ETM0010

Smart Building Energy Solutions Technologies – Possible Development and Limitations in Thailand Supermarkets

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Abstract

Currently, smart building functionalities are developed in terms of enabling technologies for providing a personalized, comfortable and productive indoor environment to occupants with low energy consumption and environment impacts. However, the status quo of these system operations is, non-personalizable with low energy efficiency, high operation and maintenance expenditure, and high environmental impacts due to 1) faults, which are inherently introduced during initial installation or developing during routine operation; 2) unexperienced building operators and maintenance teams leading to inefficient building energy management; and 3) lacking of sufficient monitoring systems and complete diagnostics. Reducing the problems and managing detected faults in time before changing to failures, many field retrofit investigations demonstrated that energy saving potential can be up to 50%. To this end, many researchers have been developing applicably enabling technologies to achieve near-optimal and high efficient building operation in the U.S. However, smart building innovation is still infancy in developing countries due to several barriers. This paper initially reviews and synthesizes the non-invasive and enabling technologies called "Smart Building Energy Solutions Technologies (S-BEST)", which have been implemented in the real world. S-BEST composes of: 1) data carrier; 2) data fusion and mining; 3) virtual sensing and modeling technology; and 4) automated diagnostics, decision-making and soft-repair technologies. To limit from small- to medium-scale commercial building, supermarkets are selected as the case study because they are one of the most electricity-intensive types in commercial building sector, and they are integrated with the complex systems including: heating, ventilation and air-condition and refrigeration (HVAC&R) systems; these two systems are coupled in terms of energy interaction and are the integrated largest contributor of energy usage and electricity peak demand. Then, the limitations and development of S-BEST are systematically discussed and envisioned by a successful case in Nebraska and the example of the author's current project in Thailand. Monitoring systems of HVAC&R are analyzed and improved for high fault detection and diagnosis (FDD) efficiency. Eventually, typical faults diagnostics which are significantly required to develop as commercial product or benchmark guideline are concluded for Thai smart supermarket in near future.

Keywords: Commercial Supermarket, Data Exchange Carrier, Data Fusion, Virtual Sensor, Fault Diagnostics

1. Introduction

Smart building solutions are perspective technologies to efficiently improve building energy systems. In each modern building, a BAS is one of the current solutions installed to collect real-time data from wired or wireless sensors and equipment controllers in order to perform the building control and operational system and intelligent building services through the central computer stations. The building control of modern BAS utilizes four level architectures including: management level; integration level; field controller level and sensor/actuator level. Meanwhile, the building services are all building facilities consisting of heating, ventilation and air-conditioning (HVAC) systems, electrical systems, lighting systems, fire systems and security systems and life systems. To communicate and exchange information between each device and subsystem of the BAS, BACnet which is a communication protocol for building automation and control network has been developed and became ASHRAE/ANSI standard 135 in 1995 [1]. With this communication protocol, web-based energy applications can be used to connect a local BAS to automatically collect online data or to control the system operations in appropriate performances.

In commercialization, there are five levels of BAS: Level 0: manual on-off; Level 1: reactive on-off; Level 2: programmable on/off; Level 3: variable response; and Level 4: intelligent controls. Most of BAS functions in developed counties have been continuously enhanced to Level 3 or 4 because building operation data have been effectively collected and utilized efficiently for optimal control functions and typical fault diagnostics. With these outstanding functions, low energy efficiency, high operation and maintenance expenditure and high environmental impacts are improved leading to ongoing processes for further developing: 1) embedded self-diagnose functions for on-board controllers of smart equipment; and 2) high performance supervisory control.

To sum up, high energy savings and potential building operations and maintenances can be conducted via experienced building operators with standard BAS and sufficient data measurement and storage; however, those good sides of standard building management performances are barriers in developing countries like Thailand or small- to medium scale buildings because: 1) high performance BAS levels are still infancy since most of BAS systems are level 0 due to cost-prohibitive issue; 2) building operators lack of well-trained standard and well-experienced performance; and 3) non-standard commissioning procedure is used to firstly run and test first installation of equipment leading to faulty operations from near-design concept.

