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Energy Consumption Control of An Air-Cooled Chiller from the Use of An Automatic ON/OFF Timer System: A Real Case Study of the Penang State Mosque

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ABSTRACT

The manual operation of an ON/OFF controller that is being widely used in the air-cooled chiller of the air conditioning system is found to have resulted in a significant daily variation of electricity usage. As such, this study had aimed to investigate the effect from the application of a pre-programmed auto timer control system (ADTCS ON/OFF) on the performance of an air-cooled chiller and its main components in the Penang State Mosque. The ADTCS ON/OFF that had been developed for both the indoor and outdoor usage was installed to an existing air conditioning electrical distribution board (DB) via an external control panel, which had consisted of a selector switch with a timer operation, a power supply, an ON/OFF push button for the AHU, a lamp indicator as well as that of a digital timer (brand Honeywell HWTHC711A). Apart from demonstrating the implementation of the ADTCS ON/OFF control system as contributing to a more consistent operation time, this study had also shown the manual operation of the air-cooled chiller as contributing to an impactful loss of approximately 9.6 hours or 3182 kWh on a normal day when being compared to that of the ADTCS ON/OFF control system. Since the findings from this research had shown the use of an ADTCS ON/OFF control system in the air-cooled chiller system as providing a positive implication of the monthly electricity cost to the Penang State Mosque and the mosque institutions as a whole, this therefore suggests that a big savings of expenditure can also be achieved from the implementation of such a system.

Keywords: Energy consumption; auto timer controller; air conditioning; mosque

ABSTRAK

Kawalan manual ON/OFF yang digunakan secara meluas dalam sistem penyamanan udara jenis unit penyejuk dingin air-udara telah didapati menyebabkan berlakunya variasi dalam penggunaan elektrik harian. Oleh itu, tujuan kajian ini adalah untuk mengkaji kesan aplikasi sistem kawalan masa automatik menggunakan alat kawalan ADTCS ON/OFF terhadap prestasi sistem penyejuk dingin air-udara dan komponen-komponen utamanya di Masjid Negeri Pulau Pinang. Alat kawalan ADTCS ON/OFF yang telah direka untuk penggunaan dalaman dan luaran telah dipasang terus kepada panel pengagih kuasa elektrik (DB) melalui panel kawalan luar yang terdiri daripada suis pemilih operasi masa, bekalan kuasa, butang ON/OFF untuk AHU, lampu penunjuk dan alat pemasa digital jenama Honeywell HWTHC711. Selain menunjukkan sumbangan kepada masa operasi yang lebih konsisten, kajian ini juga membuktikan bahawa kawalan operasi secara manual telah menyebabkan kehilangan masa sebanyak 9.6 jam atau 3182 kWh berbanding penggunaan kawalan automatik alat kawalan ADTCS ON/OFF. Memandangkan penemuan daripada kajian ini telah menunjukkan implikasi positif penggunaan sistem alat kawalan ADTCS ON/OFF terhadap sistem penyejuk dingin air-udara dalam aspek kos elektrik bulanan kepada Masjid Negeri Pulau Pinang dan institusi masjid secara keseluruhan, ini menandakan bahawa penjimatan perbelanjaan yang besar juga boleh dicapai daripada penggunaan sistem tersebut apabila ianya dilaksanakan.

Kata kunci: Penggunaan tenaga; kawalan masa automatik; penyamanan udara; masjid

INTRODUCTION

The use of an air-conditioning and mechanical ventilation system (ACMV) has now become a necessity in places such as residential and commercial buildings. Together with lighting and elevators, these three were seen to have contributed to about 20% to 40% of the global total energy consumption (Ouf et al. 2016) with the ACMV system accounting to nearly half of the total building electricity usage (Zheng et al. 2016). Since the management of the building's air conditioning system is seen as a key factor for contributing to the savings of energy, this has thus prompted the study of an energy efficient design and optimisation of the ACMV system that not only provides an acceptable level of thermal comfort (Hussin et al. 2018), but also for achieving a better economic and environmental outcome (Chang 2010).

As such, among the various methods of energy savings that had been proposed for the different types of air conditioning, climatic and indoor thermal environment were found to have included the use of a variable speed drive compressor control in the refrigeration system (Chuang et al. 2019); an energy savings device with an outer shell that simultaneously decreases the shell temperature and power consumption, while increasing the energy efficiency ratio (EER) and the formulation of an efficient control algorithm that had been based on a non-linear programming and a closed loop model predictive control (Mei et al. 2018). From the energy-saving methods that had been described above, it is apparent that the improvement of the air-conditioning system had either involved the addition, integration or alteration of both the hardware and software components as well as controlling both active and reactive power (Abunima et al. 2019).

