ENERGY QUIPSYS

Energy Equipment and Systems

Indoor temperature and energy optimization using Energyplus and Taguchi method: A case study

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ABSTRACT

Cooling system is in charge of a high percent of total energy consumption in buildings. Different cooling systems and devices have different effects on the cooling load and energy consumption. The main objective of this paper is to study the effects of floor and ceiling temperature in comparison with other parameters including location of air diffusers and application of insulation and sealant. On the other hand, hospitals are huge buildings with high energy requirements and systems compared to other buildings such as universities, schools and offices. In this paper the impacts of these different cooling parameters on the temperature and cooling load in a room of a hospital are studied using Design of Experiments (DOE) and the Taguchi method. The experiments are simulated in Energy Plus to achieve the comfort temperature in one hospital's room in Iran during six months of spring and summer. Using different cooling systems such as chilled floor (during night to decrease the peak load during day) and ceiling in combination with air handling unit can provide people satisfaction while optimizing energy consumption. The results show that the location of inlet and outlet diffusers has the most effect while the chilled floor (when the other systems are off) has the less impact on reaching comfort temperature. The ranking of parameters and their interactions has been discussed through the paper.

1.Introduction

Energy consumption by hospitals, industries and residential and commercial buildings are growing in present days. The high demand for energy, could rapidly increase the earth temperature and environmental pollution. It should be mentioned that about 60% of the total energy requirement in the building is assigned for different cooling systems [1]. Therefore, studying different methods of reducing cooling

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load is one of the most important ways to minimize energy consumption. Cooling load is a function of temperature, so defining the optimized temperature could decrease that. Different factors can affect the temperature in a building with different magnitudes; therefore, the problem is to find out the priority of these factors. In previous literature, factors affecting energy performance in a building are categorized into building characteristics, main elements and equipment, climate factors, occupants and sociological influences [2]. In this paper five element and equipment factors, affecting a hospital building's cooling load are sorted using DOE (Design of Experiments)

technique and Taguchi method. Some of the studies that used DOE to optimize energy are mentioned in next paragraph.

Evins et al. (2012) by a full-factorial DOE separated the significant and non-significant inputs to the outputs of SAP (Standard Assessment Procedure): carbon emissions, running costs and overheating risk. The results of this part define 21 significant inputs that were studied in an optimization model at the next stage [3]. Zhu et al. (2013) used OED (Orthogonal Experimental Design) to develop a new optimization method for the lowest carbon emission of a public building in China. The building characteristic factors have been studied in this research including window frame type, exterior wall type, glass type, floor type, shading type and roof type [4]. Zahraee et al. (2014) used DOE for assessing the effect of climate factors including environment temperature, humidity and airflow on energy saving and cooling load in a residential building. The cooling load as the output is simulated in Energy Plus [5]. In another research in a residential building, for optimizing user's comfort and energy consumption, Artificial Bee Colony (ABC) has been used and comfort is formulated as the difference between users' set parameters and environmental parameters. The factors of this research that can be categorized in elements and equipment include temperature, illumination and air quality [6]. Kim et al. (2016) used Energy Plus simulation to predict building energy performance in an integrated system of daylight, heating, ventilating, and air conditioning (IDHVAC). The factors in this research include controllable (venetian blind slat angle, AHU (air handling unit) supply air set point temperature, AHU operation status, relative water flow rate of FCU, outdoor-air mixing ratio) and uncontrollable ones (outdoor temperature, sun azimuth angle, outdoor luminance, energy used in office equipment, indoor temperature in the previous time step) [7]. Pezeshki et al. (2020) considered thermal comfort as the set point of the cooling or heating devices for occupants to activate HVAC devices below or above the set point. They used Taguchi method for EM process optimization to predict the best location for heating and cooling appliances [8]. Ogunleye et al. (2020) investigated the influence of design parameters

on the energy efficiency of a GSHP (Ground Source Heat Pump) using an underground tunnel as the energy geostructure. They used experimentally validated 3-D numerical model and then deploying the Taguchi method to efficiently explore parameters space [9]. Abdullah and Alibaba (2022) used DOE to find the optimal window design to reduce indoor carbon dioxide (CO_2) and optimize the thermal comfort while minimizing heating/cooling loads. The model has been simulated in an office at the Department of Architecture in Famagusta city [10]. In manufacturing systems Costa and Fonts (2020) by combining DOE and a simulation model, run some experiments to find the best variables to improve furnace's energy efficiency [11].

