Cloud Computing Software to Simplify HVAC Operational Performance Analysis

Bernt A. Askildsen* and Charles Tolle†
South Dakota School of Mines and Technology, Rapid City, SD 57702 USA

Lance Weaver‡
Lloyds Systems LLC, Rapid City, SD 57702 USA

Abstract

Current commissioning and retro-commissioning procedures for Heating, Ventilation and Air-Conditioning (HVAC) systems are limited by existing measurement techniques and allow most systems to operate at a much lower level of efficiency than their intended design. The consequences are waste of building energy, poor indoor air quality (IAQ) and increased operating costs. Current operations measure airflow by use of Pitot tubes, hotwire anemometer or tracer-gas but these methods are often inaccurate or cost prohibitive. A newly developed measurement technique known as Time-Stepped Enthalpy (TSE) measures actual airflow volume [1], heat transfer, and other system performance parameters. It has been coupled with a very easy-to-use and scalable cloud software (SW) application.

Key Words: HVAC, retro-commissioning, commissioning, energy audit, cloud computing.

1 Introduction

The average yearly energy consumption in U.S. commercial buildings is almost $51 billion dollars, thus the return on investment for even small fractions of introduced energy efficiency is in the billions of dollars [2-21]. It is a usual practice for HVAC engineering contractors to install systems constructed of modules from various manufactures. The control system, often purchased from yet another manufacturer, links all the components together without first verifying that the system is operating at optimal efficiency before the control parameters are set. Figure 1 illustrates a typical pull-through HVAC system for warm climates where the fan pulls air from the building space as return air (R/A) and a portion becomes exhaust air (E/A) to meet the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 62.1-2007 ventilation requirements. Fresh outside air (O/A) is pulled in to replace the E/A volume and will mix with the remaining R/A. The mixture of R/A and O/A has various air velocities and temperature profiles while being pulled through the filter bank by the fan. Some systems do not have E/A as it is desired to keep the air conditioned zone under positive pressure to prevent infiltration of air. The fan then pushes the airflow to be heated or cooled (determined by the thermostat setting and/or ASHRAE 55-2004) before it propagates into the ductwork as supply air (S/A). The S/A flow is delivered to the various rooms by interconnected ductwork and associated diffusers. The filtered and conditioned flow provides humidity adjusted thermal comfort to support healthy and productive environments for the building occupants.

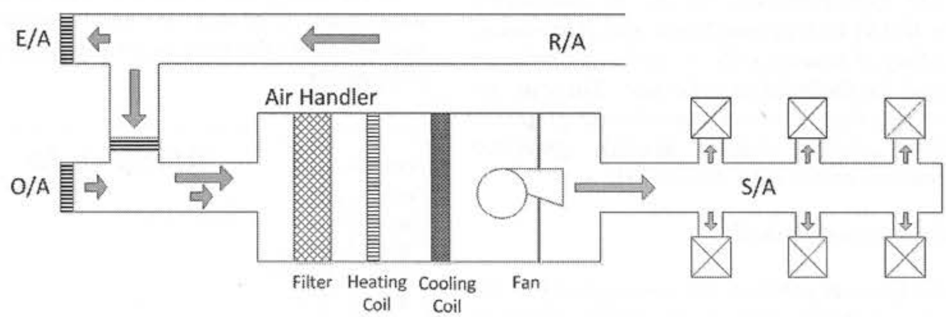

Figure 1: A typical pull through HVAC system

* MSEE, MSTM, PHD Candidate, Biomedical Engineering Department. E-mail: baskild@hotmail.com.
† Electrical and Computer Engineering Department. E-mail: charles.tolle@sdsmt.edu.
‡ BSME, Email: lance@lloydssystems.com.

