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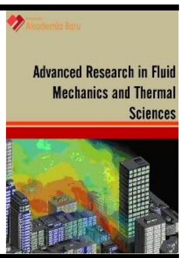


# Cooling Capacity Optimization of Absorption Chillers using Binary Integer Programming

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Fatin Nabila Jamaluddin[1,*], Zainal Ambri Abdul Karim[2], Mohd Amin Abdul Majid[1], Takashi Sasaki[3]

[1] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[2] Centre for Automation Research and Electric Mobility, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[3] Hitachi Asia (Malaysia) Sdn. Bhd. Suite 17.3, Level 17, Menara IMC, 8, Jalan Sultan Ismail, 50250, Kuala Lumpur, Malaysia

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**ABSTRACT**

In this paper, the plant runs eight units of chiller with the same design specification every hour. By contract, the plant must supply 13 205 RT per hour for 24 hours a day. However, in this plant case scenario, all units of chillers are not able to run at full capacity due to low in ΔT of CHW and it affected the CHW production. Typically, a chiller plant that has multi-chillers do not operate all units of chiller at the same time. Therefore, a simple binary integer programming model is created to reduce the number of unit of chiller operated per hour while satisfying the cooling demand by the customer and system operational constraints. The model is solved using Solver tool in Microsoft Excel. The model showed after optimization, the number of unit of chiller operated per hour is possible to reduce one despite low in ΔT of CHW especially during the day and the total CHW production per hour is reduced to 12.5%.



## 1. Introduction

Nowadays, absorption refrigeration system is well known in industries as it uses an environmental friendly refrigerants and cheap alternative sources such as geothermal, biomass, solar energy and waste by product heat source which leads to low demand of electricity [1-3]. This proved that it plays an important role in waste heat recovery and renewable energy utilization [4]. Despite having a lower coefficient of performance (COP) than the vapor compression systems, absorption refrigeration system has low noise generation, less frequent maintenance requirements, high capability and has a better capacity management and control [5].

The plant in this study runs eight units of double effect water-lithium bromide steam absorption chillers. The benefit of double effect absorption cycle is that it has better performance than single effect absorption cycle. According to Herold *et al.,* [6], the range COP for double effect absorption chiller is between 1.0 – 1.2. Gomri [7] also claimed that COP of double effect is twice the COP of single effect.

* *Corresponding author.*
*E-mail address: fatin3584@gmail.com (Fatin Nabila Jamaluddin)*

There are many works that focused on optimizing the operating condition of the chiller's components. Studies have been done by controlling the generator temperature is helping to improve the COP and exergy efficiency of the chiller [8-10]. Maryami *et al.,* [11] analyzed that the COP value is increased when the condenser temperature decreased and evaporator temperature increased.

According to the Abdullah *et al.,* [12] chiller system is one of the contribution to the electrical consumption of the building. Besides that, handling a chiller plant is common as a complex and difficult task. Hence, there are many researches had studied methods to improve the individual chiller performance by using operations research technique. Maria *et al.,* [13] applied non-linear programming method to determine the optimal distribution of a given amount of total heat transfer and to maximize the COP. Besides that, Chaves-Islas *et al.,* [14] implemented mixed integer nonlinear programming method to optimize the NH3-$H_2O$ absorption refrigeration system while Rubio-Maya *et al.,* [15] using nonlinear programming method to minimize the annual operating cost of single effect water-lithium bromide absorption refrigeration.

Then, several studies are done related to multiple chillers in chiller plant. Usually for a chiller plant that has multiple chillers, not all chillers are operating at the same time. This is because by reducing the number of chiller operated at one time, it can help to reduce the number of auxiliaries along with the chillers and to help optimize the kW/ton. Saeedi *et al.,* [16] applied a robust optimization method based on uncertainty of cooling demand in multi-chiller system with the objective to minimize the electric power consumption. Wei *et al.,* [17] developed a schedule for multiple chillers according to the demand period to minimize the total cost of the chiller plant. Chang [18] suggested using dynamic programming and Chang *et al.,* [19] proposed branch and bound method to solve the optimal chiller sequencing and the results showed a reduction in energy consumption.