In a hot and humid country like Malaysia, the operation of an ACMV system in commercial buildings has been shown to contribute to about 57% of the country's total electricity consumption (Saidur 2009) mostly for meeting the thermal comfort needs in mosques (Hussin et al. 2015); offices/ universities (Asadi et al. 2014) and hospitals (Khalid et al. 2018).

Generally, the ACMV system is made up of evaporators, compressor and condenser units, an expansion valve as well as the air-cooled and water-cooled chillers that are connected to motors and water pumps (Teke and Timur, 2014). Since chillers form the heart of a chilled-water air-conditioning system, a poor management of its operation may then be seen as compromising its performance and resulting to a higher level of energy consumption (Afroz et al. 2018).

With this in mind, some of the studies that had been conducted for improving the air-cooled chiller performance were found to have included the use of a mist pre-cooling strategy, where along with the optimal condenser speed control, had helped to maintain a higher coefficient of performance and a 17%-19% reduction of its electricity consumption (Yu et al. 2013). By using the Stochastic Frontier Analysis (SFA), the same researchers (Yu et al. 2015) had also compared the energy performance of an existing air-cooled chiller before and after being retrofitted with a mist system, which had allowed the inflow of the pre-cooled outdoor air into the condenser unit.

Apart from the above, various control methods had also been employed to enhance the flexibility and consistency of energy savings in the air conditioning system. Two such examples had been the optimization of the ON/OFF methodology in the HVAC system along with a mechanical ventilation operation schedule that was suggested by Manjarres et al. (2017) and the culmination of a set-point reset and bilinear control techniques for reducing the on/off frequency of the chillers that was proposed by Gao et al. (2017).

In one of their studies, Budaiwi and Abdou (2013) had suggested the use of a pre-programmed ON/OFF timer system as part of an operational strategy for reducing the energy consumption in buildings with intermittent occupancy. Although the pre-programmed ON/OFF timer system had been proven to be a simple and workable method for contributing to a reduction in its energy consumption, the researchers had however, discovered its validation as being restricted by the insufficient field and measurement data.

By referring to the previous study that had been conducted on the energy consumption and the operational behaviours of the auto digital timer ON/OFF control system (ADTCS ON/OFF) in an air-conditioning system, this study had therefore attempted to extend its design and application in the air-conditioning system of a mosque as a way of gauging its energy savings effect.

METHODOLOGY

BUILDING CHARACTERISTIC

The Penang State Mosque is a historic building that is centrally located in the Penang Island with GPS coordinates of 5.406 N, 100.3006 E, which was built and opened to the public in 1981. The mosque is built like a dome and is consisted of the ground and mezzanine floors. With a total floor area of 2920 m^2, the main prayer halls on the ground floor are opened every day for praying purposes, while the mezzanine floor area that spans a total of 65.69 m^2 is only opened for special events and ceremonies such as those of *IdulFitri* prayers and religious celebrations. The Penang State Mosque has the capacity of accommodating up to 5,000 of worshippers at one time and is currently managed by the Penang Religious Affairs Department.

ACMV SYSTEM DESCRIPTION

The Penang State Mosque was originally built without any air-conditioning system, but was subsequently retrofitted with three units of 100 tonnes air-cooled water chiller system in 2003 with the intention of providing thermal comfort to the congregation in the main prayer hall.

As depicted in Figure 1 (Diagram 5 to 9), the air-conditioning and mechanical ventilation (ACMV) of the air-cooled chiller is consisted of the compressor and condenser units, a thermal expansion valve, an evaporator, an air handling unit (AHU), a water pump system, an air distribution system (ducting and diffusers) as well as an electrical control panel with a 415 V, 3 ø and 50 Hz power supply. The air cooled chiller component had relied on a reciprocating (semi hermetic) compressor (Model: Carrier 30GT 100) and a HCFC-22 refrigerant (R22) with a capacity

