Optimization of Multi-zone Building HVAC Energy Consumption by Utilizing Fuzzy Model Based Predictive Controller

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ABSTRACT

The rapid improvement of living standards has led to increased energy consumption in buildings worldwide. Globally, the energy consumed in buildings accounts for 20.1% of total delivered energy (EIA 2016). Improving energy efficiency in buildings therefore is an important component for combating climate change. This paper aims to improve end use energy efficiency in multi-zoned residential buildings through the application of thermal comfort based, energy optimization algorithms. We use a case study approach with a detailed analysis of a 4-story residential apartment building in central Illinois. The study building constitutes 21 thermal zones modeled in EnergyPlus. The model is validated using monthly energy consumption data. The effectiveness of four different steam heating system control methods are evaluated and described: a) a Model Predictive Controller (MPC) design based on neuro-fuzzy temperature predictor; b) a Proportional-Integral-Derivative (PID) tuned by fuzzy logic; c) a PID tuned by a genetic algorithm; and d) an on/off controller and the flow regulator based on indoor temperature. All are optimized for energy consumption reduction potential and thermal comfort. The main effect of the various control methods is tuning boiler feed flow by regulating the condensing cycle. A reduction in circulated steam flow results in decreased direct energy consumption and improved condensing pump efficiencies. We find that the MPC design using a neuro-fuzzy temperature predictor can reduce heating energy use by up to 38% in comparison with an on/off controller baseline.

1. INTRODUCTION

Improvements in living standards and the associated environmental and energy problems have become critical challenges worldwide. More than 40% of primary energy use worldwide is related to the heating, cooling and lighting of buildings (Fan *et al.*, 2018). The development of better modeling and control techniques for Heating, Ventilation and Air Conditioning (HVAC) systems has therefore, become critical for providing occupancy driven energy and comfort management, prioritizing carbon emission reductions, and decreasing overall consumed energy (Mary Reena *et al.*, 2018). Building energy modeling techniques are making it easier to design efficient control and management techniques for building HVAC systems. Multi objective optimization methods that use thermal comfort and energy efficiency as two conflicting objectives of a controller design can be simulated using these modeling platforms (Mary Reena *et al.*, 2018). In this paper, we use these techniques to model end use energy efficiency in a multi-zoned residential building.
The literature on building Management Systems (BMS) and automation show them to be expanded to reduce energy demands and preserve thermal comfort mainly through sophisticated control strategies (Michailidis et al., 2018). For example, Ahn et al. (Ahn *et al.*, 2017) utilize Fuzzy Inference System (FIS) and Artificial Neural Network (ANN)

for simultaneously controlling the amount of supply air and its temperature. They note that using this method, the thermal demands in disturbance condition is controlled and the consumed energy is reduced in comparison to a simple thermostat on/off controller (Ahn *et al.*, 2017). A smart strategy based on Model Predictive Control (MPC) is employed to improve the performance of hydronic radiant floor systems in office buildings. The system is noted to minimize energy consumption while providing thermal comfort - a 16% energy savings compared to baseline (Joe & Karava, 2019). MPC using ANN was implemented to improve consumed energy in residential buildings by Finck et al. (Finck *et al.*, 2019). They modified MPC by considering a function to adapt energy demands and supplies during fluctuations in supply resources (Finck *et al.*, 2019). The control methods are utilized for HVAC subsets including economizers, variable air volume dampers, pumps and air handling. Based on Shea et al. (2019), implementing controllers for all economizers in commercial office buildings results in an average of 17% cooling savings (Shea *et al.*, 2019). The various control methods utilized for optimizing heat pump systems in buildings are reviewed by Péan et al. which demonstrate the MPC as the most considered method in the literature (Péan *et al.*, 2019).