Furthermore, the installation of thermal energy storage (TES) is proved to be a great help to minimize the energy consumption for chiller plant. Phase change material (PCM) is one of the evolution TES technique and Mohamad *et al.,* [20] had investigated the phase change behavior and mechanism to optimize the thermal properties of calcium chloride hexahydrate/ graphene nanoplatelets ($CaCl_2$-6$H_2O$/GNP) nanocomposite PCM for TES application operation. According to the Alva *et al.,* [21] and Selamat *et al.,* [22] the TES used a lower rate when cooled the water at night and can operate solely during peak hours.

In this paper, the plant operated eight units of chiller with same design of specification for 24 hours and required to supply 13 205 RT per hour to attain the chilled water (CHW) demand as per contract. Theoretically, if eight units of chillers operate at full capacity, the total CHW production will exceed the CHW demand. Thus, instead of running eight units of chiller at one time, it is better to reduce number of chiller operated because it can help to save the energy consumption and avoid the excessive of total CHW production per hour.

### *1.1 Chiller System Description*

The plant runs eight units of steam absorption chiller to attain the CHW demand by the customer. Every chiller has a same design specification with a maximum capacity of 2 500 RT and is labeled alphabetically. According to the plant design, the steam and chilled water flow are from the same header sensors respectively. Thus, the steam temperature, mass flow rate ($\dot{m}$) of chilled water, CHW supply temperature and CHW return temperature should be distributed equally.

In order to achieve an optimum COP value, 8 bar of saturated steam pressure and a saturated temperature of 170.4°C is supply to the all units of chiller. Each chiller has a same drain temperature, 65°C. While, to achieve a maximum cooling capacity, the mass flow rate of CHW should be 300 kg/s with a fixed CHW supply temperature 6°C, CHW return temperature 13°C and delta-T (ΔT) of CHW 7°C as per shown in Figure 1.

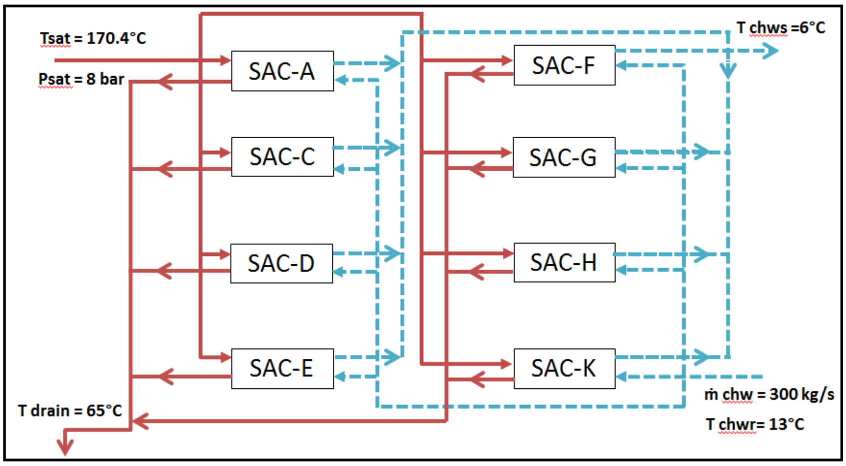


**Fig. 1.** Chiller system schematic diagram

However, in real life situation, the average CHW production per chiller is around 1 700 RT to 2 000 RT per hour depending on the CHW return temperature with an average total CHW production of eight units of chiller operated at the same time is 13 600 RT to 16 000 RT per hour

## 2. Methodology

### *2.1 Model Description*

The plant main aim is to supply the CHW demand as per contract, 13 205 RT per hour. Theoretically, it is possible to run only six units full capacity of chiller with total CHW production of 15 000 RT per hour to attain the CHW demand. However, in real life situation, the ΔT of CHW is too low especially during the off-office hours due to low usage at the customer side and it affected the CHW production which led to more number of units of chiller to operate. Thus, the objective of the model is to minimize the total CHW production per hour while satisfying the customer cooling demand and system operational constraint by applying the binary integer programming.