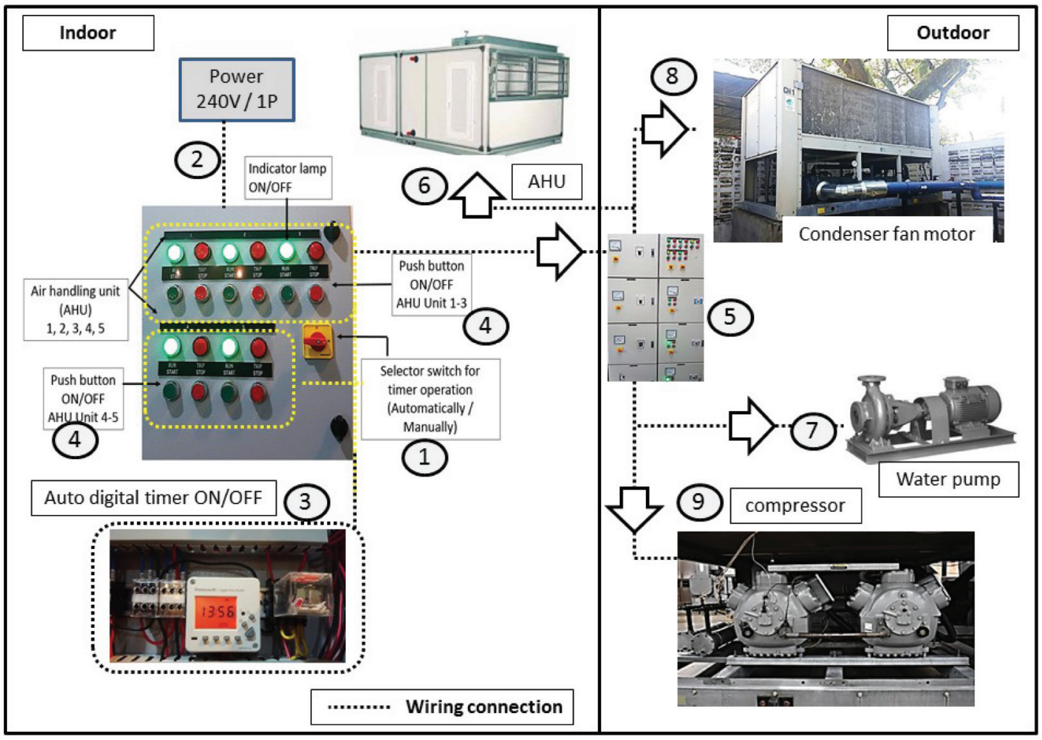


FIGURE 1. Development of the ADTCS ON/OFF control panel system with wiring connections

of 1.27 kW per ton at full load that operates at an outdoor temperature of 35 °C.

Prior to the implementation of an ADTCS ON/OFF control system, the switch panel, which is located about 30 m distance away from the mosque building, has been manually controlled by a mosque officer, who has a limited technical knowledge of the ACMV system.

THE DEVELOPMENT AND INSTRUMENTATION PLACEMENT OF THE AUTOMATIC ON/OFF DIGITAL TIMER CONTROL SYSTEM

The aim of this study had been to investigate the ACMV energy consumption and performance of the air-cooled chiller system from the application of an automatic ON/OFF digital timer control (ADTCS ON/OFF) system. The energy consumption from the air conditioning system was measured with the use of a PEL Ver. 102 data logger, which had consisted of the MA193 flexible current sensors and black safety leads that had been attached to the black alligator clip voltage sensor and has the capability for measuring the instantaneous electric variables from the 3ø 415 V terminal wire supply with the accuracy of the current and voltage probes set at ± 1% ± 15 A and ± 2.5% ± 0.4 V, respectively. As shown in Figure 2, the PEL instrument is being kept in the electrical room, which is located in front of the air-conditioning electrical power panel. All of the instantaneous data that were captured automatically at a 2-minute interval would then be saved directly in the PEL memory card and subsequently downloaded to a computer for analysis purpose.

The ADTCS ON/OFF control system that had been developed for both the indoor and outdoor usage was then installed into the existing air conditioning electrical distribution board (DB) via an external control panel, which had consisted of a selector switch with a timer operation, a power supply of 240V, an ON/OFF push button for the AHU, a lamp indicator as well as that of a digital timer (brand Honeywell HWTHC711A). The Honeywell digital timer has a total of 17 programmable ON/OFF channels with an accuracy of ± 1s/day at 20 °C, while the overall indoor and outdoor system had been connected to the ADTCS ON/OFF controller as shown in Figure 1. A detailed list of the items and the wiring diagram are thus depicted in Table 1.

EXPERIMENTAL SETUP AND ANALYSIS

The development and experimental setup for the ADTCS ON/OFF controller is thus shown in Figure 3 and had been applied on two manually operated air-cooled chillers, but without the use of a timer (normal without timer), two fully functional chillers (Case 1) and on all of the fully operated air-cooled chillers (Case 2).

