CONSORTIUM for BUILDING ENERGY INNOVATION

FINDINGS

The Consortium for Building Energy Innovation

CBEI is focused on generating impact in the small and medium-sized commercial buildings (SMSCB) retrofit market. CBEI is comprised of 14 organizations including major research universities, global industrial firms, and national laboratories from across the United States who collaborate to develop and demonstrate solutions for 50% energy reduction in existing buildings by 2030. The CBEI FINDINGS series highlights important and actionable technical, application, operation and policy research results that will accelerate energy efficiency retrofits when applied by various market participants. CBEI views these FINDINGS as a portal for stakeholders to access resources and/or expertise to implement change.

Automated Fault Detection and Diagnostics (AFDD)

Field data reveals the same story for small and medium sized commercial HVAC systems under today's operation and maintenance regimes, which is that approximately two thirds of all systems are operating at reduced performance levels. There is a rich amount of literature that documents air handling unit (AHU) fault energy impacts. It is estimated that 15 to 30 % of energy is wasted in commercial buildings due to various HVAC equipment and control faults[1].

The performance of AHU systems significantly affects a building's energy consumption and indoor air quality. Over the years, many types of AHU automated fault detection and diagnostic (AFDD) methods have been reported in the literature. Due to unique AHU AFDD challenges, such as the variety of AHU systems and control strategies, dynamic operating modes of AHU systems, poor measurement quality, and cost of implementation, a novel approach was needed to develop robust, plug-and-play, and low cost AHU AFDD methods.

The extent to which AFDD methods overcome the key difficulties outlined above, with an implementation cost acceptable for more than just one specific building, is essential. Furthermore, maintenance of high accuracy and low incidence of false alarms as buildings shift through different modes of operation must be proven.

Research Finding: Automated Fault Detection and Diagnostics in AHUs

Pattern Matching PCA[2]-based fault detection method developed by CBEI consistently detected faults at a detection rate of 94% with no false alarms.

This AFDD Methodology is a low cost minimal touch method of detecting and diagnosing AHU faults because:

- Of its passive detection strategy
- No requirement for fault data
- No modeling requirements
- Automated threshold generation
- No requirement for additional sensors beyond what is installed

Energy impacts of various faults can vary greatly depending on temperatures, loads, and operational conditions. Only via a pattern-matching framework is it possible to identify a suitable baseline for calculation of the energy impact.

This AFDD methodology offers service providers the ability to quantify customer value for FDD in existing buildings and therefore generate a value proposition that can pay for the small incremental software approach and generate customer savings to make the transaction work.

Successful uptake of this new AFDD tool has the potential to improve HVAC performance in commercial buildings.

[1] Katipamula, S. and M.R. Brambley, 2005a,b. Methods for fault detection, diagnostics, and prognostics for building systems, Part I and II, HVAC&R Research Journal, Jan, April.

[2] Principal component analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components.

AFDD methods for AHU Variable Air Volume (VAV) systems

Over the past couple of decades, significant research efforts have been undertaken to address the need for reliable AFDD methods for AHU-VAV systems. The research can be grouped into three broad categories of approaches: physical modeling methods, rule-based methods, and data-driven methods. Physical modeling methods have proven to be too expensive for small and medium sized buildings.

The National Institute of Standards and Technology (NIST) generated a useful set of AHU performance assessment rules that were demonstrated to be effective at detecting and diagnosing faults when the proper fault thresholds were identified for specific applications. The rules are typically based on a priori knowledge of the system dynamics, and these variable interactions can be studied to infer values for variables that are difficult to measure, like flow through a valve, or variables that are known to be unreliable, like air flow rates. The key to simplifying the modeling required with these methods is the use of a 'genetic' algorithm-based optimization method that reduces the residual between the actual and predicted values to continuously refine the model as the system operates.

Rule-based methods are a straightforward method for detecting and diagnosing faults, but it can be difficult to select fault detection thresholds that maintain fault detection accuracy without generating excessive false alarms. This difficulty is due to the uniqueness of different system installations, the transient and multi-model nature of the systems, and the noise in the sensor measurements. As a result, many of the rule-based methods can require a significant engineering effort for each installation. In an effort to overcome this obstacle many studies have utilized various statistical process control (SPC) data-based methods for AHU-VAV AFDD applications.