### *2.2 Model Formulation*

Assume that for CHW supply and return temperature and the ṁ of CHW are distributed equally to all units of chiller. There are eight units of chillers and the plant operates for 24 hours.

The chiller, i is ON (1) at hour, j when the total CHW production is less than CHW demand and OFF (0) when the total CHW production is equal or more than CHW demand.

$$X_{ij} = f(x) = \begin{cases} 1, & when\ the\ total\ CHW\ production < CHW\ demand \\ 0, & otherwise \end{cases} \tag{1}$$

The objective function of the model is total CHW production of total $i^{th}$ units of chiller for $j^{th}$ of 24 hours.

$$\sum_{i=1}^{8} \sum_{j=1}^{24} \dot{Q}_{CHW} X_{ij} \tag{2}$$

The CHW production per unit chiller is ṁ of CHW multiplying with ΔT of CHW and specific heat capacity of water.

$$\dot{Q}_{CHW_{ij}} = \dot{m}_{CHW_{ij}} C_{Pwater}(T_{CHWR} - T_{CHWS}) \quad (3)$$

where $\dot{m}_{CHW}$ is mass flow rate of CHW, $T_{CHWR}$ is CHW return temperature and $T_{CHWS}$ is CHW supply temperature. $C_{pwater}$ is a specific heat capacity of water and it is a constant value, 4.187 kJ/kg. °C. Several constraints are applied to model to ensure the objective function is achieved. First constraint is every chiller must operate at least one hour.

$$\sum_{j=1}^{24} X_{ij} \geq 1 \quad (4)$$

Second constraint is the total CHW production of operated total $i^{th}$ units of chiller must be more than or equal to CHW demand at $j^{th}$ hour

$$\sum_{i=1}^{8} \sum_{j=1}^{24} \dot{Q}_{CHW} X_{ij} \geq \dot{Q}_D \quad (5)$$

The binary integer programming is solved using a Solver tool in Microsoft Excel and spreadsheet formulation template by [23] is used as a reference. The model has two sets where every set run a test for 12 hours as per shown in Table 1 and later, the summation of two sets is accumulated to determine the total CHW production achieved per day. The time started with $t_1$ is equivalent to 12.00 am and ended with $t_{24}$ is equivalent to 23.00 pm. The result of data is shown in graph form using Microsoft Excel as per shown in Result and Discussion section later.

**Table 1**
Number of hours per set

| Set | Number of hours |
|---|---|
| 1 | $t_1 - t_{12}$ |
| 2 | $t_{11} - t_{24}$ |

## 3. Results and Analysis

According to the contract, the plant requires to supply 13205 RT per hour. However, the chillers are not able to run at full capacity due to the low ΔT of CHW as per shown in Figure 2 and it affected the CHW production. Figure 2 shows the relationship between the ΔT and ṁ of CHW taken every hour on Monday, 20th March 2017.

It can be observed that the ṁ of CHW is constant at 300 kg/s while ΔT of CHW is not constant every hour. The ΔT of CHW trend decrease from $t_4$ to $t_5$ before increase slightly at $t_6$ and drop back at $t_7$. Later, the ΔT started to increase at $t_9$ to $t_{12}$ before drop back at $t_{13}$ and increased again at $t_{14}$ to $t_{19}$. The ΔT eventually decreased at $t_{20}$ until $t_{24}$ due to the CHW supply is not fully utilize by the customers during the off-office hours caused the CHW return temperature to be low. Hypothetically, the CHW return temperature should be around 13°C to 14°C. However, in this plant case scenario, the CHW return temperature is too low, 10°C to 12°C. Based on plant design, the CHW supply temperature and ṁ is the same every hour as it measured by the sensors while the CHW return temperature has to return equally to all units of chiller from the customers as per represent in Figure 2.