To overcome these barriers, non-invasive solutions with existing enabling technologies have been developed for small- to medium-scale commercial buildings in the U.S. [2, 3]. Especially, in retail stores or supermarkets [4], "Smart Building Energy Solutions Technologies (S-BEST)" consisting of: 1) data carrier; 2) data fusion and mining; 3) virtual sensing and modeling technology; and 4) automated diagnostics, decision-making and soft-repair technologies have been developed and applied to energy, HVAC, refrigeration, and lighting systems so as to reduce building operating costs and carbon emissions via low-cost solutions. The key features of possible S-BEST implementations are: 1) standard onboard data from American HVAC manufacturer; 2) data communication protocol standard is provided in HVAC units; and 3) fault-free data and fault simulation can be obtained from HVAC laboratory demonstration used as the fault-free model of equipment (e.g. rooftop unit (RTU) in University of Nebraska [5] and water-cool chiller in Purdue University [6]).

To design and analyze the possibility of S-BEST implementations in Thailand, this paper firstly reviews and synthesizes the smart operation project based S-BEST function in supermarkets to limit from small- to medium-scale commercial building as the case study. Then, the possibility of Thailand supermarkets is systematically discussed and envisioned by some examples of the author's a current project. Additionally, the details of research synthesis and conclusion is introduced to Thai HVAC&R designers, contractors, manufacturers and building operators to obtain qualitative results for further developing commercial products and benchmark operation and guideline in near future.

2. S-BEST Implemented in Smart Supermarket Model of University of Nebraska – Lincoln (UNL)

The smart building solutions as shown in Fig. 1 enhance the multi operations and multiple connections of energy systems, building environment, community and manufacturers through data exchange carrier which performs plug-and-play (PnP) connectivity and has unlimited data memory of a could computing technology. With the final process in terms of diagnostics and soft-repair decisions for building routine operations, the building community (owners, contractors, operators, energy consultants and so on) can directly evaluate or analyze building performance through big data via web-based energy technologies. In addition, sufficient operations proved by lab testing or field data can be used as tools, applicable technologies or implementable experience for educational demonstration prototypes, educational outreach program and a commercial smart building diagnostics prototype. , the associated works and backgrounds with S-BEST are briefly discussed as follows:

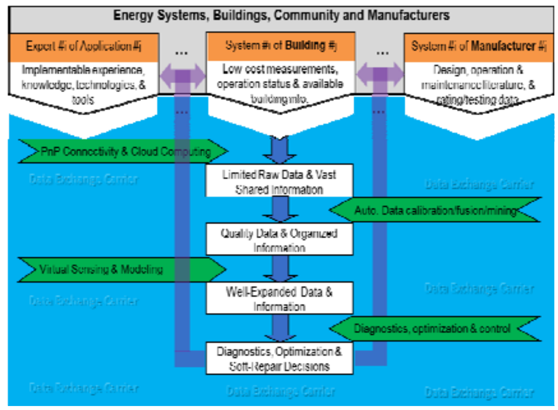

Fig. 1 Vision of smart building solutions [4]

2.1 Supermarket Backgrounds in USA

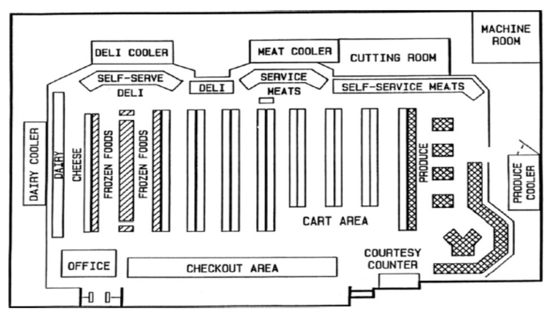

Fig.2 Layout of a typical supermarket [7]

Commercial supermarkets consist of HVAC units and refrigeration equipment as shown in Fig. 2; HVAC units provide heat and cool air by RTUs, which generally have oversized capacities [8], resulting in decreased efficiency in absorbing latent load [9]. Even through zone air temperature is controlled at a set point temperature, indoor air humidity cannot be maintained at 50 - 55 percent RH because the temperature controller is typically independent of the humidity controller. This situation called "interaction" is particular to supermarkets rather than other general commercial buildings. As a result, the installation of dehumidification units is required to retain RH at set point level.