Even though different studies are focused on using DOE for optimizing energy consumption, but the main contribution of this paper is to compare the effects of combining different cooling system including AHU supply air location, chilled ceiling and chilled floor with and without using insulation in the building. As mentioned, the cooling and heating equipment is one of the effective factors in energy consumption. Therefore, study the combination of different cooling systems can be useful to optimize energy consumption. DOE approach besides Energy Plus (design builder) simulation is used to sort the effects of different parameters by importance.

2.Material and methods

Design of experiments (DOE) approach helps in finding the optimal design of experiments in order to affect the output. In this technique a series of experiments are designed and done by changing some input variables. The results of DOE shows the most important variables that influence output. Therefore, this tool can improve the performance of a system with some inputs and outputs and provide insight into certain factors that have the most influence on response [5]. Taguchi method, firstly designed by Genichi Taguchi in Japan, tries to design experiments in order to examine the parameters affecting a process performance. In this technique, instead of having to test all possible combinations of factors' levels, some pairs of combinations will be examined to find the most

effective inputs [12, 13]. Different steps have been developed for Taguchi design of experiments. The overall process used at current paper are through these steps:

1) Describe the characteristics of building

One office room in a hospital (with 740 beds) was simulated in a hot and dry climate in summer in Tehran (Tehran, latitude 35.689N, longitude 51.389E), as the case study shown in Fig. 1 .The brief description of the reference building is shown in Table 1.

Figure 2 shows a schematic of the cooling system used in the reference building. As it is demonstrated, chilled ceiling and floor are combined with AHU.

It should be mentioned that the peak cooling load for this building calculated by Energy plus (design builder) is validated with Carrier (Hap 4.9) and the results are shown in Table 2. As demonstrated, the results are in good agreement.
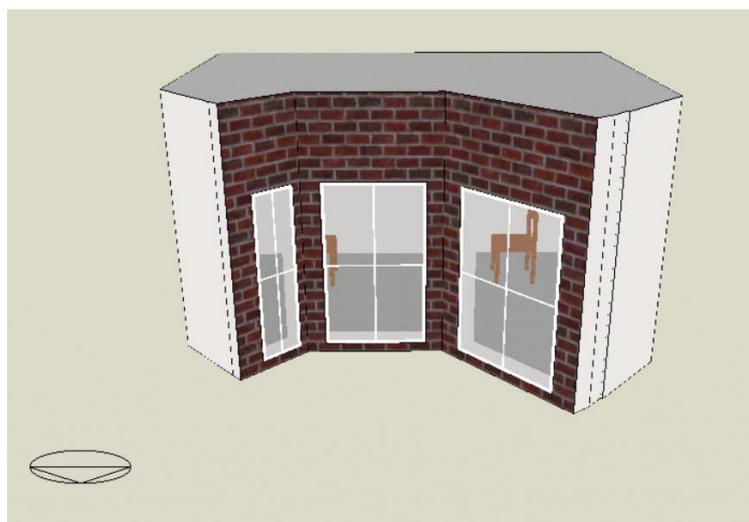

Fig. 1. 3D model for the reference building

Table 1. Description of the building

Section	Details
Location	Tehran (latitude 35.689N, longitude 51.389E), Iran
Building	Office room in hospital, 5 floors above grade and 4 below grade (constructed in 2021). This room is in a first floor.
Floor Area	12.3 m^2
Height	4 m
Operation months	Spring and summer
HVAC parameters	AHU system: temperature in diffuser is 20 C Chilled floor: chilled water enters in with T=11C and exits with T=15C Chilled ceiling: chilled water enters in with 15C and exits with T=17C
Design parameters	Occupancy=4 people Electrical equipment=550 Watts Overhead lighting=10 W/m^2
External wall	25mm gypsum board, 105mm air space, 120mm polystyrene, 600mm HW concrete block, 60mm ceramic (U=0.258 W/m^{2}K)
window	Double glass (U=1.4 W/m^{2}K)