The design cycle of a high-performance automobile relies on modeling, design analysis, module implementation and system integration. At each successive step in the process the design is subjected to rigorous performance testing. The final product is then fine-tuned to meet design objectives. Additional re-tuning of a car takes place as the mileage accumulates and parts wear out. The segment of the HVAC industry that addresses building energy efficiency is fragmented. Two dominant provider groups have emerged: the energy audit service consultant and the contractor that takes a project from start to finish. The energy auditor holds certifications such as Professional Energy Manager (PEM), Certified Energy Manager (CEM), Carbon Reduction Manager (CRM), Certified Energy Auditor (CEA), Leadership in Energy and Environmental Design (LEED), Test and Balance Engineer (TBE) and Testing Adjusting and Balancing Bureau (TABB). Often the auditors are engineers that use ASHRAE's level 1 through 3 energy audit approaches. Contractors working the project from start to finish most often base their efforts on energy use modeling [12, 15-16] and ensure that the project is completed as planned. Independent of the building energy conservation measures (ECM) used, the underlying fundamentals only yield a promise of savings with no actual guarantees.

2 Time-Stepped Enthalpy Method

The TSE method is the first break-through for the building energy audit industry that allows for a comparison of actual system performance to intended design [1, 5-6, 8-9, 14]. Additional measurements enable a complete HVAC system diagnosis with information that may assist the building owner to bring the system performance towards the design intent. This revolutionary capability has been combined with all major elements of the dominate state-of-the-art energy programs being implemented in the industry. An additional enhancement is the implementation of the Environmental Protection Agency (EPA) Energy Star Score and green-house gas (GHG) accounting in tandem with the ability to estimate LEED credit potential for the building under test. These are all features made available through a very easy-to-use graphical user interface (GUI) coupled with an instantly generated independent third-party report [11, 13, 17-20, 23].

2.1 Time-Stepped Enthalpy Method

The TSE method (patents pending and copyrighted) is the underlying technique for this study [1, 3, 7]. TSE is based on psychrometrics and thermodynamics and utilizes various measurements to quantify the energy released into or extracted from the system (1). The energy value is then substituted into the total heat formula (2) to calculate the airflow volume. For the hydronic cooling system investigated in this study only three measurements were required to quantify the energy extracted from the buildings airflow: water fluid flow (V_{water}) and the temperatures in and out of the heat transfer device. These measurements are substituted into the water system equation (1).

$$Q_W\left(\frac{BTU}{hr}\right) = V_{water}\left(\frac{G}{\min}\right)\cdot 60\left(\frac{\min}{hr}\right)\cdot 8.33\left(\frac{lb}{G}\right)\cdot 1\left(\frac{BTU}{lb\cdot{}^{\circ}F}\right)\cdot \Delta T({}^{\circ}F) \quad (1)$$

The constants provided in the equations are derived for systems running at sea level and would be adjusted for those running at higher elevations. Nevertheless, the total heat (Q_W) is found by converting water flow in gallons per minute to gallons per hour multiplied by the weight of one standard gallon of water, the heat content constant, and the delta temperature of the water flow. The total heat in and out of the airstream (Q_A) transferred from the up-stream heat ladened airflow is equal to the Q_W transferred in the water fluid flow to satisfy the first two laws of thermodynamics. If a glycol mixture is used then the flow's heat content capacity is corrected to the specific gravity value. To find the actual airflow, the calculated value of Q_w is substituted for total heat Q_A in Equation 2. Delta enthalpy is measured by means of an enthalpy meter when the system is running at full system capacity (h_1) and then with no heat transfer present (h_2).

$$Q_A\left(\frac{BTU}{hr}\right) = V_{airflow}\left(\frac{cf}{\min}\right)\cdot 4.5\left(\frac{\min\cdot lb}{hr\cdot cf}\right)\cdot \Delta h\left(\frac{BTU}{lb}\right) \quad (2)$$

2.2 Airflow Error

The percentage error for a delta enthalpy of 1 BTU/lb, due to the inverse multivariable nature of the formula (2), translates into a 10 percent error with a variation of only 0.1 BTU/lb. From Figure 2 it can be seen that the expected accuracy with a 0.1 BTU/1b variance converges to 1 percent error when the delta enthalpy is 10 BTU/lb.