The interaction of the supermarket environment provided by those HAVC units with the refrigeration equipment is the driving force of indoor temperature and humidity. Meanwhile, another significant driving condition is outdoor air temperature influencing both RTU and refrigeration condensers. The refrigeration systems cannot be operated optimally with refrigeration systems cannot be operated optimally without a well-conditioned space served by HVAC operations without a well-conditioned space served by HVAC operations. These coupled systems load to more complex data analysis than other building types.

2.2 Data Exchange Carrier for Supermarket Operations

The goal of the control platform as depicted in Fig. 3 is therefore to provide a scalable low-cost method called "S-BEST" that can be implemented via a plug-n-play solution (no additional sensor) in constructing new or retrofitting existing RTUs-served commercial supermarkets and refrigeration systems to significantly improve the operation energy efficiency without any intrusive methods.

Fig.3 UNL controls and data exchange carrier platform

The original RTU laboratory as shown in Fig. 4 is interfaced with the control platform; this lab is one of most potential testing facilities utilized for automated fault detection and diagnosis (AFDD) research. It composes of 1) two psychometric chambers; 2) portable packaged HVAC systems and 3) sophisticated controls and data acquisition systems. With the fault-free operations testing of the commercial RTUs, the non-fault data are invaluable to train fault-free model for fault diagnostics and faulty operations.

In order to reduce cost operations for supermarket analysis, the data exchange carrier platform is developed by using the standard communication protocol - BACnet to link RTU controllers, building BAS and local computer server with cloud-based web browser interface. With increased amount of supermarkets/systems/client users connected to this platform, the amount of shared information and the platform will be more powerful to trend more sufficient and effective fault-free model for fault diagnostics. The building community connections can reduce the cost of use in terms of unnecessary data storage, can enhance more field-proven demonstration and are more scalable for optimally managing energy efficiency in the same similar supermarket brand or similar equipment operations based the typical layout

2.3 Data Collection with Automated Data Fusion

Data fusion is an automated process to increase data quality for training fault-free model or suitable routine operations; it is further used to permanently reduce or eliminate inherent errors occurring in physical sensors which are practically caused by bad location of a sensor, out-of-calibration and sensor failure. With the potential implementation of this automated data improvement process [10], it can eliminate location-related errors, sensor-inherent errors, avoid utilizing failed measurements and replace failed measurements with alternatives. These avoidances lead to energy saving at field control levels of a BAS because sensor errors will result in waste energy consumption in buildings.

For the example of data fusion to obtain a benchmark data analysis solution in a supermarket environment, the interaction analysis is considerably challenged ,and has been significantly concerned more than two decades; the results of power reduction percentages were concluded in the database review presented in Ref. [11]; however, a few supermarkets have been tested for indoor humidity level impacting on refrigeration system energy uses because there are cost-prohibitive and time-consuming in terms of long-term data collections so as to quantify the effect of store humidity to refrigeration power consumptions. To overcome these issues, the field testing data of six supermarkets located in different climate in the U.S. were connected to the data acquisition platform for studying the data analysis. As a result, energy interaction rules of the typical HVAC&R interaction in supermarkets were obtained. [9].

Overall, the UNL test-bed platform can store over 2000 field testing as zero-connectivity data platform in USA; the data were established to deploy AFDD research [12] and to analyze RTUs oversizing in retail stores [8] and energy interaction among HVAC systems and refrigeration systems [9] for further cooperating with FDD in building supermarkets.

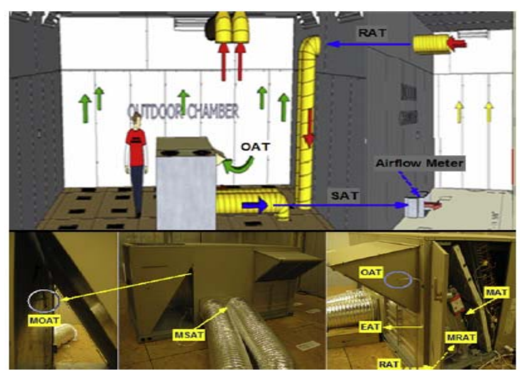

Fig.4 real experiments for developing virtual sensors for a standard RTU in UNL [13]

2.4 Virtual sensing and modeling technology

Virtual sensing and modeling technology are mainly developed for expanding limited sensing with low-cost measurements and available data of manufacturers. The concepts of virtual sensors can be categorized in three criteria [5]: measurement characteristics-based criterion (transient-state and steady-state data-based approach); modeling method-based criterion (white-box, gray-box and black-box models) and application purposes-based criterion (replacement and observing).