The ADTCS ON/OFF controller was then installed into an existing electrical power distribution board (DB), which connects the controller to all of its components and was used in the pilot test that had been carried out on 04th August 2018 to 05th August 2018 (n = 2 days).

Since the ADTCS ON/OFF control system had exhibited good operational behaviours from the pilot test, a comparative study was then conducted on the respective three scenarios with the following time frame: 6th August 2018 to 10th August 2018 (n = 5 days) for Case 1, 16th August 2018 to 20th August 2018 (n = 5 days) for Case 2

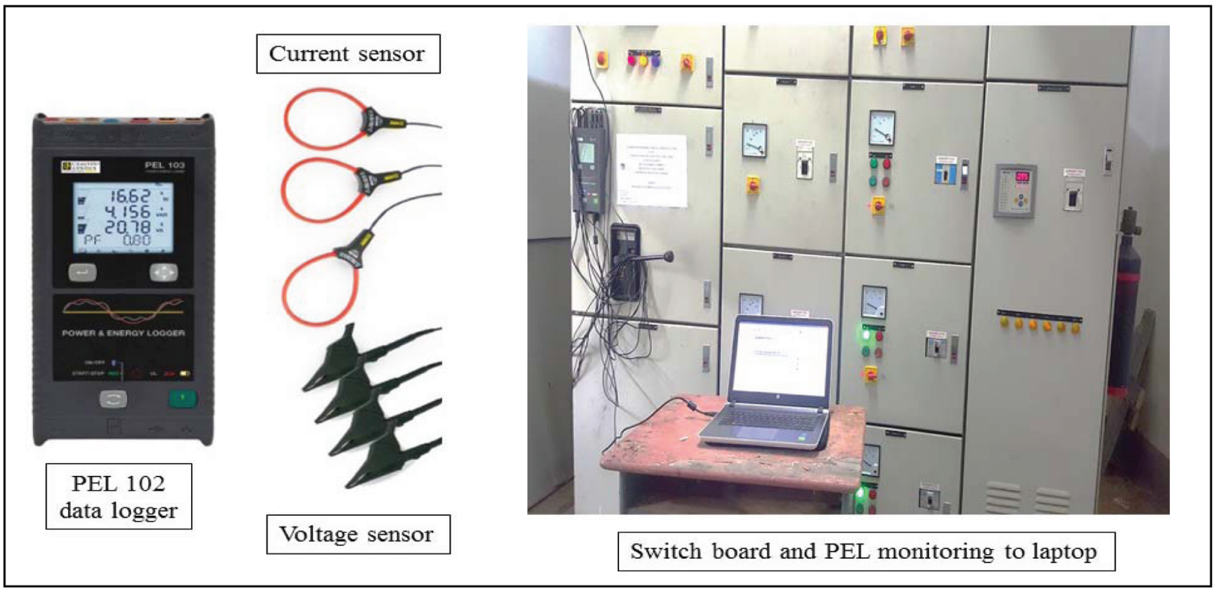


FIGURE 2. The placement of the PEL ver.102 instruments on the electrical power panel

TABLE 1. The list of items and the respective wiring diagram

Items	Type	Diagram	Function
Selector switch	-	1	Selection of a manual or automatic ON/OFF auto timer
Power supply	1ø 240 V	2	Provides the electric supply to the timer system
ADTCS ON/OFF	Honeywell HWTHC711A	3	Automatically controls the ON/OFF timer according to the programmed schedule
Push button	-	4	To turn on/off the ACMV system by pushing the ON/OFF button
Power DB	3ø 415V 50 Hz	5	Provides the electric supply to the ACMV component system
Air handling unit	Carrier 39GH	6	Turns on the AHU as shown by the wiring connection in 5
Condenser fan motor	-	7	Turns on the fan as shown by the wiring connection in 5
Water pump	Regaline 65-32	8	Turns on the water pump as shown by the wiring connection in 5
Compressor	Reciprocating induction	9	Turns on the compressor as shown by the wiring connection in 5