The delta enthalpy in this study was in the range of 7.23 to 9.36 BTU/lb., which made the airflow volume calculations less susceptible to large volume swings as the enthalpy variances were small. This met the intrinsic sensitivity goal of the TSE method where the error in airflow volume should converge to one percent.

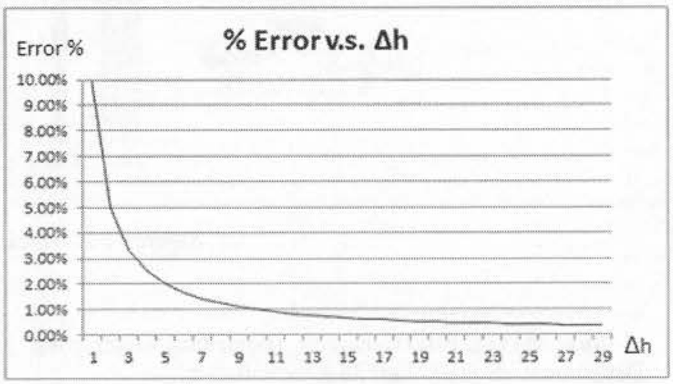

Figure 2: The airflow error percentage converges to less than one percent for a delta enthalpy above ten when experiencing a 0.1 variation over time

2.3 Wet versus Dry Cooling Coil

Static pressure (SP) measurements are used to support the diagnostic features of the TSE method. However, to properly utilize SP data for decision making it is important to account for the dynamically changing environment e.g., relative humidity and dew point. These properties change when the airstream is gradually cooled or heated and have a direct effect on SP readings. Cooling the airstream at or below its dew point makes the evaporative cooling coil accumulate precipitation as moisture is extracted from the airstream. It is for this reason that cooling coils have a drain pan and piping that drains water from the air-handler. Both types of humidity cause increased air resistance through the system due to molecular friction and decreased free area. Studies performed as part of this effort indicate that variations between wet and dry conditions range from four to seven percent. Therefore it is recommended that SP measurements be taken only when the cooling coil is dry and when the relative humidity is below 55 percent.

2.4 Repeatability Accuracy

Several repeatability studies have been performed with very good results. One study that focused on marginal enthalpy conditions in a heat-recovery system was published in an Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) conference paper [1]. The main findings were that the method accuracy converged to ±4 percent with delta enthalpy in the range from 1.0 to 1.4 BTU/lb. This is significant as enthalpy variances of 0.1 BTU/lb would alone be the cause of an inaccuracy equal to 10% for a delta enthalpy of 1.0 BTU/lb. Furthermore, the TSE method converges to an error of less than 1 percent at enthalpy variances of 0.1 BTU/lb when the delta enthalpy is ten or more. The published results show that the TSE method is repeatable when test conditions are the same.

3 Cloud Computing

Certified building energy efficiency analysts such as the Professional Energy Managers (PEM) collect voluminous amounts of data for analysis. Weeks of effort will then be presented in a report that takes a few months to publish. The information provided in these energy estimates most often falls short of anything but a promise of savings. To the contrary, the future of building energy efficiency services will require accurate assessments of actual energy savings so decisions may be made based on information rather than a best guess or an energy modeling software that comes with intrinsic assumption errors. These requirements, in tandem with accurate measurements for repeatable results, will prevail to properly assess the health of an HVAC system in a timely manner. To accomplish this monumental task that secures quality assurance and an objective instantaneous independent third party report, various SW architectures were compared using scoreboards. A cloud computing architecture, as illustrated in Figure 3, quickly emerged as a viable solution that supports all these objectives in tandem with the goal of being globally scalable.

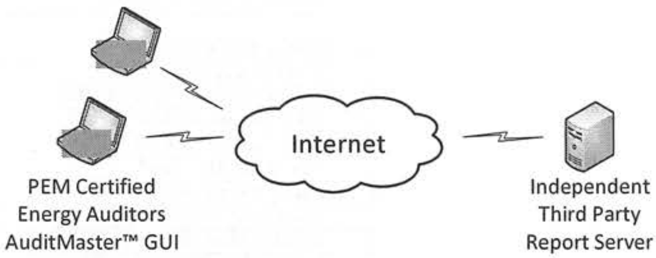

Figure 3: Cloud computing system architecture

Figure 3 shows the architecture for the system presented in this paper. A client application is running on a PEM certified energy auditor's laptop. The PEM collects data locally and then uploads it to the application server for an instantaneously generated third party report.