In the UNL demonstration project, the virtual flow meter sensor is one of the developed virtual sensors for real fault diagnostics. The virtual sensor can be developed based on the four onboard air-side sensors (outdoor air temperature (OAT), return air temperature (RAT), zone air temperature (ZAT) and supply air temperature (SAT)) and recorded control operations (damper positions) of a standard RTU. The experiments were conducted as demonstrated in Fig. 5.

2.5 Automated Fault diagnostics

Automated diagnostics can be fully referred to automated fault detection and diagnosis (FDD) which currently plays increasingly important role in the operation and maintenance of HVAC equipment because faults are practically occurred by improper routine operations, field commissioning, installation and maintenance. To prevent these happenings, AFDD has been intensively developed as embedded intelligence for two main reasons: improved safety (e.g. nuclear power plant, aircraft and chemical process plant) and decrease of operational cost in terms of service and utility costs. Ensuring safety is not the first priority in HVAC&R applications; it is mainly used to improve productivity in terms of equipment efficiency and better thermal comfort and to reduce operating costs and potentially schedule maintenances.

Enabling AFDD can eliminate waste energy caused by faults and non-optimal operations in HVAC systems up to 30% in average [14] and enhance productivity and reduce maintenance costs by 70% of yearly preventative maintenance [12] because sudden or degradation faults occurred during routine operations, service maintenance and commissioning are practically caused by unsuitable and/or faulty design and system operations; they can be diagnosed before the systems become failure. For the Nebraska project outcomes, rule-based automated fault diagnostics were implemented via cloud service operations for collecting a total of 555,200 data points from 16,480 machines in 252 retail store locations. 27,754 problem issues were identified by the cloud based AFDD platform causing an annual calculated savings of $3,790,000.

3. Smart Supermarket Limitations and Possible Development in Thailand

Regarding the benchmark model based on S-BEST procedures in UNL, there are many significant challenges to possibly apply the successful S-BEST model in Thailand supermarkets since the commercial compressor rack refrigeration system and store layout as depicted in Fig. 5 are similar to the model. However, some limitations are needed to be improved as Thailand criteria. To this end, section 2 can be applied as a guideline or tool to set up an efficient-standard supermarket system in Thailand. For these challenge issues, Thailand Research Fund (TRF) awards the funded project under the scope of MRG-5980208 entitled “development and assessment of FDD for HVAC&R in commercial supermarkets”. For the project contribution, FDD development envisions S-BEST model as plug-n-play diagnostics and optimization for smart supermarkets in future. To this end, the required limitations are improved as follows:

The research methodology of MRG-5980208 mainly improve the three monitoring categories including: zone interaction, a HVAC system (air-handling units, AHUs) and compressor rack refrigeration system. The monitoring systems of each sub-system are analyzed and modified to obtain more significant and sufficient variables for FDD approach. With the feasible investigations of existing available data obtained, the existing parameters are insufficient for FDD analysis.