Table 2. Cooling load calculated by two softwares

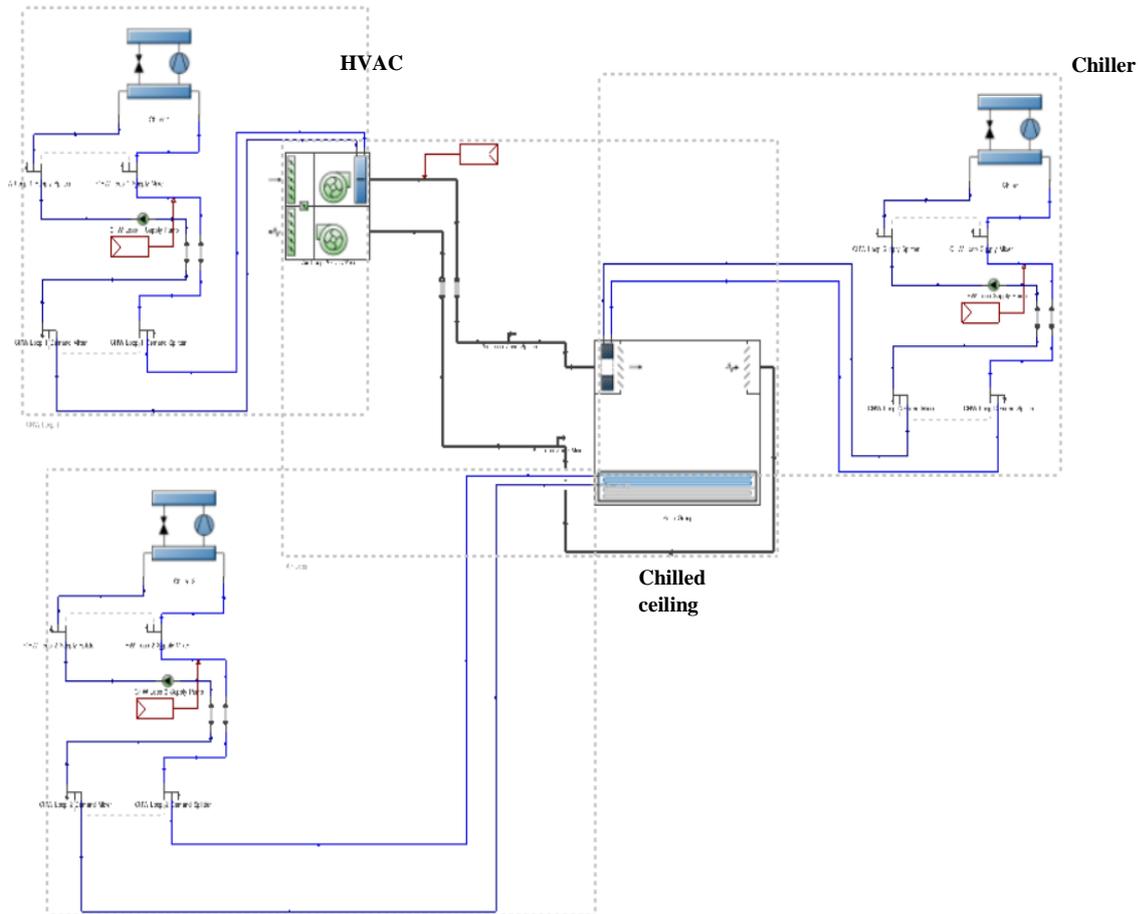| Software	Hap result (kBtu/h)	Design Capacity (kBtu/h)
Cooling load	5.3	5.6

Fig. 2. A schematic of cooling systems in the reference building

The indoor temperature can show people satisfaction from the air-conditioning. Therefore, in this paper the effects of the location of inlet and outlet diffuser, using chilled ceiling, using chilled floor, using sealant for windows and using insulation for external wall (polystyrene) are investigated by design builder. In the following sections, the Taguchi method will be described.