3.1 AuditMaster™

The client SW that runs on the PEM's laptop is reconfigured depending on the HVAC system design. The application brings the PEM through a sequence of dialogs to ensure that all pertinent system information is collected along with the required measurements. Figure 4 depicts a few select GUI dialogs of the client SW.

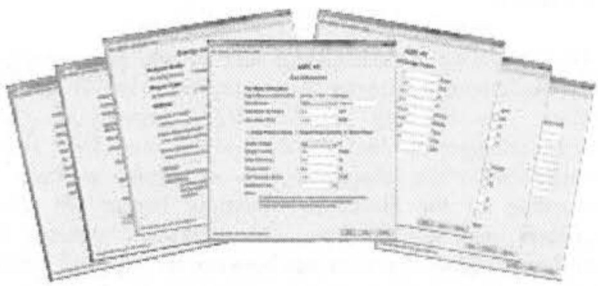

Figure 4: Select AuditMaster™ GUI pages

When pertinent data and measurements are uploaded, a computational analysis is completed within ten minutes. The generated report that is automatically e-mailed to all concerned parties lists main operational performance parameters along with the design values and actual measured results. The format is user friendly and easy to read. It supports quick reviews of actual systems performance compared to design intent. To comprehend the importance of this information it is very crucial to understand that a control system cannot compensate for lack of heat transfer, duct air leakage or other system deficiencies that may be occurring. Figure 5 depicts how results are presented in the report.

AHU 1	Design Value	Actual Value	Deviation	Perf. %
AHU 1 Airflow				
Total Fan Airflow (CFM)	20900	11637	9263	56
Compare to Design				
Total Fan Airflow (CFM)	20900	11637	9263	56
Total Outside Airflow (CFM)	2400	809	1591	34
Total Return Airflow (CFM)	18500	10828	7672	59
Duct Leakage (CFM)	0	1525	1525	86
Fan Motor HP/BHP	40	13.0	27.0	33
Thermal Performance				
Total Heat Transfer (BTU/hr)	764430	392243	372187	52
Sensible Heat Transfer (BTU/hr)	764430	287568	476862	38
Latent Heat Transfer (BTU/hr)	0	104674	104674	N/A
Upstream DB/RH (F/%)	-	77/48	-	-
Downstream DB/RH (F/%)	-	54/87	-	-
Coil (BTU/hr)	764430	392243	372187	52
Hydronic Flow (GPM)	153.0	98.1	54	65
Hydronic Delta Temp	10.0	8.0	2	80
Water Coil Carryover (FPM)	477	266	211	56
Ventilation				
Total Outside Airflow (CFM)	2400	809	1591	34
Total Return Airflow (CFM)	18500	10828	7672	59
Coil Cleaning				
Chiller Coil (BTU/hr)	764430	392243	-	7.84
Estimated EPA Energy Star Score	-	82%	-	-
Totals				

Figure 5: Intended design with actual performance

3.2 Airflow

Due to variable environment and system parameters, the most challenging parameter to measure in the HVAC system is airflow. As building pressure, VAV demand or damper position changes so does the airflow volume. Duct leakage reduces SP while clogged coils or filters increase SP. According to the Bernoulli equation, higher SP usually translates into less airflow. Most HVAC systems have nonlinear airflows that alternate between laminar and turbulent flows within a duct cross section. Furthermore, the temperature profiles vary throughout the system as O/A mixes with R/A and heat is added or removed from the airflow at the coils, fan motors and internal heat sources. All measurement techniques except for tracer gas and TSE rely on the existence of laminar flow for accurate measurements. Therefore, most airflow measurements have errors above the rated accuracy of the device. Before executing airflow measurements the system should be set to design specifications and the variable frequency drive (VFD) set to run at maximum capacity. The AuditMaster™ SW allows the user to select and enter the measurement technique preferred: TSE, Pitot tube, hotwire anemometer or tracer gas. Entered values are used to determine the system airflow that is used to calculate other parameters such as O/A volume, duct leakage, fan motor operation, sensible heat, latent heat, coil water carryover, etc.