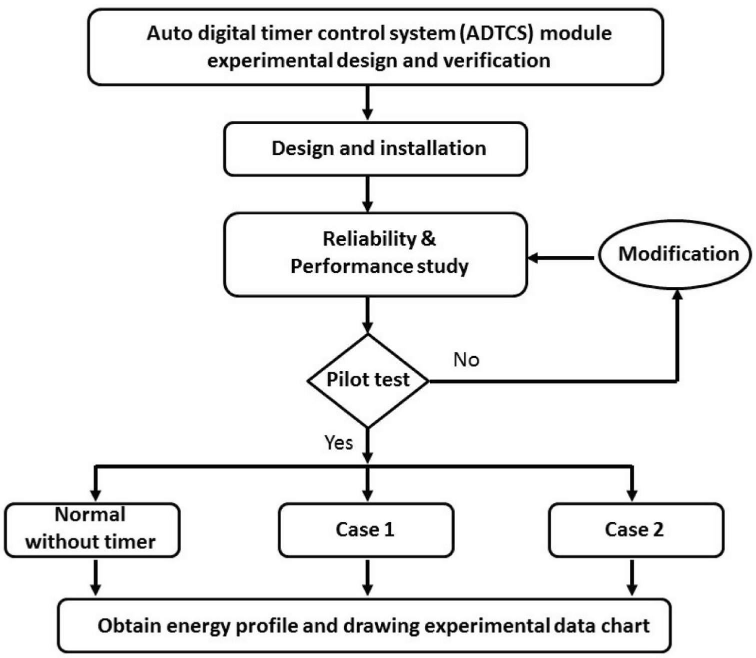


FIGURE 3. Experimental flow diagram

and 24th August 2018 to 28th August 2018 (n = 5 days) for the manual operation of the ADTCS ON/OFF controller.

As shown in Table 2, the sequence of the start-up components had been synchronized with a proper timer step control of the ADTCS ON/OFF control system with a 3.00 pm to 9.30 pm of operating time on a normal day (Saturday to Sunday) and from 10.30 in the morning until 9.30 at night on Fridays. The energy profile of the case studies that had been generated from the graphical illustration of the current (ampere) and power consumption (kW) usage of the case studies were then analysed with the use of an IBM SPSS software version 21.0 (SPSS 2012). By using the Analysis of Variance (ANOVA), a 5% of significance was then employed to quantify the idea of the statistical significance.

TABLE 2. Schedule of the ON/OFF chiller system that is controlled by a digital auto timer

Operation days	On time	OFF time	Duration	Remarks (hrs.)
Monday	3.00 PM	9.30 PM	6.5	Normal day
Tuesday	3.00 PM	9.30 PM	6.5	Normal day
Wednesday	3.00 PM	9.30 PM	6.5	Normal day
Thursday	3.00 PM	9.30 PM	6.5	Normal day
Friday	10.30 PM	9.30 PM	11.0	Friday prayer
Saturday	3.00 PM	9.30 PM	6.5	Normal day
Sunday	3.00 PM	9.30 PM	6.5	Normal day

RESULTS AND DISCUSSIONS

By referring to the electrical current (ampere) that had been plotted in Figure 4, the results had clearly shown the use of a ADTCS ON/OFF control system in Case 1 and Case 2 as consistently adhering to the scheduled operating time, while those from the manually operated ON/OFF system was found to have contributed to the erratic schedule and also to the fluctuating electricity consumption of the air-cooled chiller system.

As shown in Figures 5, 6 and 7, the standard power consumption of the air-conditioning system that were obtained from the strict timing of the ADTCS ON/OFF control system in Case 1 and Case 2 had thus implied the ability of the controller for overcoming the mishandling and inconsistencies from the use of a manually operated system, although the power consumption of the chillers in Case 2 had shown to be 27% higher than that of Case 1. Since there had also been a minimum fluctuation of energy consumption that was observed from the use of a fixed operating time, the newly proposed ADTCS ON/OFF controller can thus be regarded as a form of energy savings strategy. In one of their studies, Budaiwi and Abdou (2013) had not only observed the adaptability of the ADTCS ON/OFF control system when being used with the other apparatuses, but also no occurrence of breakdowns or delays when the system was being used along with the other components.

As shown by the results in Figure 7, the obvious variations that were observed from the manual operation had also implied the susceptibility of the system to human errors as resulting in a high monthly variation of energy consumption as opposed to the daily energy savings of 52 kW and 88 kW on Fridays from the use of an automated ADTCS ON/OFF control system. Terrill and Rasmussen (2016) have found that an intermittent occupancy and limited operator expertise in many religious facilities are the major impact to the energy consumption of ACMV system. Apart from the human errors, the energy usage fluctuation that had been due to the ad-hoc activities in the mosques were also found to