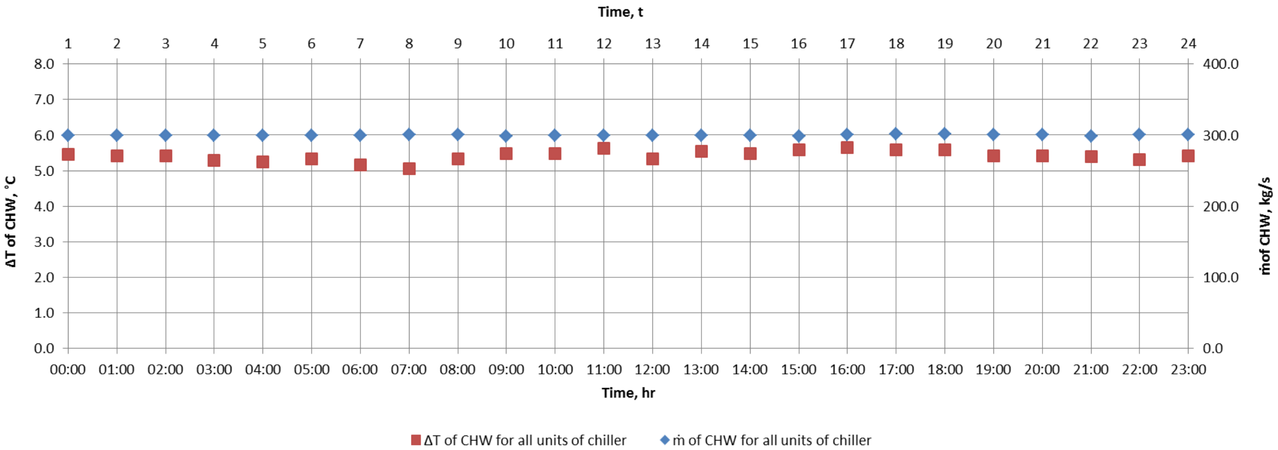


**Fig. 2.** ṁ and ΔT of CHW for all units of chiller

### *3.1 Total CHW Production After Optimization*

Based on the model, every unit of chiller will be ON state until the total production of CHW achieved the CHW demand. Once, the CHW demand achieved, the next chiller will automatically OFF. In this model, it is set to allow the chiller OFF in alphabetical order due to the chiller arrangement. Figure 3 shows the total CHW production after optimization using data on 20th March 2017. Most of the hour, especially during the day, the number unit of chiller operate per hour is reduced to one as per shown in $t_9$ onward. After midnight especially at $t_4$ until $t_8$, the consumers didn't fully utilize the CHW supply temperature caused the CHW return temperature to be low and all units of chiller need to operate at the same time to attain the CHW demand.