3.3 Ventilation

Ventilation is required for buildings to keep the CO_2 at acceptable levels, to expel odors, VOC, and humidity. However, ventilation is costly as conditioned air is expelled either through natural building openings, bathroom, hall, toilet or HVAC exhaust air. For this reason many HVAC systems now have heat recovery systems installed on E/A to capture a portion of the expelled energy and reapply this to the incoming unconditioned O/A. Tracer gas is known in the industry to be the most accurate method to measure actual O/A percent. Other methods to find O/A percent use CO_2 concentrations and dry bulb temperatures of O/A, R/A, and S/A. The O/A percentage is multiplied by the measured airflow to find actual O/A airflow. The implementation supports all three alternatives to determine O/A as there is limited applicability for the methods across the board. The dry bulb method will yield fairly accurate results when the fan motor is outside the airstream and all heat transfer in and out of the system is either kept constant or turned off. Using CO_2 concentrations to calculate O/A is effective when the occupancy load is held constant or if the building is not occupied at the time of the test. Tracer gas will yield accurate results in both scenarios but is a substantially more complex, error prone and time consuming measurement to make.

3.4 Airflow Heat Transfer

The heat transfer into the airflow determines the load to the chillers or boilers, maintains thermal comfort, and assists in system diagnosis. If thermal comfort is not met or if latent heat is not properly removed, the occupants will either complain or they will change the thermostat settings and cause the system to use more energy. Many chillers run 24/7 to reduce the mean time between failure, to manage humidity, and to take advantage of the cooler air and lower electricity rates at night. Other chillers now also store overcooled glycol produced at night to further leverage the mentioned benefits. Therefore, the main advantage of bringing the system up to intended design is to allow the chiller to always run at its optimal energy efficiency point, let VFDs work optimally by ramping down pumps and fan motors quickly and more frequently, allow the system to always provide proper thermal comfort and prevent any IAQ issues. For chillers that cycle on and off both the duty cycle and runtime at optimal energy efficiency will substantially reduce the energy usage.

3.5 Indoor Air Quality

A properly designed, installed and operated HVAC system will normally be energy efficient and mitigate most IAQ issues. The application compares the analysis results to the essence of ASHRAE standards 62.1-2007, 55-2004, 55.2-1999 and 91.1-2007: ventilation, thermal comfort, air filters, and building energy. It is important to recognize that dense (efficient) filters require the system to use more energy to maintain the same airflow. IAQ issues include thermal comfort, humidity, airborne particulate, ventilation, odors, and VOC. A too humid environment will cause building materials to expand, mold growth, bacterial growth, musky odors and uncomfortable air. It hastens the deterioration of the HVAC system over time. Lack of proper filtering and a dusty building environment cause the inhalation of allergens and causes respiratory illness. Examples of common allergens are airborne pollen, dust mite particles, mold spores, mycotoxins, cat and dog dander and latex dust. Building dust provides harbor for bacteria that can easily spread throughout the building. Poor ventilation will increase CO_2 levels and lead to fatigue and inability to concentrate. The AuditMaster™ SW prepares an analysis that quickly identifies issues and provides data for the selection of proper remediation methods.

3.6 Diagnostics

A powerful feature in the AuditMaster™ SW is its diagnostic algorithm. It uses psychrometrics, various industry standards, mold characteristics, known problem areas, and actual measured performance characteristics to diagnose the HVAC system in regards to IAQ, operation, life cycle, maintenance, and energy efficiency. The SW prepares a report and recommends adjustments to the control settings so that the HVAC system performs to design requirements. An additional application for the diagnostic algorithm is to allow manufacturers to verify that delivered equipment meets specification after it has been installed in the field. Conflicts between manufacturers and contractors occur rather frequently so a system diagnosis should be required on all new construction, retrofits and renovations.