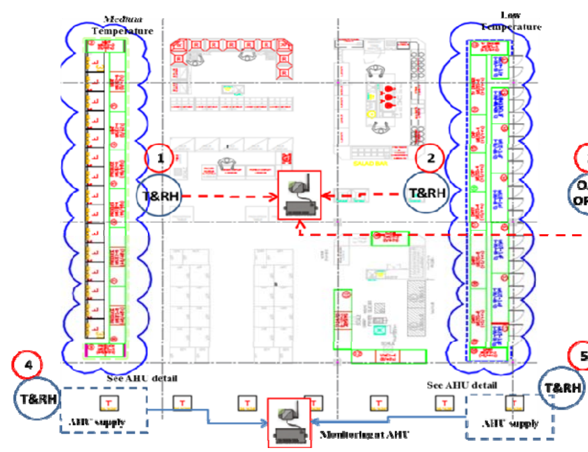

Fig.5 Thailand supermarket layout

3.1 Monitoring System Improvement in Zone Interaction

In Fig. 5, especially from highlighted read circles from No. 1 to 5, additional monitoring systems are installed to measure the interaction between AHUs and refrigeration systems including HVAC&R machine power consumptions. The zone interaction measurement includes the zone air temperature (ZAT) and indoor air relative humidity (IARH) sensors of AHUs (point 4 and 5) and two conditioned spaces at point 1 (medium-temperature display cases) and 2 (low-temperature display cases). Meanwhile, outdoor relative humidity (RH) and outdoor temperature (OAT) are also measured as the outdoor condition used for the interaction analysis.

3.2 Monitoring System Improvement in Refrigeration Systems

According to Fig. 6, the simplified centralized refrigeration system is composed of the identified measurement; this compressor rack system located in a control room is used to provide refrigerant to display cases in the zone interaction. The centralized refrigerant system includes: the existing monitoring system in the control panel; multi-compressor racks; outdoor condenser unit; liquid receiver; suction manifold; and refrigerant piping system. The indoor temperature of each display case will be controlled via the thermal expansion valve (TXV) which controls the refrigerant flow rate of a refrigerant circuit supplied from the control room.

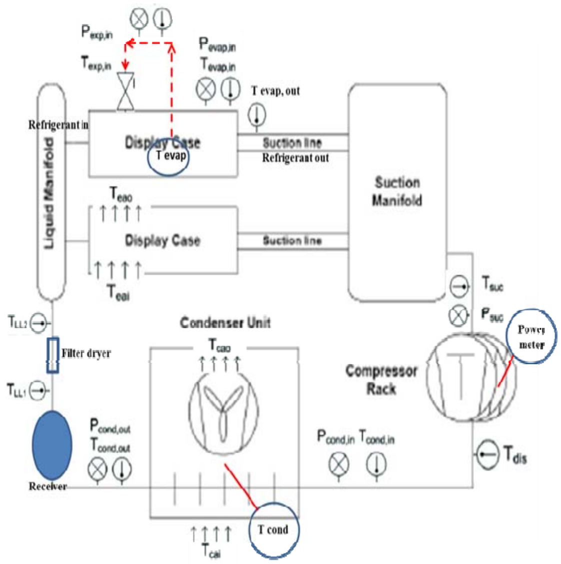

Fig. 6 simplified compressor rack refrigeration system used in a hypermarket for the research

For modified measurement system via non-invasive solution, the existing commercial monitoring system based web service interface was installed by contractor which can be downloaded via browser user interface (BUI); however, some parameters such as P and T sensors of the refrigerant-side at the identified positions in Fig. 6 are not provided on the BUI. Fortunately, they are availably embedded on the control unit for efficiently manipulate the system performance. To this end, the web service can be used to write out these parameters without additional sensors (PnP) in the refrigerant cycle. Except the outside unit, the condenser refrigerant or water temperature of an inlet and outlet are additionally installed depending on for efficient FDD development and analysis.

3.4 Monitoring System Improvement in Air-conditioning System

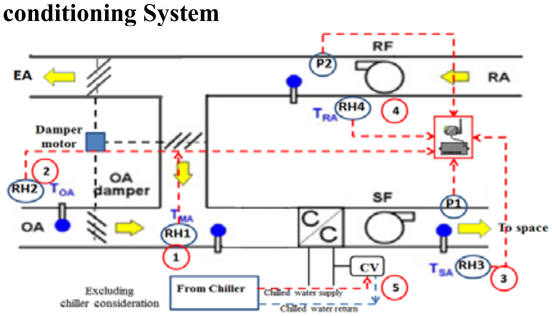

Fig. 7 A typical variable air volume AHU system

In Fig. 7, the typical VAV AHU composes of: 1) supply (SF) and return fan (RF) with constant air-flow rate; 2) fixed exhaust air (EA), outdoor air (OA) and return air damper (RA); 3) solenoid cooling vale (CV) to control zone temperature; and 4) additional monitoring system unit for measuring pressure (P), RH and T at OA, RA, mixing air (MA) area and supply air. These mentioned values are sufficient to effectively develop FDD on AHUs [15].