2) Define the process inputs and outputs

To define the studied process, at first step, the output / response parameters are identified and selected. Among the responses of system, the main objective is the temperature near chair located in the office room which is selected to be minimized and approach to the comfort temperature of 25°C during summer.

The next step in defining a process, is selecting the input parameters and their levels. The different input parameters has been identified and the most important ones by their studied levels are selected as shown in Table 3.

3) Design and simulate the experiments

In order to design a suitable experiments using Taguchi array selector, the economic matrix of Fig.3 has been selected in Minitab 20.

To calculate the results of each combination of inputs, they are simulated in Energy Plus (design builder) software and the achieved temperature near the chair is recorded. In the selected design, 16 combinations of input parameters have been selected and simulated. These combinations and their results are shown in Table 4.

Table 3. The input parameters and their levels

Parameter code	Description	Level code	Meaning
Location	Supply and return diffuser	L1	Both located on top of the wall
		L2	Both located on the bottom of wall
		L3	Supply diffuser located on the top of the wall and return one is on the bottom
		L4	Both located on the ceiling.
Floor	Chilled floor	Yes	Chilled floor controls the floor temperature
		No	The floor temperature is variable
Ceiling	Chilled Ceiling	Yes	Using chilled ceiling panel with HVAC
		No	Using HVAC without ceiling panel
Sealant	Window sealant.	Yes	Using sealant around window
		No	Without sealant
Insulation	Polystyrene insulation in external wall	Yes	Using polystyrene
		No	Without polystyrene insulation

Fig. 3. Available Taguchi designs for mixed 2-4 level designs and the selected design

Table 4. The L16 design of experiments and the response of simulation

Input codes					Output
Location	Floor	Ceiling	Sealant	insulation	Temperature
L1	Yes	Yes	No	No	75.00
L1	No	No	No	No	81.40
L2	Yes	Yes	No	No	78.00
L2	No	No	No	No	96.00
L3	Yes	No	No	No	80.00
L3	No	Yes	No	No	73.50
L3	Yes	Yes	Yes	Yes	70.50
L3	Yes	Yes	No	No	96.50
L3	No	No	Yes	Yes	77.50
L3	No	No	No	No	96.13
L4	Yes	No	Yes	No	76.50
L4	No	Yes	No	Yes	81.50
L4	Yes	No	No	Yes	85.00
L4	No	Yes	Yes	No	71.00
L4	Yes	No	No	No	76.00
L4	No	Yes	No	No	72.50

4) Data analysis and conclusion

The output of statistical analysis in Table 5 shows delta, the difference between highest and lowest response of each factor. Ranks in the next row, are assigned based on delta values and show the priority of factors in gaining less temperature. The graphic output in main effects plot of means (Fig. 4) shows the best locations for achieving less temperature L4 (both diffusers located on the ceiling) and L1 (both diffusers located on top of the wall) respectively. The magnitude of slopes for each line shows the magnitude of factor effect on the result in this figure. As expected, all the selected inputs have influence on temperature, but their impact largely differs and the three most

influencing ones are diffuser location, sealant and using chilled ceiling.

Another important output of the study is the interaction of variables. An interaction occurs when two variables act together to impact the process output. If the interaction plots display parallel lines, it means little or no interactions occur between variables. The interaction plot of means in Fig. 5 shows the main interactions between chilled floor and chilled ceiling. By the matrix, it can be concluded that when chilled floor is not used, the best result can be achieved by using chilled ceiling Also, because of the low priority of chilled floor in Table 5, it can be concluded that there is no need to combine factors and individual tests will suffice the design.