3.7 Energy Efficiency Measures (EEM)

The report provides a list of suggested EEM's with associated cost savings based on the diagnostic algorithm implemented. The saving models are currently based on heating and cooling degree days and are adjusted by the latent heat factor of the O/A. Common EEM's are pulley adjustments, fan motor resizing, and duct sealing, air- and system balancing. In contrary to all other performance percentages provided in Figure 5 the reporting on the coil cleaning EEM is the maximum possible improvement. The reason is that this percentage is the remaining system inefficiency not attributed to other causes.

3.8 EPA Energy Star Score

The EPA energy star score for a building is the only recognized benchmark that compares energy efficiency in similar constructions. However, the regression models used to calculate the ENERGYSTAR score use heating and cooling degree days as a parameter and ignore the humidity in the outside air (latent heat). These models also ignore important architectural and building orientation parameters that affect the lowest possible energy consumption baseline. These effects could have been mitigated by considering the rated heating and cooling capacity for a building. Therefore, the benchmark is useful to a certain extent but susceptible to errors when comparing similar buildings across various climate zones. Since the LEED status of a building affects the resale value and the USGBC relies on the EPA Energy Star for LEED credits, the LEED regression models have been implemented into the AuditMaster™ SW.

4 Auditmaster™ Case Study

The data presented in this paper was obtained at a hospital in South Dakota as part of a field study using the TSE method. All data was captured using the AuditMaster™ client SW. Although the current version of the SW supports both hydronic and direct expansion cooling systems as well as hydronic and electric heating systems, the effort as shown in this case study focuses only on hydronic cooling systems. A PEM would normally not perform data logging as shown here, but it has been included to illustrate what TSE is. The instruments used in this case study were: Vaisala gm70, Testo 175-T3, GE pt878, Fluke 430 and Shortridge 88L. All were configured to log data and time stamp these in one minute steps. Outdoor enthalpy typically increases at a slow pace throughout the day as the energy delivered by the sun accumulates. The histogram labeled 1 in Figure 6 shows where the enthalpy increases from approximately 21.8 BTU/lb to almost 22.0 BTU/lb in 23 minutes. The histogram labeled 2 has captured the TSE

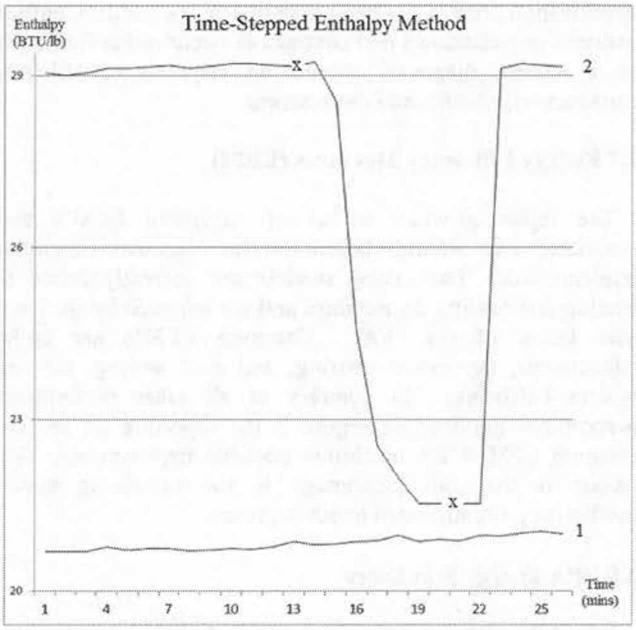

Figure 6: Graph 1 shows the increasing outdoor enthalpy while graph 2 plots the time-stepped enthalpy method

method where the cooling coil runs at full capacity until it is de-energized.

The timed response of the system is seen as the energy is slowly removed. It is the time difference between the energized and non-energized states of the system that yields the pertinent delta enthalpy, thus given the name TSE method. During the process it is very important that the system steady state is reached to ensure that the transient conditions do not skew the calculated results. As seen in Figure 6 the delta enthalpy in this case would be calculated using the values at time 13 and 21. By using Δh and Q_A the airflow may be calculated as presented in the graph in Figure 7.