4. Data Fusion for Data Quality Improvement

This section provides a simple data fusion technique to improve the data quality for obtaining reliable data operations. For the analysis example, TXV position curve is used to calibrate the normal operations because valve section oversizing is a problematic to suitable refrigerant control based superheat temperature (Tsh) operations for well-conditioned display cases.

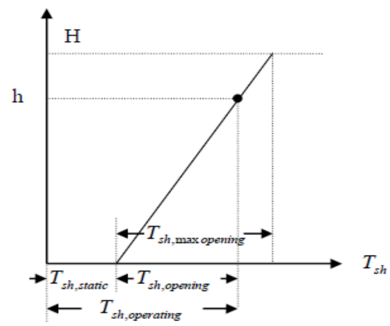

Fig. 8 TXV position curve between Tsh vs. h (valve position)

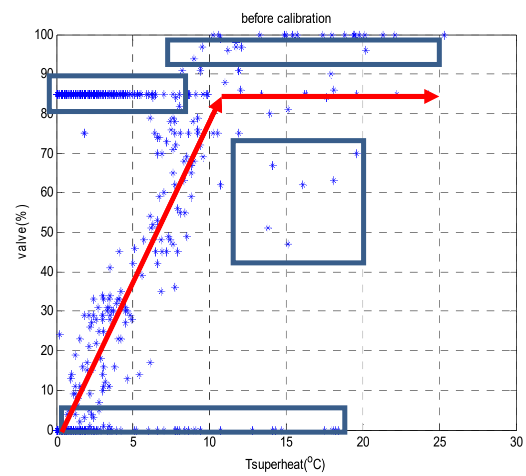

Fig. 9 Data operations example of TXV in a medium temperature display case

According to Fig. 8, the valve position is a linear function of opening superheat. By comparison between the real operations example in Fig 9 and Fig. 8, the TXV position curve obtained from manufacturers' data can be used to reduce unreliable operations or to identify how appropriate the TXV sizing is.

5. Typical Faults in refrigeration units

Based on the considered data and improve monitoring system in last two section, they are adequate to diagnose typical faults (F) leading refrigeration performance degradation called "degradation faults". They are as follows:

F1: Evaporator fouling is a reduction in airflow rate that would be occurred due to ice buildup deposits on the evaporator coil. Computed airflow rate can be used to decouple this fault.

F2. Similar to F1, fouling can be developed when the condensing coil air-side becomes dirty reducing the airflow over the coil and decreasing the coefficient of performance (COP).

F3: Refrigerant undercharge is one of service faults leading to lower heat transfer efficiency. The simple trouble shooting can be noticed if Tsc – Tsh is less than zero (Tsc – Tsh < 0)

F4: Refrigerant overcharge is caused by service causing high pressure and higher compressor work. The diagnostic condition is Tsc – Tsh > 0.

F5: Liquid-line restriction tends to accumulate during operations because a vapor-compression system can experience clogging of the filter dryer, which restricts the flow and increases pressure drop leading to a reduced mass flow rate. Temperature drop across the filter dryer is used to identify F5.

F6: Compressor valve leakage allows high-pressure refrigerant to flow back to the low side pressure causing lower the mass flow rate. Discharge Temperature (Tdis) can be used to diagnose F6.

Energy savings in terms of recovering near-design system performance can be conducted if these degradation faults are diagnosed and fixed in time. However, without physical repairs, they could be severe when the faults can gradually develop to sudden faults and failures. The diagnostics will be potentially accurate and reliable if fault-free data are available.

5. Conclusion and Contribution

Due to inefficient routine operations, system commissioning and improper system installation in HAVC&R equipment in a supermarket, degradation faults can gradually develop to sudden or severe faults. Without repairs in time, they would be failures. This paper briefly reviews and synthesizes the S-BEST solution of the UNL smart building project for automatically diagnose faults via a low-cost, non-invasive and PnP solution. Then, the methodology is applied to improve the existing HVAC&R equipment operations for Thai smart supermarket in near future.

6. Acknowledgement

The authors are deeply grateful to Thailand Research Fund (TRF) – MRG-5980208 project for financial support to further develop innovative technologies based on this work in near future.

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