Pattern Matching PCA-based Method (PM-PCA)

One of the simplest and most commonly employed SPC methods is the use of principal component analysis (PCA). PCA-based methods have been successfully employed for fault detection in many other industries. In general, the PCA-based methods demonstrate promising results, but may suffer from high false alarm rates and many of the methods proposed incorporated sensors that are not typically available in the majority of AHU installations. The use of a pattern-matching algorithm for the selection of training data for the PCA models (only selecting training data from similar operating conditions) eliminates the effects of external load fluctuations and transient system operation which are automatically eliminated from the fault detection algorithm.

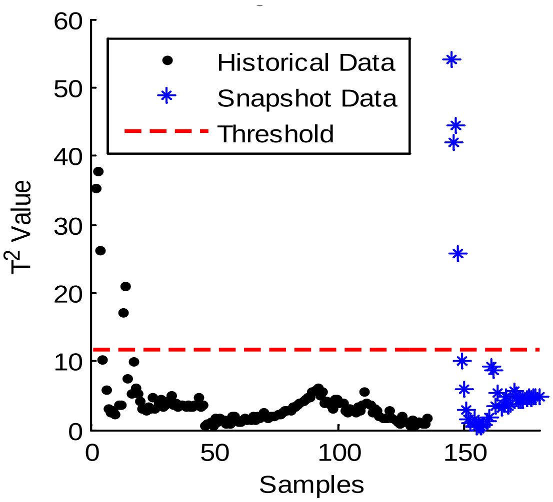
This new approach uses pattern matching techniques to:

- Identify historical data under similar operational conditions (same mode of operation under similar internal and external loads)
- Generate a PCA model using the historical data identified above
- Apply this PCA model to the current "test" data
- Determine whether the test data is operating in a normal or faulty condition (Q-residual)

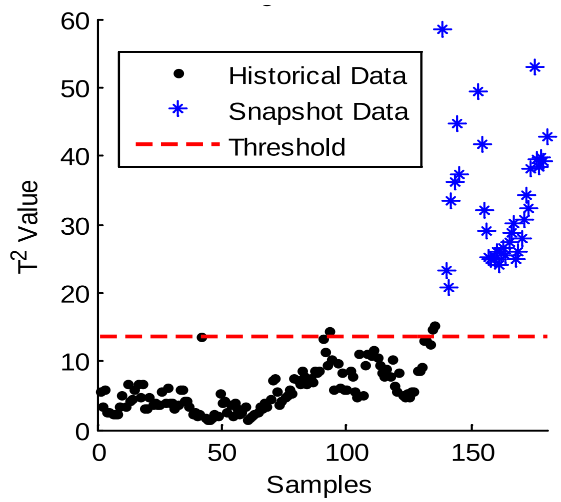
CBEI Cost-Effective Fault Diagnostic Solutions for AHU-VAV & AHU-CAV Systems

Faults are detected when a "window" of time is 90% faulty or more (see graphs below). Using ASHRAE 1312[3] data, faults (that had measurable symptoms) consistently detected, and an overall detection rate of 94% was achieved with no false alarms.