From Figure 7 it can be seen that the system reaches steady state after approximately six minutes. The airflow converges towards 11,642 cubic feet per minute (CFM) using these two numbers.

During the walk-through phase of this study it was documented that all air-handlers were well maintained and a certified test and balance company had adjusted all air and hydronic flows for both heating and cooling systems. The PEM collected data on paper while concurrently entering it into the AuditMaster™ client SW. After the initial walk-through, which normally takes four hours for this size building, an energy audit template was generated for the system to allow design information to be entered when offsite. With a well prepared energy audit template in tandem with the identification of measurement points, the actual measurement sequences could be completed on six air-handlers in less than ten hours. As the PEM completed the last measurement entry the data was uploaded and an instant retro-commissioning report was generated and e-mailed to all parties. Figure 5 depicts part of the report summary and lists the operational performance parameters of the six air-handlers under test. From Table 1 it can be seen that the hydronic flows have been somewhat properly balanced. However, the airflows are substantially short of intended design partly because the fan motors do not have the appropriate horsepower.

Measurements using traditional Pitot tubes may yield large errors, thus the air balancer will either overstate or understate the airflow which results in improper diagnostics. For example, where the fan airflow is overstated and the test and balance contractor uses a flow hood to measure the diffusers

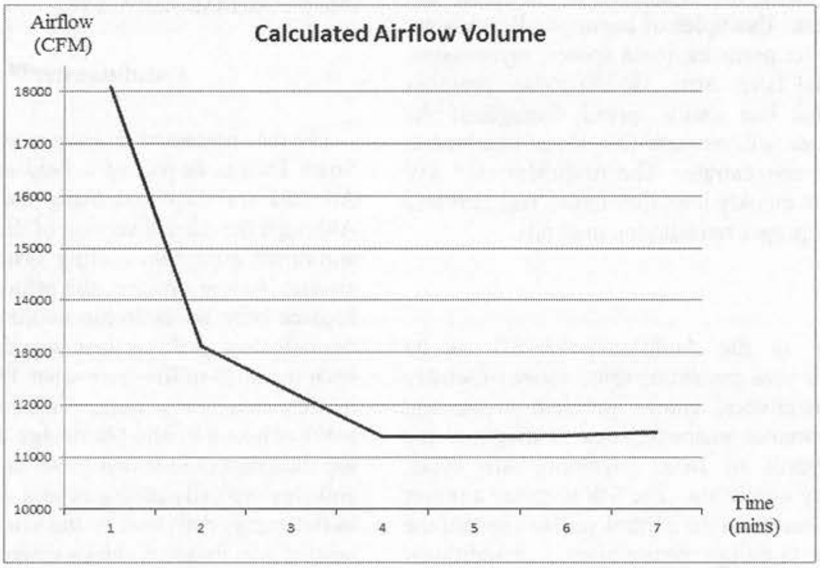

Figure 7: Airflow plotted as a function of time using the TSE method

Table 1: Compared performance to design for six main air-handlers at a South Dakota hospital

AHU	Airflow	Ventilation	Heat Transfer	Hydronic Flow	Motor HP
1	56%	34%	52%	64%	33%
2	87%	18%	99%	127%	107%
3	70%	135%	66%	112%	63%
4	64%	80%	70%	113%	75%
5	56%	4%	53%	93%	42%
6	61%	3%	55%	110%	55%