Table 5. Response table for means

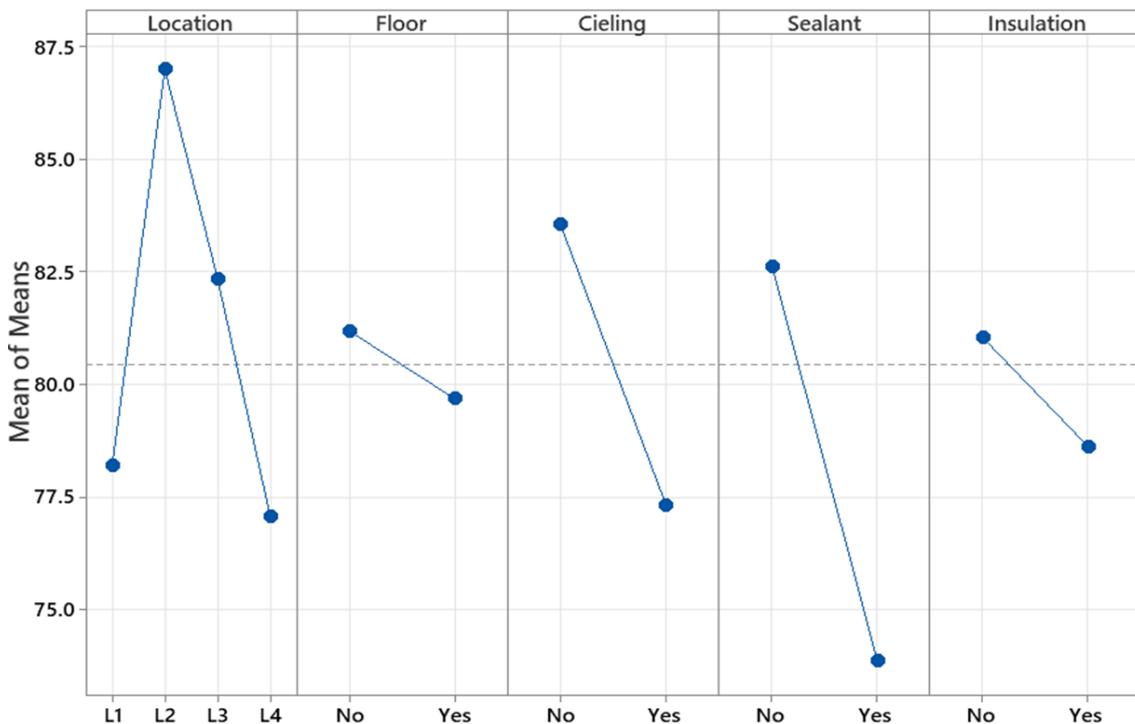| Level	Diffuser Location	Chilled Floor	Chilled ceiling	Window Sealant	Polystyrene Insulation
1	78.20	81.19	83.57	82.63	81.04
2	87.00	79.69	77.31	73.88	78.63
3	82.36				
4	77.08				
Delta	9.92	1.50	6.25	8.75	2.42
Rank	1	5	3	2	4

