms for AHU-B. Each of the test rooms is a mirror image of its match with identical construction. In this experimental study, the performance of anti-windup ESC controller was tested on AHU-B and B rooms (Iowa Energy Center, 2010).

(a) **(b)**

Figure 9: (a) Overview of air-handling unit **(b)** Overview of air-cooled liquid chiller

The standard Energy Resource Station (ERS) instrumentation is used for the test. The outdoor and return air conditions are measured with the Vaisala combination temperature and relative humidity sensor having a rated accuracy of ±1.7 %RH. The outdoor air conditions are measured in the outdoor air duct. The ESC controller implemented in Matlab is interfaced to the Metasys building automation system so that the controller takes chilled water valve position as feedback signal and drives the dampers to the position that minimize the cooling load of the system (equivalently decrease the amount of required chilled water). During the test, the supply fan speed is modulated to maintain duct static pressure at setpoint 1.4 in. W.G. by a PI controller. The return air fan speed is maintained about 90% of supply fan speed.

A step test is applied to determine the dynamic of the system from damper position to chilled water valve position with supply air temperature setpoint of 55°F, chilled water temperature setpoint of 44°F, respectively. The step change was applied at 44 min with amplitude change of 10% for outdoor air damper opening. The result is shown in Fig. 10 (a). It reveals that the delay of the step response is about 20 min, and the settling time for chilled water valve opening is about 15 min. A dither signal with amplitude of 10% and frequency of 0.001Hz is then selected. The variations of the outdoor air and return air conditions are shown in Fig. 10(b).

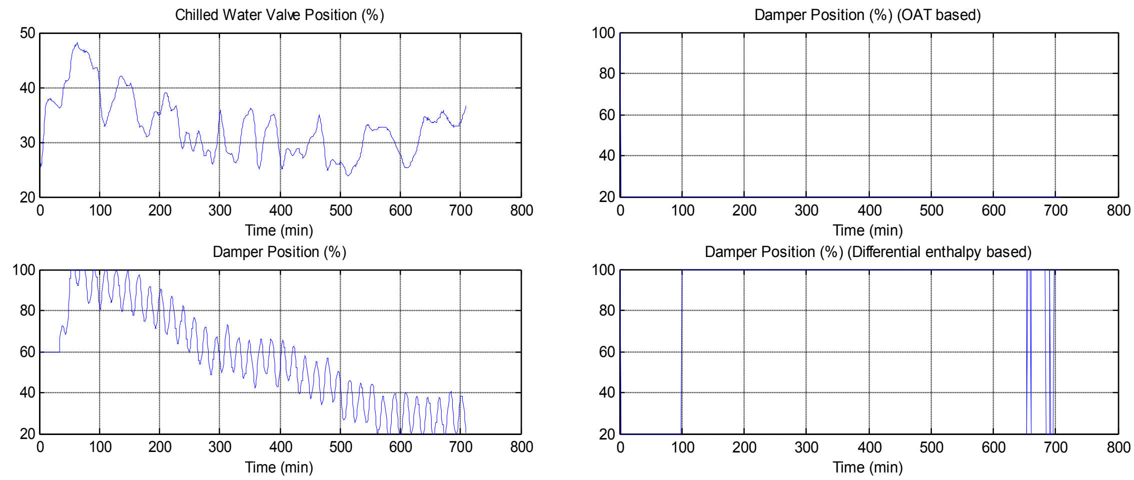


(a) **(b)**

Figure 10: (a) Step test from damper opening to Chilled water valve position **(b)** outdoor air conditions and return air conditions

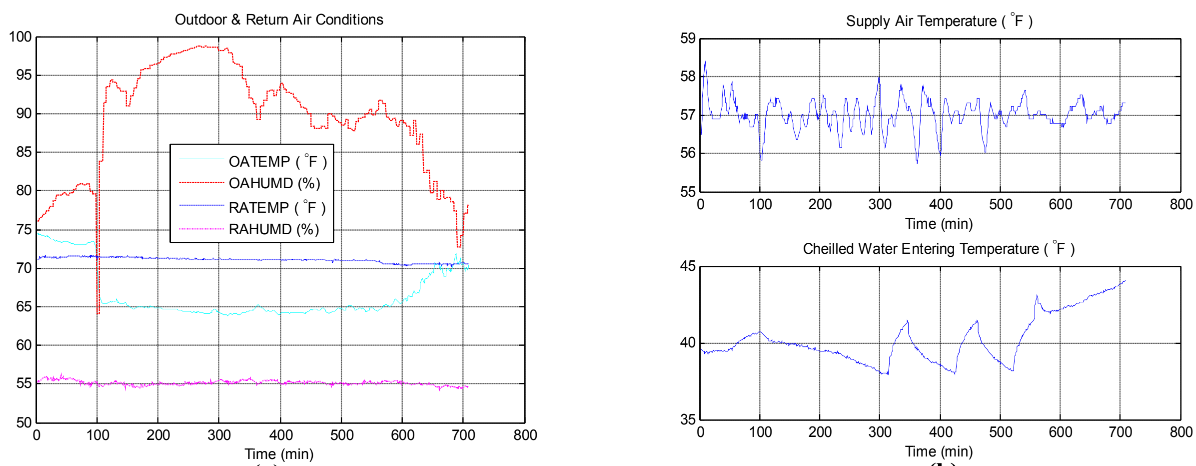
One experiment is then performed to investigate the performance of proposed ESC controller under different outdoor air and return air conditions while the setpoint temperatures for supply air temperature control and chilled water temperature control are 57°F and 40°F, respectively. The heating load for each test room is 900W, and room temperature setpoint is 68°F. Initially, the damper opening is fixed at 60% for 43 min, after that the ESC controller is turned on. As shown in Fig. 11(a), the outdoor air damper first moves up to 100% where the saturation occurs. After that the damper moves away from 100% and reaches the minimum of 20% around 600 min, and then maintains around 30%. The corresponding chilled water valve position is reduced from 40% to 30% with an energy efficiency increase of 25%.

Fig. 11 (a) shows the decisions made by traditional fixed dry-bulb control and differential enthalpy control obtained from post-test data analysis. With transition temperature setpoint at 60°F, the fixed dry-bulb temperature control is supposed to allow the minimum damper opening all the time while the differential enthalpy control should main the damper opening at 100% from 100 min to 656 min and switch between 100% and 20% between 656 min and 700 min. Fig. 12 (a) shows the corresponding outdoor air and return air conditions. Fig. 12 (b) shows the corresponding supply air temperature and chilled water temperature during the test.



(a) **(b)**

Figure 11: (a) Profiles of Chilled water valve position and damper opening **(b)** Decisions made by dry bulb temperature and differential enthalpy methods



(a) **(b)**

Figure 12: (a) outdoor air conditions and return air conditions **(b)** Profiles of supply air temperature and chilled water temperature

4. CONCLUSIONS

This study presents the initial experimental results for applying the ESC based controller for optimizing the real-time operational efficiency of an air-side economizer. The AHU test is first built upon a direct-expansion air conditioning unit. The ESC controller takes the electricity power consumption of the AC as feedback signal, and automatically discovers the outdoor air damper opening to minimize the power consumption of the system. The performance of the ESC algorithm is validated with two experiments under tested outdoor-air and return-air conditions with energy efficiency increase of 16.67% and 4.69%, respectively. The AHU test is then performed on a chilled-water based commercial HVAC system at Iowa Energy Center. The ESC controller takes the chilled water valve position as feedback signal to drive damper position to minimize the cooling load of the system. The ESC algorithm performance is validated with one experiment under tested outdoor-air and return-air conditions with energy efficiency increase of 25%.

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