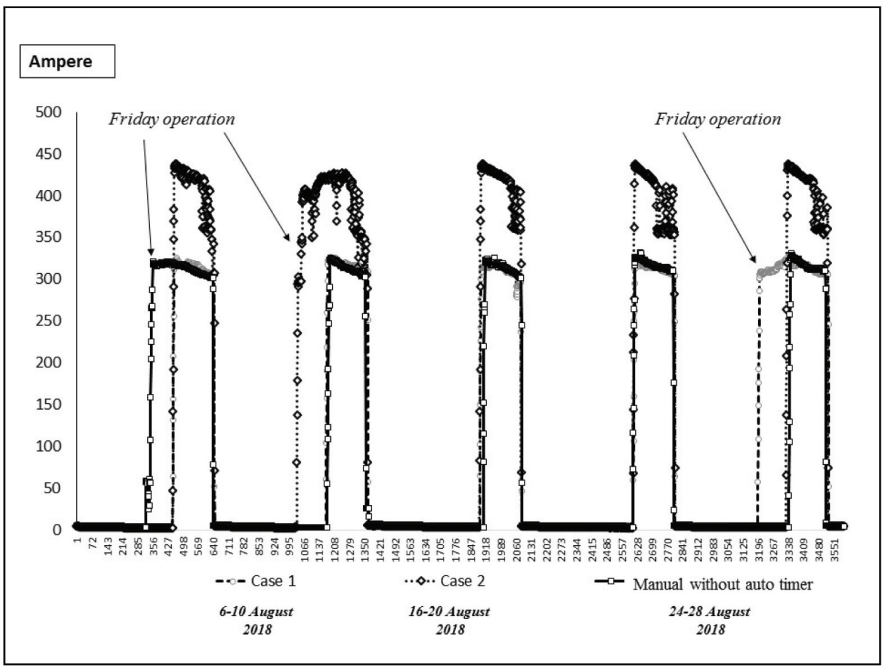
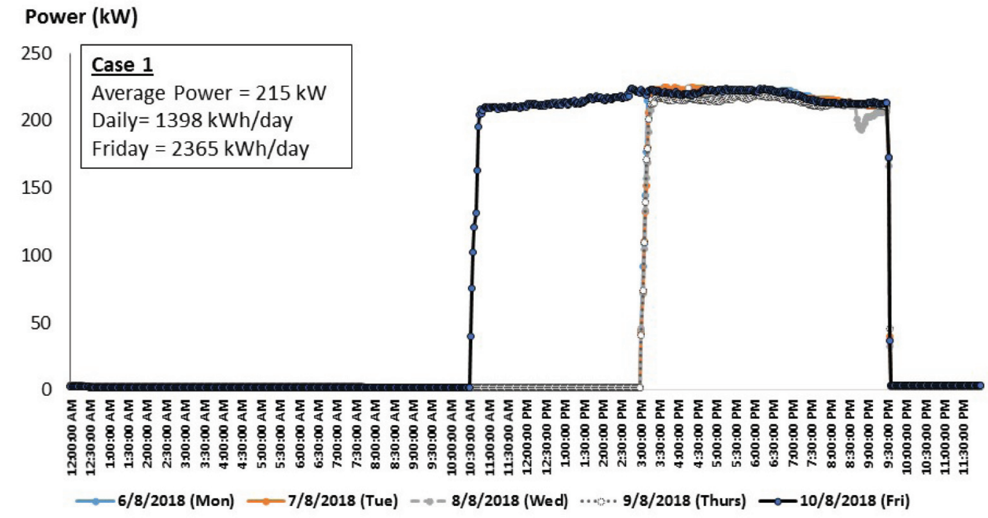
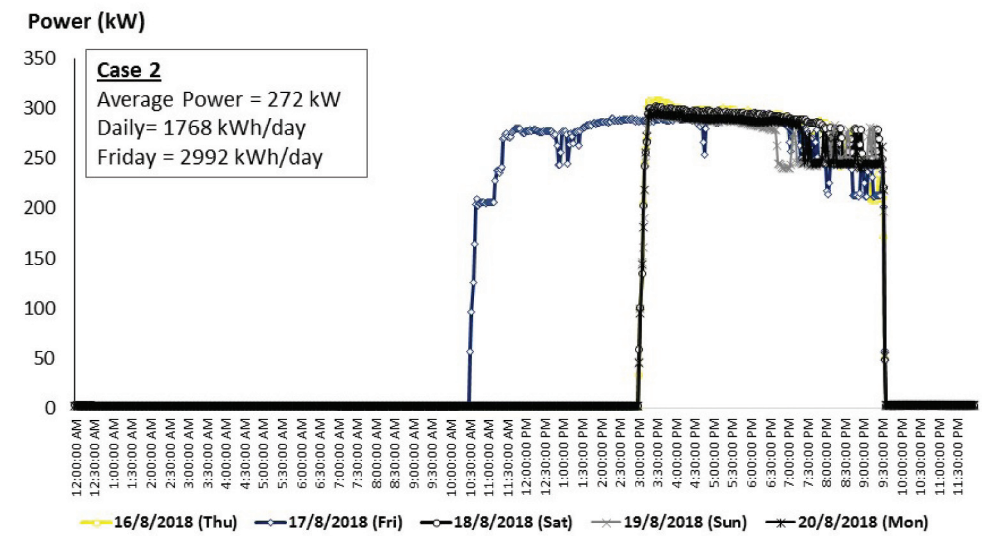