Utilizing MPC requires detailed and complex energy modeling simulations. So, a Reduced-Order Model (ROM) is utilized to design MPC for optimally planning space-heating load by Aoun et al. (2019) The utilized ROM methods are shown reliable enough for designing MPC (Aoun *et al.*, 2019). MPC has also been implemented as a parallel controller for set-point optimizers. This method resulted in the reduction of 1430 KWh (equal of 20% of total consumption) during the heating season in residential buildings with electrical under floor heating systems (Ławryńczuk & Ocłoń, 2019). Genetic Algorithms (GA) have also been shown as an effective methodology for energy optimization in various thermal building systems (Li *et al.*, 2017).

Shaikh et al. (2018) implemented a Multi Objective Genetic Algorithm (MOGA) to improve energy efficiency as well as provide comfort condition in a one day simulation. The MOGA maintained high comfort level and optimize energy efficiency (Shaikh *et al.*, 2018). The combination of ANN and MOGA is also implemented to optimize a two-chiller system, Variable Air Volume (VAV) chiller system, and Dedicated Outdoor Air System (DOAS). This combination results in a significant improvement in HVAC operation, while keeping energy consumption low compared to the base-case (Nasruddin *et al.*, 2019). GA also is used to determine the optimal operating schedules for the heat generation equipment, thermal storage, and the heating set point temperature. Based on Reynolds et al. (2019), GA optimized heat generation by 44.88% compared to a rule-based, priority order baseline strategy (Reynolds *et al.*, 2019). Utilizing MPC as a control methodology and optimizing through GA have been shown to be the most useful methods for Multi Input Multi Output (MIMO) optimization of HVAC systems in typical buildings. In most of the literature on these control strategies, thermal comfort and consumed energy are emphasized as the objectives of the optimization process, with air temperature as the thermal comfort parameter. Consumed gas and utilized electricity are considered simultaneously (as 'energy') in most studies and the application of HVAC systems typically utilize simple building parameters.

The most important contribution of this paper is the inclusion of indoor air temperature for providing occupant thermal comfort; reducing consumed gas (in boiler of steam system) and condensate pump electricity usage for energy optimization. The other novelty of this paper is simulating a real residential building including 21 thermal zones which is evaluated through real information of consumed energy.

In the following sections multi-zoned energy modeling techniques used and the ambient condition will be described. The design methodology for various control strategies are then described. The application output for each controller condition, simulation results, and the effectiveness of optimization are explained in the 'results' section. Finally, the comparison of utilized methods and the benefits each are concluded.

2. THERMAL MODELLING

2.1 Building Thermal Specification

The considered building includes 4 floors. 3 upper floors are utilized as residential building and the basement is empty looks to be common spaces of some sort. Each residential floor is separated into 7 thermal zones. The considered building is presented in figure 1.

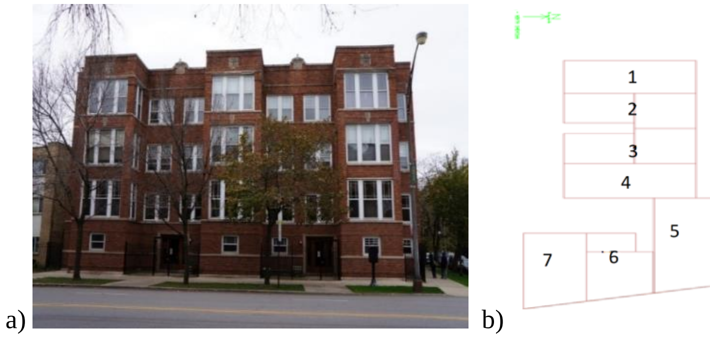


Figure 1: a) Real building East View, b) Building Floors plot including thermal zones positions

According to the structural material of the building, the standard template material presented in EnergyPlus software is implemented to model thermal energy transferred through walls, floors, windows, roofs and ground level. The basement of the building is empty and separated building thermal zones and ground. The basement of the building is considered as a separate zone coupled to the ground.