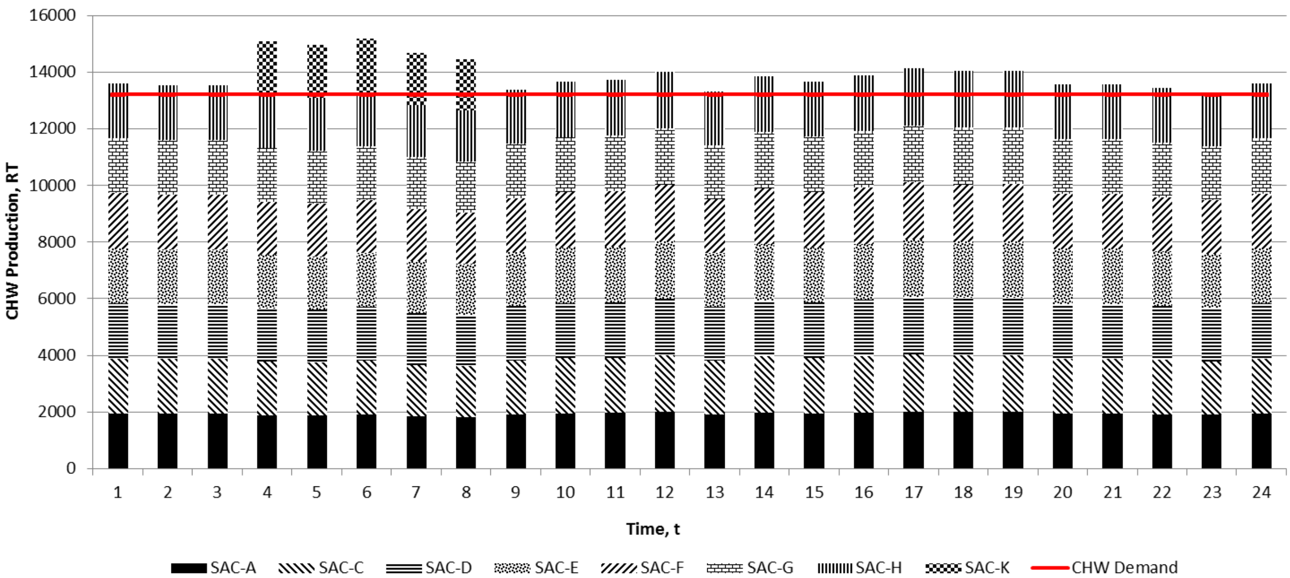


**Fig. 3.** The CHW production of all units of chiller after optimization

By reducing the one of unit of chillers operated at one time, the total CHW production per hour reduced to 12.5%. The reduction is helping to minimize the excessive production of chilled water while achieving the cooling demand by the customers. Besides that, it allows the chiller to undergo a maintenance process when needed without affecting the total CHW production.

Theoretically, in order to achieve the CHW desire by maintaining the ṁ of CHW, the ΔT of CHW must high. But, in this plant scenario, the ΔT of CHW is low especially during the after midnight because the users didn't fully utilize the CHW supply. The optimization model is solely dependent on the CHW return temperature as other parameters, ṁ and CHW supply temperature are constant. In order to improve the total CHW production and minimizing the number of unit of chiller operated at one time, the CHW return temperature must be high.

### *3.2 Total CHW Production Difference After Optimization and CHW Demand*

In Figure 4, it can be observed that, there is time, the difference between the total CHW production after optimization and CHW demand is big which led to excessive CHW production. During $t_1$ and $t_3$, the difference between the total CHW production after optimization and CHW demand is around 2% to 3%. Starting from $t_4$ until $t_8$ the difference is increased, approximately up to 15%. This is because all units of chiller had to operate at the same time due to the low in ΔT of CHW and also to ensure that the CHW demand is attained. However, at $t_9$, the total CHW production after optimization coincided again with CHW demand with 1% difference only. It can be conclude because of the starting of office hour which led to fully CHW utilization by the customers. Afterwards, the total CHW production and CHW demand gap is not that big before increase a little bit to 6% at $t_{12}$ before drop back to 1% margin at $t_{13}$.Then, at $t_{14}$ until $t_{19}$, there is a slightly increase in gap with the higher one is 7% during $t_{17}$. Later, the $t_{20}$ until $t_{23}$, the total CHW production after optimization is equivalent with the CHW demand with 1% to 3% variation.