FIGURE 4. Comparison of the measured current (ampere) between Case 1, Case 2 and the manual operation of the switch



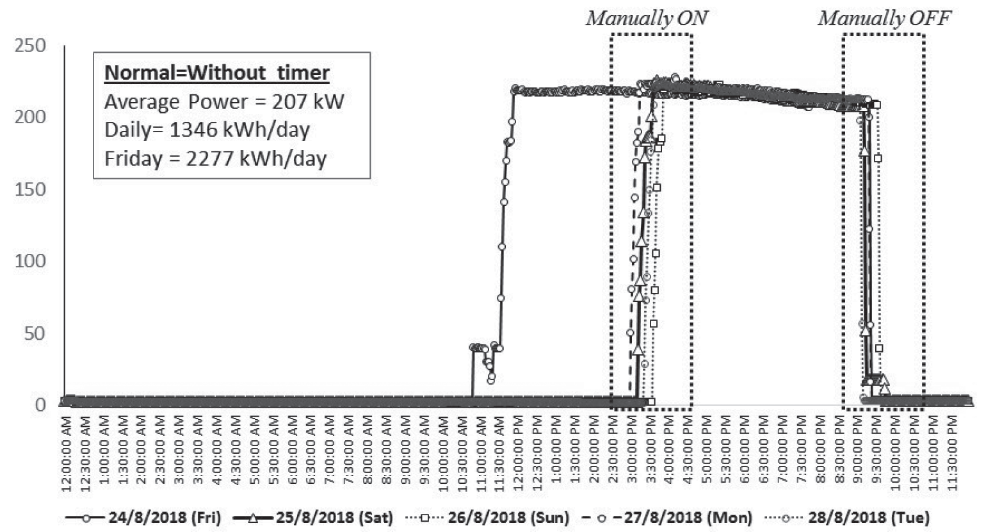
Descriptions	Status	Average Power (kW)	Load usage
Air-cooled chiller no. 1	ON	47.78	50 %
Air-cooled chiller no. 2	Standby	3.30	1.5 %
Air-cooled chiller no. 3	ON	95.56	100 %
Pump (P1, P2, P3)	ON	32.78	100 %
Air handling unit (Ahu-1,Ahu-2, Ahu-3, Ahu-4, Ahu-5)	ON	43.51	100 %

FIGURE 5. Measured air-conditioning electricity power consumption for Case 1



Descriptions	Status	Average Power (kW)	Load usage
Air-cooled chiller no. 1	ON	47.78	50 %
Air-cooled chiller no. 2	ON	47.80	50 %
Air-cooled chiller no. 3	ON	95.56	100 %
Pump (P1, P2, P3)	ON	32.78	100 %
Air handling unit (Ahu-1,Ahu-2, Ahu-3, Ahu-4, Ahu-5)	ON	43.51	100 %

FIGURE 6. Measured air-conditioning electricity power consumption for Case 2



Descriptions	Status	Average Power (kW)	Load usage
Air-cooled chiller no. 1	ON	47.78	50 %
Air-cooled chiller no. 2	Standby	3.30	1.5 %
Air-cooled chiller no. 3	ON	95.56	100 %
Pump (P1, P2, P3)	ON	32.78	100 %
Air handling unit (Ahu-1,Ahu-2, Ahu-3, Ahu-4, Ahu-5)	ON	43.51	100 %

FIGURE 7. Measured air-conditioning electricity power consumption from the manual operation of the switch

have contributed to the 5% variation of energy consumption and its different energy profile.

The overall statistical results of the power consumption from all of the setups are thus tabulated in Table 3. In the case of the manual operation setup, the power consumption for a normal day was found to have been between 2.09 kW to 227.68 kW with the mean value of 198.87 kW and standard deviation of 55.95 kW, while the power consumption on Fridays had been in the range of 2.22 kW to 220.13 kW with a respective mean and standard deviation value of 162.28 kW and 59.80 kW.