By considering every zone as a system, energy is transferred by convection, conduction, radiation and mass transferred. Based on the energy conservation law, by ignoring the negligible transferred energy through air movement by doors area (usually closed and open only a few times), the indoor air thermal energy equation of every zone is as Equation (1).

$$\dot{E}_t + \dot{E}_g = \dot{E}_S \tag{1}$$

Where $\dot{E}_t$ presents the amount of transferred energy, $\dot{E}_g$ is the amount of generated energy by HVAC system, equipment, people etc. and $\dot{E}_s$ represents the changed energy level inside the zone. When these parameters are considered in every time step, the equation of energy is utilized for every time step based on the derivative of energy. The transferred energy calculates based on the BS EN 12831 (EN, 2003) which is presented in Equation (2).

$$T,i = (Q_{tr,ie} + Q_{tr,iue} + Q_{\mathrm{tr},ig} + Q_{\mathrm{tr},ij})(T_{inside} - T_{Outside}) \tag{2}$$

In this equation, $Q_{tr,ie}$ represents heat loss coefficient of transferred energy through zone envelope, $Q_{tr,iue}$ is unheated space energy transferred coefficient, $Q_{tr,ig}$ is heat loss coefficient of ground energy transferred, $Q_{tr,ij}$ shows the transferred energy coefficient through neighboring places at a significantly different temperature. The details of these parameters and methods of calculation are described in reference (EN, 2003). Also, the energy loses through the ventilation system are considered. The other equation for simulating ventilation heat loss is as Equation (3).

$$V_i = H_{v,i}(T_{inside} - T_{Outside}) \tag{3}$$

Where, $H_{v,i}$ represents design ventilation heat loss coefficient. For more information, the details of calculating this coefficient are presented in Ref. (EN, 2003).

2.2 Heating Systems

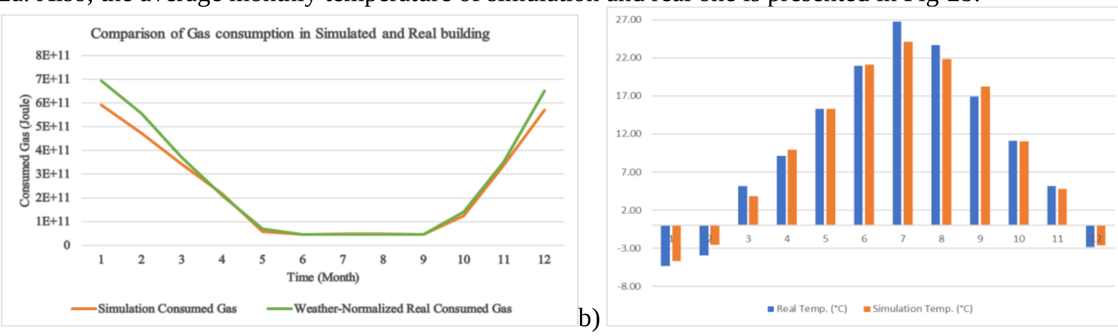
Steam supplied to cast-iron radiators is generated through a 160 Pa boiler (2,713,000 BTU/Hr. input) for the steam system and domestic hot water (DHW) is provided by a 410,000 BTU/Hr. gas-fired water heater. The variable flow pump is implemented to feed boiler and indirectly contribute to flow in the distribution system. Also, the electrical equipment and occupancies' generated energy is considered by utilizing the schedule time of presenting occupancy, implementing equipment, utilizing lighting system, and DHW flow rate.

2.3 Weather condition

A weather file for Chicago's O'Hare airport was used for this model using an EnergyPlus default.

2.4 Energy Modelling and evaluation

By considering the thermal characteristics of the building materials, ventilation system of the building, the weather condition and energy generation system, the building thermal system is modeled by Energy-plus. In order to evaluate the energy modeling, consumed gas in the sample year has been compared with real data presented in figure 2a. Also, the average monthly temperature of simulation and real one is presented in Fig 2b.



a) b)

Figure 2: a) Consumed gas in simulated and real building, b) Outdoor temperature of real building and simulation

The modeled gas consumption matches up well with the actual consumed gas in the summer months and in the spring/fall months. In the winter months, the modeled consumption is slightly lower than the actual consumption data because of the difference between actual temperatures and warmer weather in the weather file. The maximum difference between real data and simulation is less than 14% and the average error is less than 8%.
The maximum difference occurred when the temperature difference between simulation and reality is almost 12%. Also, the difference is predictable because of ignoring the effects of air changes during the door opening time. Moreover, by considering the effect of increased infiltration in winter, the model aligns well with actual consumption. Accordingly, the simulation results of the steam heating system are acceptable.