Fault Free Time Window

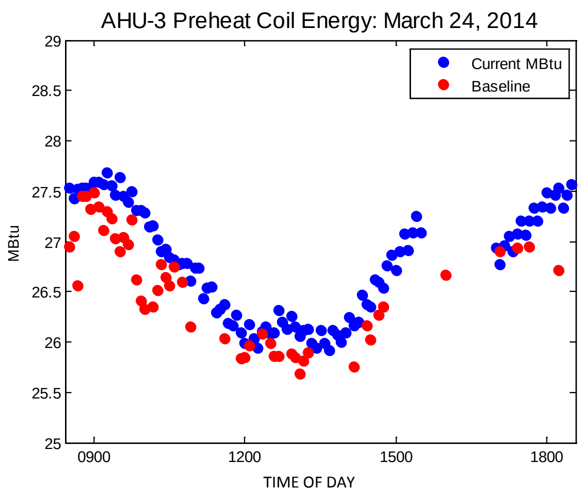


Faulty Time Window

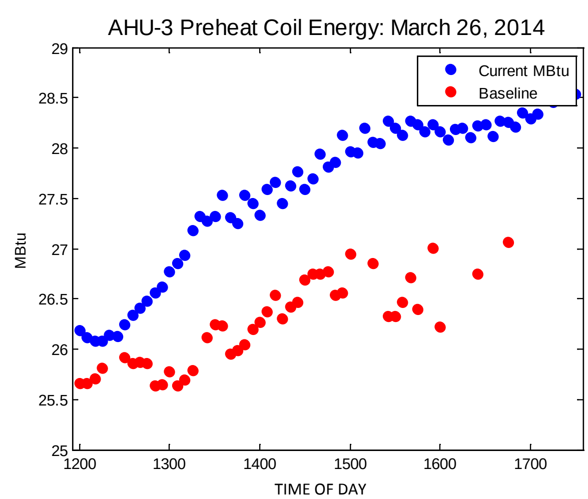


The pattern matching algorithms used for fault detection identifies historical periods of time with similar operating conditions. The same algorithms can also be used to identify "baseline" energy consumption for a given set of operating conditions, and compute the energy impact of faults.

Fault Free Operation



Preheat Valve Stuck at 10% Open



[3] American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) "Tools for evaluating fault detection and diagnostic methods for air-handling units." This provides researchers with reliable dynamic performance data under fault-free and faulty operation for a number of different types of faults and for a range of severity levels in order to evaluate AFDD methods for AHU systems.

Lessons Learned AFDD

AHUs serve 18% of the total commercial building floor area[4] and consume 20-30% of primary energy[5].

AHUs serve 14-19% of small and medium sized commercial building's (SMSCB's) floor area[5]. AHUs consume similar energy consumption in SMSCBs as in the overall commercial building sector.

It is estimated that 15-30 % of energy is wasted in commercial buildings due to various HVAC equipment and control faults[6].

CBEI data confirms the literature results that the most important AHU VAV faults that cause energy loss are:

- clogged air filters,
- fouling on coil fins and tubes,
- abnormal outside air (OA) damper opening, and
- improper static pressure sensor location.

CBEI performed AHU fault energy impact analysis using ASHRAE 1312[7] data (small commercial building) and a portion of Building 1018[7] (medium-sized commercial building). The conclusions are similar to those reported in other studies, i.e., the fault energy impacts vary with the type of faults and seasons and their impact varies from 10% up to 100% of an AHU's energy consumption

[4] DOE 2011 Databook Table 5.5.2
[5] DOE 2011 Databook Tables 5.3.11 and 5.3.12
[6] http://www.eia.gov/consumption/commercial/data/2003/
[7] ASHRAE research project (ASHRAE RP 1312, Wen and Li, 2011)
[8] Building 101 is located at the Philadelphia Navy Yard

Moving Forward

CBEI methods can be applied both as an embedded solution (it does not require high computational capacity) and can reside in a typical AHU controller, as well as, an offline and/or cloud-based solution.

The initial market pathway focuses on working with smaller and cloud-based service providers to introduce this new approach. Service providers are seen as having the ability to quantify customer value for FDD in existing buildings and therefore generate a value proposition that can pay for the small incremental software approach and generate customer savings to make the transaction work.

Once market acceptance is established, then the larger control companies may be more willing to engage.

Two companies (one focusing on cloud-based diagnosis solutions and the other focusing on retro-commissioning and continuous commissioning) are currently working with CBEI to deliver to the market CBEI's Volttron Compatible and Cost-Effective Fault Diagnostic Solutions for AHU-VAV & AHU-CAV Systems.

Note that Volttron is an agent execution platform engineered for use in the electric power system to support building software agents to perform both information sensing and control actions. Devices deployed in the electric power system have to meet very strict requirements for availability, reliability, and security which impose requirements for agent execution platforms.

Volttron is an agent execution platform that is engineered for use in the electric power system. Volttron provides resource guarantees for agents and the platform including memory and processor utilization; authentication and authorization services; directory services for agent and resource location; and agent mobility.

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