As for Case 1 with the use of an ADTCS ON/OFF control system in two of the fully-operated chillers, the power consumption for a normal day and Fridays were discovered to have been between 2.09 kW to 224.74 kW and 2.12 kW to 218.28 kW with a respective mean and standard deviation values of 224.74 kW and 22.20 kW as well as that of 218.28 kW and 31.27 kW, while the power consumption (kW) for Case 2 had shown a range of 1.66 kW to 307.81 kW on normal days and 2.31 kW to 289.28 kW on Fridays with a respective mean and standard deviation values of 273.16 kW and 35.31 kW and those of 258 kW and 45.22 kW.

A one-way ANOVA that was conducted between the studied cases for evaluating the effect from using the ADTCS ON/OFF control system (in Case 1 and 2) with those of a manually operated air-cooled chiller system had revealed a statistically significant difference between the Friday groups ($F(2,361) = 80.81$, $p < 0.05$) as well as that for a normal day ($F(2,589) = 241.42$, $p < 0.05$).

TABLE 3. The overall statistical results of the power consumption for Case 1, Case 2 and the manual operation of the switch

	Friday 10.30 am -2.30 pm	Normal 3.30 pm-9.30 pm
Manual control of the air-conditioning system		
Mean	*162.28	**198.87
Min	2.22	2.09
Max	220.13	227.68
Std. Dev	59.80	55.95
Case 1	Friday 10.30 am -2.30 pm	Normal 3.30 pm-9.30 pm
Mean	*205.39	**213.66
Min	2.12	2.09
Max	218.28	224.74
Std. Dev	31.27	22.20
Case 2	Friday 10.30 am -2.30 pm	Normal 3.30 pm-9.30 pm
Mean	*258.00	**273.16
Min	2.31	1.66
Max	289.78	307.81
Std. Dev	45.22	35.31

*Significantly different at p<0.05 **Significantly different at p<0.05

TABLE 4. Summary of the variation that had occurred from manual operation of the ON/OFF switch

Date	Actual ON	Schedule	Diff (hrs.)	Actual OFF	Schedule	Diff (hrs.)
24/8/2018	10.50 PM	10.30 PM	-0.2	9.10 PM	9.30 PM	-0.2
25/8/2018	3.12 PM	3.00 PM	-0.12	9.22 PM	9.30 PM	-0.08
26/8/2018	3.36 PM	3.00 PM	-0.36	9.46 PM	9.30 PM	+0.16
27/8/2018	3.00 PM	3.00 PM	0	9.22 PM	9.30 PM	-0.08
28/8/2018	3.22 PM	3.00 PM	-0.22	9.08 PM	9.30 PM	-0.18
		Total	0.90			0.70

These differences could have been due to the manual operation of the ON and OFF control at different hours, the untrained personnel in handling the system facilities and the lack of standard operation procedures for operating the air-conditioning system which was common found in religious facilities (Terrill and Rasmussen, 2016). Hence, by basing on the above findings, these results had thus suggested the power consumption as having an effect on the operational behaviours since the energy consumption on Fridays and daily air-cooled chiller operation was found to have been controlled and minimized with the application of a pre-programmed ADTCS ON/OFF control system.

The time variations of the operating hours that were resulted from the manual handling of the ON and OFF operating process as shown in Table 4 had also revealed the daily average variation for turning on the system as being 18 minutes and the turning off the system as 14 minutes. As such, the monthly variation that had resulted from the respective manual activation and deactivation of 5.4 hours and 4.2 hours were found to have contributed to a monthly operation loss of 9.6 hours. However, the acceleration on the wear and aging of the air-cooled chillers components from the manual operation that had compromised the thermal comfort aspect (Gao et al. 2017) and the monthly electricity cost would require a further analysis on the Penang State mosque and those of the other mosque institutions.

CONCLUSION

This study had presented an auto digital timer ON/OFF control system (ADTCS ON/OFF) for managing and controlling the power consumption of the daily operation in the Penang State mosque. The findings had not only demonstrated the use of an ADTCS ON/OFF control system as contributing to an energy savings of 52 kW and 88 kW in the respective daily and Friday operation during its intermittent occupancy, but can also be retrofitted into the existing air conditioning components without causing any delay, issues or breakdown in its operation. Apart from showing the power consumption as having an effect on the ON and OFF operational behaviours as shown by its controlled energy consumption usage, this study had also demonstrated the manual activation and deactivation of the switch as contributing to a 5.4 hours and 4.2 hours variation in the monthly time, respectively. Based on the above results, the empirical experiment approach had thus furnished an energy savings strategy in the ACMV operating system that can be specifically applied to the Penang State mosque and to the mosque institution as a whole.

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