2.5 Pre-Upgrading of Heating System

Based on the initial system, application of smart controllers seems impossible because of the boiler condition, radiators valve, and simple regulator of burner. So, upgrading boiler and its burner to a new one including the ability for variable flow could results in application of control methods potential. Also, steam traps must be redesigned including control valve to regulate the steam based on the zones temperatures, and smart thermostats have to be installed on radiators to prepare the condition of application of control system.

3. DESIGN CONTROL METHODOLOGY

The designed steam heating system includes lots of constraints which force us to optimize systems by utilizing variable speed equipment. By considering the upgraded system including control valves, smart thermostats, and variable speed flow pump as the condensate system, flow control could be employed to improve steam heating system efficiency. In other words, in order to minimize consumed energy in steam system, the rate of pump flow which feeds the boiler and the steam rate which is controlled by control valve in heating system is optimized. The controllers are designed based on minimizing consumed energy as well as providing thermal comfort condition in various thermal zones. Based on the initial assumptions, the thermal zones are occupied all day long, so are the set points at comfort for each zone. By considering the utilized facilities in HVAC system including steam boiler, burner controller, control valve, and pump, the flow rate could control the consumed energy based on the fixed output designed temperature. In other words, while you are going to set boiler output steam temperature at 107°C, and the transferred flow is reduced, the burner must work less to supply required energy and consumed gas decreases by this method. On the other hand, the transferred heating rate in every zone is reduced because of less feed hot steam. The steam flow rate is determined based on the condensate pump flow rate and indoor temperature. So, tuning the flow of condensate pump as well as regulating radiators steam flow based on condensate flow by considering both objectives is required to provide comfort condition as well as optimized energy consumption.
By considering the initial condition of the real building, the indoor temperature of the first floor, second floor, and third floor is set on 20 °C, 23 °C, and 25 °C respectively.

3.1 On/Off Controller

The initial controller which is used to set indoor temperature is an on/off method which controls the temperature by the steam regulator of the zones. Also, an energy management method is utilized to improve comforts by fixing temperature through regulating the flow rates in various thermal zones. The upper and lower level of hysteresis loop are set on 108°C and 103°C for boiler output respectively. In order to reduce the consumed energy of HVAC system, the regulator controlled by an on/off switch is employed to turn the burner on/off based on the zones thermostats feedback. Also, the flow of feed water pump and steam flow rate are reduced by considering the comfort condition which is resulted in increasing the time of releasing energy through steam. The mean temperature is considered in the range of (20,25) and the hysteresis loop is designed based on this period. Based on the initial system and by considering the upgraded facilities, the on mode is designed based on the 0.6 of the initial flow rates.

3.2 PID Controller

The PID controller is a common feedback controller widely used in industry. This controller could be tuned by numerical methods such as Ziegler Nichols, GA, and fuzzy logic system (Khanmirza *et al.* ,2016). By considering energy optimization as well as setting indoor temperature as the objectives, GA and fuzzy logic systems are utilized to tune PID coefficients. The PID controller is designed to regulate the flow rate of condensate pump in HVAC system. The output of the controller is forced to set in the range of (0.03,0.6) based on the initial system to improve controller effectiveness. The PID controller is implemented in SIMULINK to tune building HVAC system. The PID output is defined as the input of Energyplus combined with SIMULINKK through MLEP.

3.2.1. PID Tuned by GA

GA is a metaheuristic optimization method which selects the parameters by the natural process. By utilizing GA, initial population improves step by step resulted in parameters which is near the final optimum state (Khanmirza *et al.*, 2016). The designing parameters of GA including population, iteration, mutation percentage, and minimum error are considered as 20, 10, 0.1, and 0.00001 respectively.