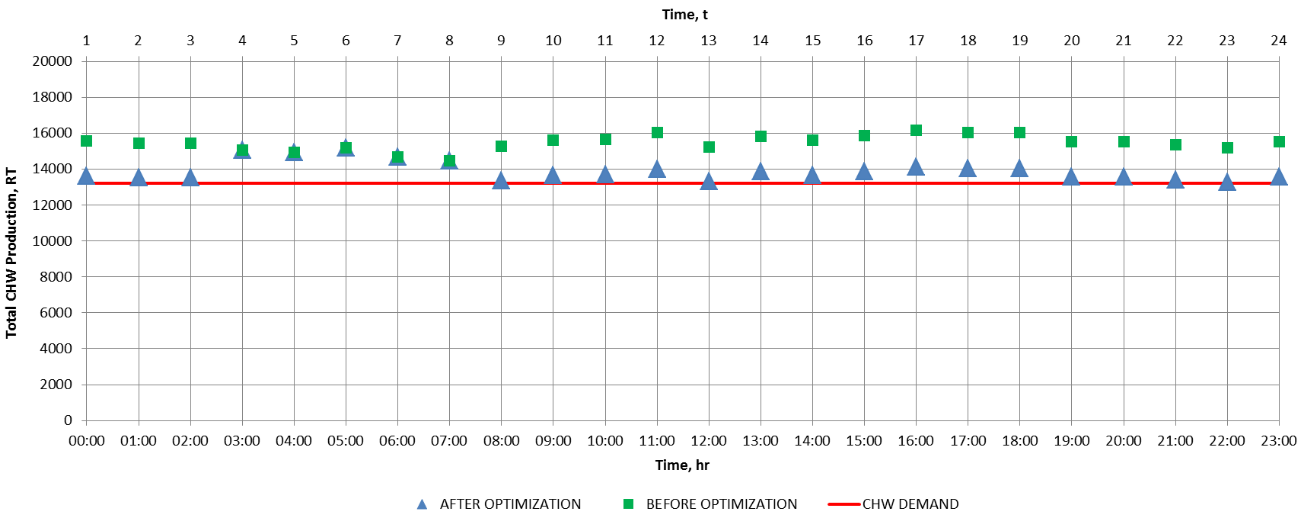


**Fig. 4.** Total CHW production before and after optimization

The Solver tool in Microsoft Excel is used to solve the problem. The results is obtained using Simplex LP engine with the solution time of 1.281 seconds. The precision of the results is 0.000001. The setup of the model is also easy to create in Microsoft Excel. This is proved that Solver tool is a user friendly. However, the only disadvantage of the Solver tool is the inability to solve a big problem due to the limitation in the variable cells and constraints. Therefore, the model has to be divided into two sets where every set run a test for every 12 hours and after that, the summation of two sets is accumulated to determine the total CHW production achieved per day.

## 4. Conclusions

Reducing number of unit of chiller operated per time can help to minimize the energy consumption while attaining CHW demand as per contract. After optimization, the total CHW production per hour can reduce to 12.5%. However, there are hours, the margin between the total CHW production after optimization and CHW demand is too big due to low in CHW return temperature.

Therefore, since the plant doesn't have thermal energy storage (TES), it is suggested for the plant to install the TES to store the excess chilled water for future usage and this will help to reduce the number of unit of chiller operate per time especially during the night. Besides that, the plant operator should have a flow control based on the CHW utilization to avoid excessive total CHW production.

In the future also, it is suggested to use other alternative user friendly software to solve the model due to the Solver tool in Microsoft Excel limitation in solving a big problem.