delivered airflow, the results provided are substantially less than expected. The difference between the fan airflow and the accumulated total of diffuser airflow is assumed to be duct leakage. The normal prescriptive measure calls for sealing the air-ducts with assumed leakage while the actual issue was an improper fan airflow measurement. To keep up with the cooling demand, and to satisfy ASHRAE standard 55-2004, the control system restricts the outdoor air for all but air-handler 3 [18]. Reduced O/A will make the CO_2 levels build in violation of ASHRAE 62.1-2007. High CO_2 levels directly affect the health and performance of the buildings medical professionals. A well maintained system that cannot maintain system set-point for a myriad of reasons will sacrifice ventilation for increased thermal control without key personnel being informed. The AuditMaster™ analysis not only identifies and diagnoses issues like the one previously described but it also provides very accurate assessments on wasted energy. In addition to the direct utility cost of the wasted energy are penalties for HVAC equipment that is required to run longer due to system inefficiencies. AuditMaster™ identifies the interventions needed to resolve system problems and also provides an estimate of ECM improvement costs. Subsequently, the return on investment can be calculated enabling building owners, facility managers and building engineers to make educated decisions based on reliable information. To further elevate the utility of the AuditMaster™ SW the EPA Energy Star Score has been incorporated along with their carbon credit accounting values. This score is used to determine the LEED credit potential the building has available by utilizing the United States Green Building Council (USGBC) guidelines. Using the provided data the energy score calculated was only 50 percent being average in its class.

5 Conclusions

The presented research and associated SW shows that the underlying fundamentals of complex buildings, and more specifically complex HVAC systems, may be accomplished in a fashion that brings energy efficiency assessment to a new tier utilizing a cloud computing application. Not only has the AuditMaster™ application, built around the TSE method, allowed simplification of the tedious data collection and solution process, it has combined psychrometric calculations, thermodynamics, associated energy savings, ECM's, energy models and cost models. The solution enables extremely accurate results with measured and calculated parameters that are instantly used to generate a report via the cloud where accuracies converge to 1 percent under proper test conditions. Proper test conditions include, but are not limited to, a delta enthalpy of at least ten, dry cooling coil and relative humidity of less the 55 percent. The process to collect and complete a typical HVAC energy performance audit can be completed very quickly. A walk-through including the actual performance assessment for a building with up to six air-handlers serving 112,000 square foot may now be completed in two days versus several weeks without the AuditMaster™. The instant report generated is multi-faceted; it spans building commissioning and retro-commissioning, Government Energy Reduction Mandates and HVAC energy performance assessments.

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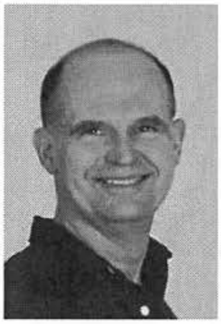
Bernt Askildsen is a Doctor of Philosophy candidate in Biomedical Engineering and holds Master of Science degrees in Electrical Engineering and Technical Management. Mr. Askildsen's research focus is nosocomial infections in health care facilities and optimizing of HVAC systems for energy and indoor air quality objectives. Mr. Askildsen has 19 years of hardware and software research and development experience in tandem with sales and marketing of technical products. Mr. Askildsen is an expert interdisciplinary project manager and has authored various technical publications and been a presenter at various conferences.

Charles Tolle was a former Group Leader at the DOE's Idaho National Laboratory (INL). His 21 years of research has included system identification, fractals, analysis of signals, target detection, chaos and complexity theory, control of thermal mechanical processes such as welding and tube making, signal motivation, vector quantization for image compression, fuzzy logic modeling and control, biological and biomedical control systems, as well as aircraft guidance. His research has been supported by General Electric, Hamilton Ventilators, Honeywell CFGS, and TARDEC & ARL, U.S. Army research labs, the RMt.NASASGC, and the DOE Offices of Science, Industrial Technology, and Fossil Energy. He has authored/co-authored over 50 conference presentations, invited talks, conference papers, and peer-reviewed papers on research performed to date.



Lance Weaver holds a Bachelor of Science degree in Mechanical Engineering and has been pioneering robotic technologies for HVAC systems for over 20 years. Mr. Weaver is an experienced interdisciplinary project manager for products spanning from software to electromechanical appliances. He has managed several products from the idea stage through the product market lifecycle where three products have received product of the year awards. As a HVAC expert Mr. Weaver has extensive understanding of HVAC performance and how it relates to indoor air quality issues. Mr. Weaver has authored and co-authored various technical publications and been a presenter at various seminars and conferences.