3.2.2. PID tuned by fuzzy logic system

The other effective method of PID coefficient tuning is fuzzy logic system. By utilizing this methodology, the PID coefficient is determined based on the (Wang, 1999) described instruction. The difference between systems output temperatures and the set point temperatures are considered as the errors of systems. The fuzzy logic system is designed based on the error and its derivative. The coefficients of PID controller are calculated by fuzzy logic system and always have the values in the range of (0, 0.1). In order to design fuzzy logic system, 3 membership functions for error and 3 membership functions for error derivative are considered.

3.3 Model Predictive Control

One of the most effective methods in building energy efficiency is Model Predictive Control (MPC). In order to simplify complicated multi-zone nonlinear system, the neuro-fuzzy method is utilized to determine the relation of condensate pump flow rate, ambient temperature and the mean zones temperatures. In the neuro-fuzzy method, the back-propagation method is utilized to optimize grid partitions. The information on January and February 2011 is implemented for training and testing respectively. Based on the testing results, the mean zones temperatures could be determined by model accurately (The error is less than 5%). Then, The MPC is designed based on simplified model. The prediction horizon and control horizon are assumed equal to 20 and 5 respectively.

4. RESULTS

The effectiveness of defined optimization methods is evaluated by co-simulation of different control methods in SIMULINK and building energy model in EnergyPlus. Accordingly, the building HVAC system is simulated for a sample month (January) and different control methods are applied to provide their performance.
One of the designed controllers' objective is providing thermal comfort condition especially indoor temperature. The considered set point temperatures of different thermal zones are applied in the simulation. On the other hand, the effect of every zone is considered on error (calculated based on the zones air temperatures and setpoints) applied as the input of designed controllers. The zones air temperatures resulted from application of controllers are presented in figure 3.

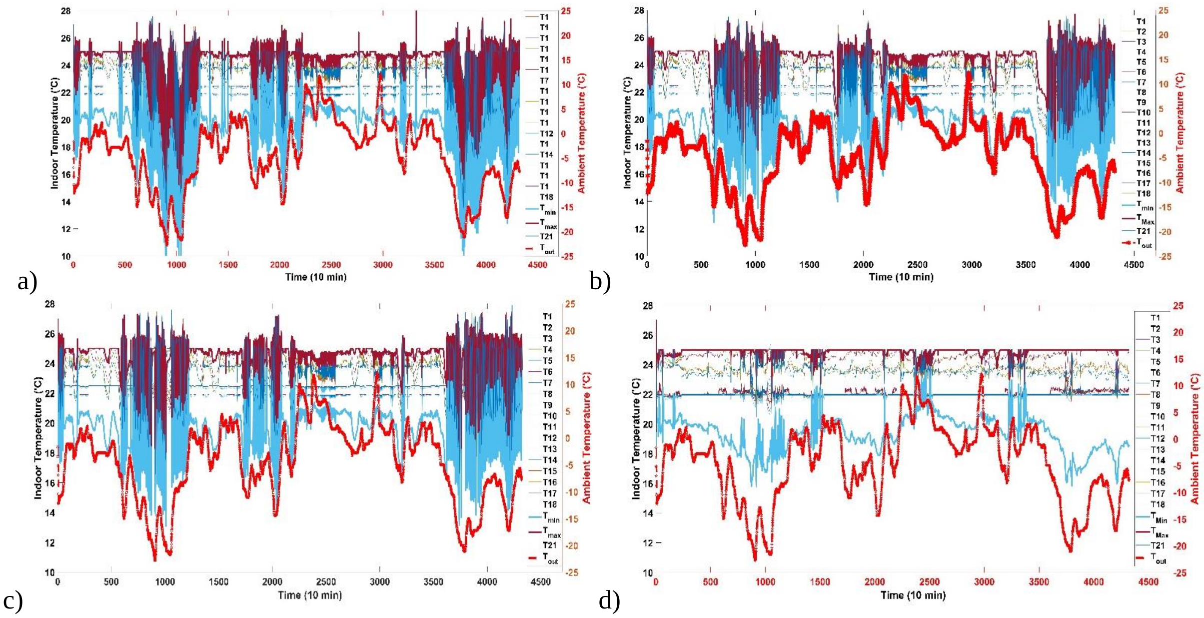


Figure 3: The zones temperatures (T1, T2, …, T21 represent the zone 1, zone 2, …, zone 21 temperature) by application of a) On/Off Controller, b) PID-GA controller, c) Fuzzy-PID controller, and d) MPC