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## References
[1] Modi, Bhaumik, Anurag Mudgal, and Bhavesh Patel. "Energy and exergy investigation of small capacity single effect lithium bromide absorption refrigeration system." *Energy Procedia* 109 (2017): 203-210.
[2] Gong, Sunyoung, and Kiari Goni Boulama. "Parametric study of an absorption refrigeration machine using advanced exergy analysis." *Energy* 76 (2014): 453-467.
[3] Koroneos, C., and M. Tsarouhis. "Exergy analysis and life cycle assessment of solar heating and cooling systems in the building environment." *Journal of Cleaner Production* 32 (2012): 52-60.
[4] Chen, Yi, Wei Han, and Hongguang Jin. "Analysis of an absorption/absorption–compression refrigeration system for heat sources with large temperature change." *Energy Conversion and Management* 113 (2016): 153-164.
[5] Jafari, Azadeh, and Amin Haghighi Poshtiri. "Passive solar cooling of single-storey buildings by an adsorption chiller system combined with a solar chimney." *Journal of cleaner production* 141 (2017): 662-682.
[6] Herold, Keith E., Reinhard Radermacher, and Sanford A. Klein. *Absorption chillers and heat pumps*. CRC press, 2016.
[7] Gomri, Rabah. "Investigation of the potential of application of single effect and multiple effect absorption cooling systems." *Energy Conversion and Management* 51, no. 8 (2010): 1629-1636.
[8] Azhar, Md, and M. Altamush Siddiqui. "Energy and exergy analyses for optimization of the operating temperatures in double effect absorption cycle." *Energy Procedia* 109 (2017): 211-218.
[9] Arora, Akhilesh, Manoj Dixit, and S. C. Kaushik. "Energy and exergy analysis of a double effect parallel flow LiBr/H2O absorption refrigeration system." *Journal of Thermal Engineering* 2, no. 1 (2016): 541-549.
[10] Ghani, Muhammad Usman, Muhammad Zaman, and Imran Khan. "Thermodynamic modeling and optimization of double effect series flow LiBr-H 2 O vapor absorption chiller." In *2016 International Conference on Emerging Technologies (ICET)*, pp. 1-6. IEEE, 2016.
[11] Maryami, R., and A. A. Dehghan. "An exergy based comparative study between LiBr/water absorption refrigeration systems from half effect to triple effect." *Applied Thermal Engineering* 124 (2017): 103-123.
[12] Abdullah, Mohammad Kamil, and Mohd Hafiz Mohamad. "Building Energy Performance: A Case Study at G2 Building UTHM." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 50, no. 2 (2018): 161-169.
[13] Mazzei, María S., Miguel C. Mussati, and Sergio F. Mussati. "NLP model-based optimal design of LiBr–H2O absorption refrigeration systems." *International journal of refrigeration* 38 (2014): 58-70.
[14] Chávez-Islas, Luz María, Christopher L. Heard, and Ignacio E. Grossmann. "Synthesis and Optimization of an Ammonia− Water Absorption Refrigeration Cycle Considering Different Types of Heat Exchangers by Application of Mixed-Integer Nonlinear Programming." *Industrial & Engineering Chemistry Research* 48, no. 6 (2009): 2972-2990.

[15] Rubio-Maya, Carlos, J. Jesús Pacheco-Ibarra, Juan M. Belman-Flores, Sergio R. Galván-González, and Crisanto Mendoza-Covarrubias. "NLP model of a LiBr–H2O absorption refrigeration system for the minimization of the annual operating cost." *Applied Thermal Engineering* 37 (2012): 10-18.
[16] Saeedi, Mohammadhossein, Mahdi Moradi, Meysam Hosseini, Armin Emamifar, and Noradin Ghadimi. "Robust optimization based optimal chiller loading under cooling demand uncertainty." *Applied Thermal Engineering* 148 (2019): 1081-1091.
[17] Wei, Xiupeng, Guanglin Xu, and Andrew Kusiak. "Modeling and optimization of a chiller plant." *Energy* 73 (2014): 898-907.
[18] Chang, Yung-Chung. "An outstanding method for saving energy-optimal chiller operation." *IEEE transactions on energy conversion* 21, no. 2 (2006): 527-532.
[19] Chang, Yung-Chung, Fu-Ann Lin, and Chin Huang Lin. "Optimal chiller sequencing by branch and bound method for saving energy." *Energy conversion and management* 46, no. 13-14 (2005): 2158-2172.
[20] Mohamad, Ahmad Tajuddin, Nor Azwadi Che Sidik, and M'hamed Beriache. "Thermo Physical Enchancement of Advanced Nano-Composite Phase Change Material." *Journal of Advanced Research in Applied Mechanics* 54, no. 1 (2019):1-8.
[21] Alva, Guruprasad, Yaxue Lin, and Guiyin Fang. "An overview of thermal energy storage systems." *Energy* 144 (2018): 341-378.
[22] Selamat, Ubaidullah, Kahar Osman, and Arul Hisham A. Rahim. "Heat and Flow Analysis of a Chilled Water Storage System using Computational Fluid Dynamics." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 57, no. 1 (2019): 131-140.
[23] Hillier, F.S. and G.J. Lieberman, Introduction to Operations Research, 9th edition, New York : McGraw-Hill, 2010.