While applying On/Off controller in upgraded system reduces the consumed energy of the HVAC system, the indoor temperature could not be set in the range of comfort accurately, especially in the very cold periods of the month. The zones temperatures are fluctuated based on the turning burner On/Off counters. Application of On/Off controller results emphasizes on the necessity of implementing smart controller for improving HVAC system efficiency and its comfortability results.

Application of GA to tune PID controllers' coefficients results in thermal comfort conditions in most of the time, while it is not useful for colder condition. Accordingly, temperature reduction is occurred in the thermal zones when the weather temperature is decreased to less than -10 °C and makes problem for the system. The zones temperatures reduction is related to extremum outdoor temperature and is not acceptable during the application. So, while the PID-GA reduces the consumed energy by the 26% in comparison to On/Off method, the occasional low interior temperature is not acceptable.

While the fuzzy-PID controller reduces the consumed energy as well, the effectiveness of this method in providing comfort condition is not acceptable based on decreasing indoor temperature of all zones in the extremum outdoor temperatures. This problem is happened more than 10 days for January. After the huge reduction, controller tries to supply required energy resulted in increasing the temperature more than setpoints. Therefore, the thermal comfort does not meet by application of fuzzy-PID controller.

Application of MPC improves energy efficiency of HVAC system as parallel of setting zones indoor temperatures in the range of comfort. According to the results, the thermal zones temperatures are controlled accurately except one zone. In one thermal zone, the air temperature is set in the range of comfort while the set-point is different and the temperature error is about 15%. In other words, the first floor, second floor, and third floor temperatures are set on 20 °C, 23 °C, and 25 °C respectively while one zone temperature is set on about 19 °C. The maximum error of the controller during 1-month application is investigated less than 15% which is occurred only in 1 zone. The performance of Neuro-fuzzy system is evaluated by temperature reduction in decreasing weather temperature. Accordingly, the Neuro-fuzzy system predicts outdoor temperature reduction accurately and increases flow to prevent decreasing indoor air temperatures.

5. DISCUSSION

In order to understand the effect of different control methods in HVAC system, the pump flow rate by application of control methods (including PID-GA, Fuzzy-PID, MPC, and On/Off) and the consumed gas in boiler burner are presented in Figure 4 to compare their effectiveness. It is expected that increasing transferred flow to boiler forces the burner to work more intensely to supply required energy. The burner injection gas and its regulation are presented by the consumed gas in burner.

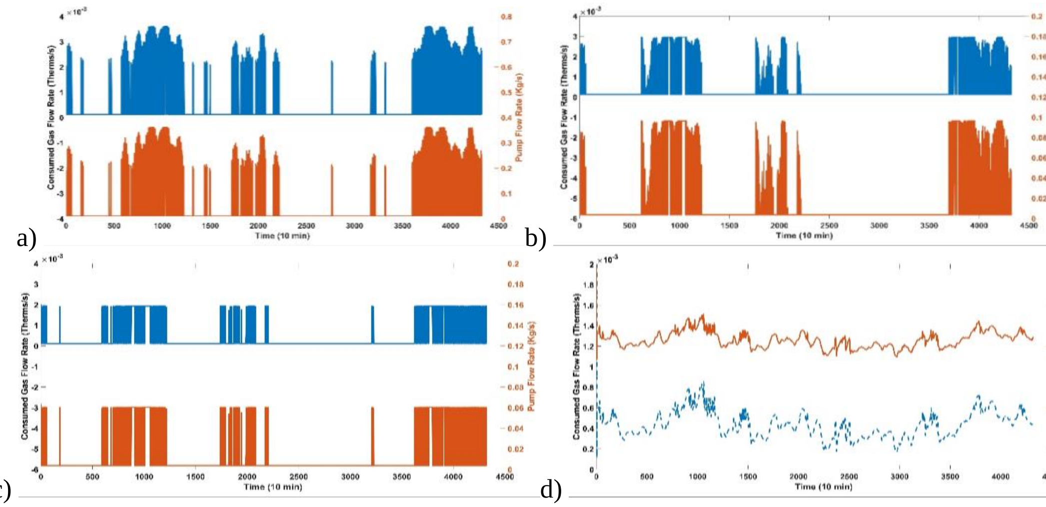


Figure 4: Flow rate of condensate pump and consumed gas of burner. a) On/Off. b) PID-GA. c) Fuzzy-PID. d) MPC

The pump flow rate and steam flow rate directly effect on consumed gas in burner. The gas flow in burner follows the pump flow rate exactly to supply required energy in order to set outlet temperature on 107°C. Decreasing consumed gas fluctuation by injecting exact flow of gas to burner reduces the energy consumption strongly in MPC. Also, turning burner on for a while by less consumed fuel is another effect of MPC while the fuzzy and GA inject fuel to burner by number of fluctuations in the extremum outdoor temperature. The On/Off controller continuously turns burner on/off to set indoor temperature in the hysteresis loop.

The other important parameter in designing controllers is consumed energy. In order to find the best control method, the integration of consumed gas in the burner and integration of electricity usage in the HVAC system are presented in figure 5.

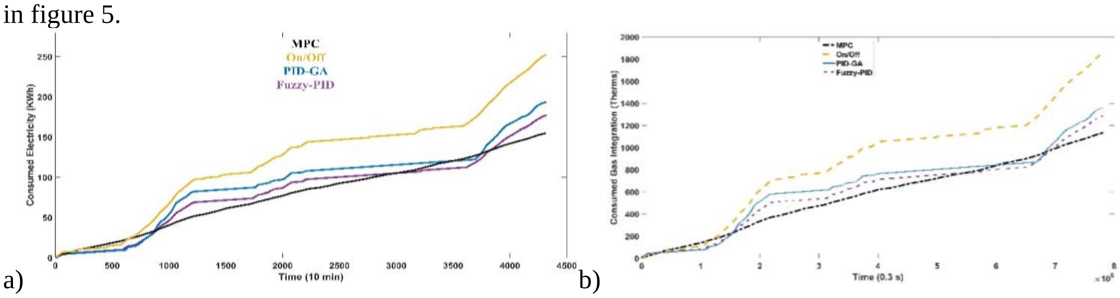


Figure 5: a) Consumed electricity integration of HVAC system (1KWh=3,600KJ). b) Consumed gas integration of HVAC system (1Therm = 105,480 KJ)

The upgraded boilers, burners and application of control valves and thermostats improve the energy efficiency of the building by more than 50% resulted in the application of On/Off controller. Based on the results, application of controllers reduces consumed energy of the upgraded system. The minimum reduction is related to PID-GA controller. In order to understand the effectiveness of controllers, the methods are compared with On/Off system. Accordingly, MPC, GA and fuzzy logic system reduce consumed energy (including gas and electricity) in HVAC system by 38%, 26%, and 30% respectively. The powerful effectiveness of MPC in reducing consumed energy represents the effect of prediction in optimizing energy consumption specially based on the comfort condition. In other words, MPC optimizes energy efficiency as well as providing comfort conditions in the acceptable range.

6. CONCLUSIONS

The tested control methodologies for providing thermal comfort and reducing energy consumption in buildings, showed that utilizing variable flow system including control valves, variable flow pump, smart thermostat, and building management system could improve the energy efficiency of the test building. Also, utilizing MPC coupling by neuro-fuzzy temperature predictor improves energy efficiency of the HVAC system by 38%. The application of fuzzy-PID controller and GA-PID controller on HVAC system reduced consumed energy by 30% and 26% respectively. The MPC approach outperformed other approaches tested in energy optimization and comfort.

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