Fig. 4. Main Effects Plots for Means

In according to the results, the location of diffuser and using window sealant have the most effects on providing the comfort temperature. So, in the following, the temperature distribution in the office room during six months in the spring and summer is shown in Fig. 6. As illustrated by using right place for inlet and outlet diffusers and also using sealant, the comfort temperature will be near 25˚C all the time. The temperature distribution in the peak load time (during 5 days in July) is demonstrated in Fig. 7 to show the results better.
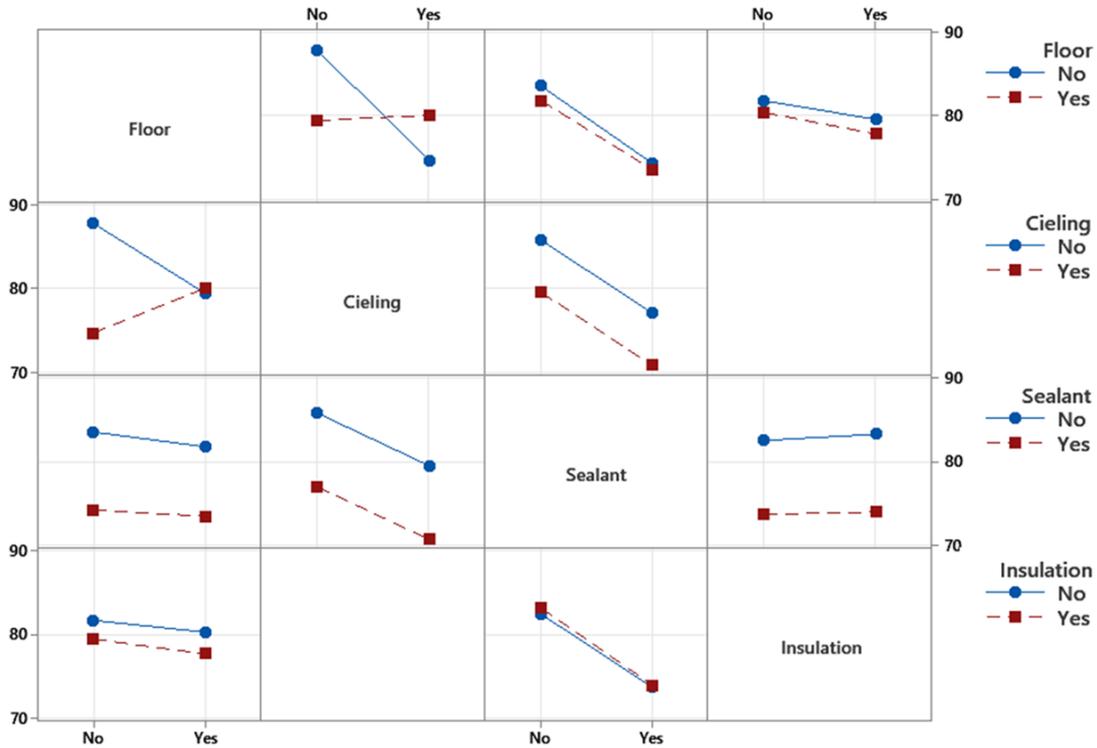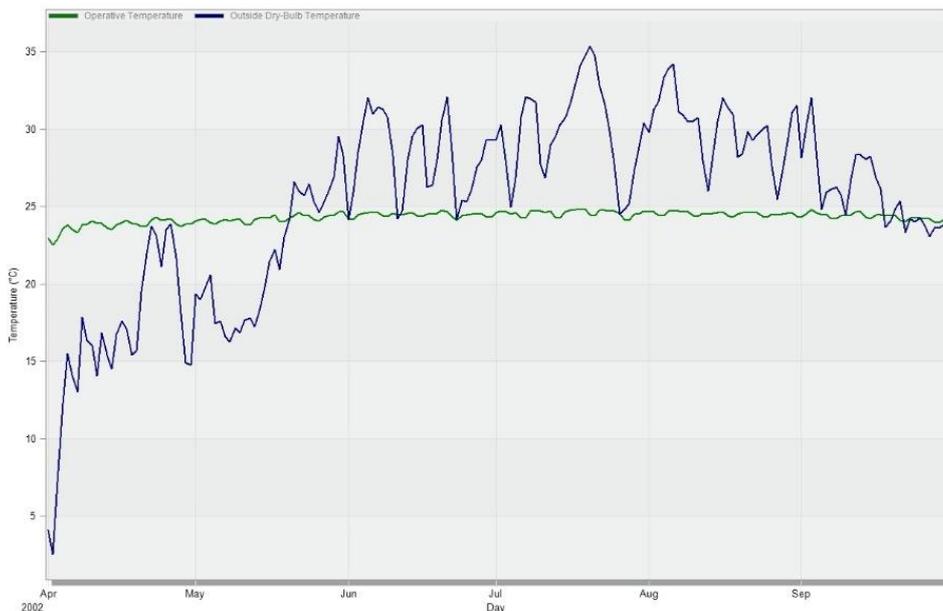

Fig. 5. Interaction plot for means

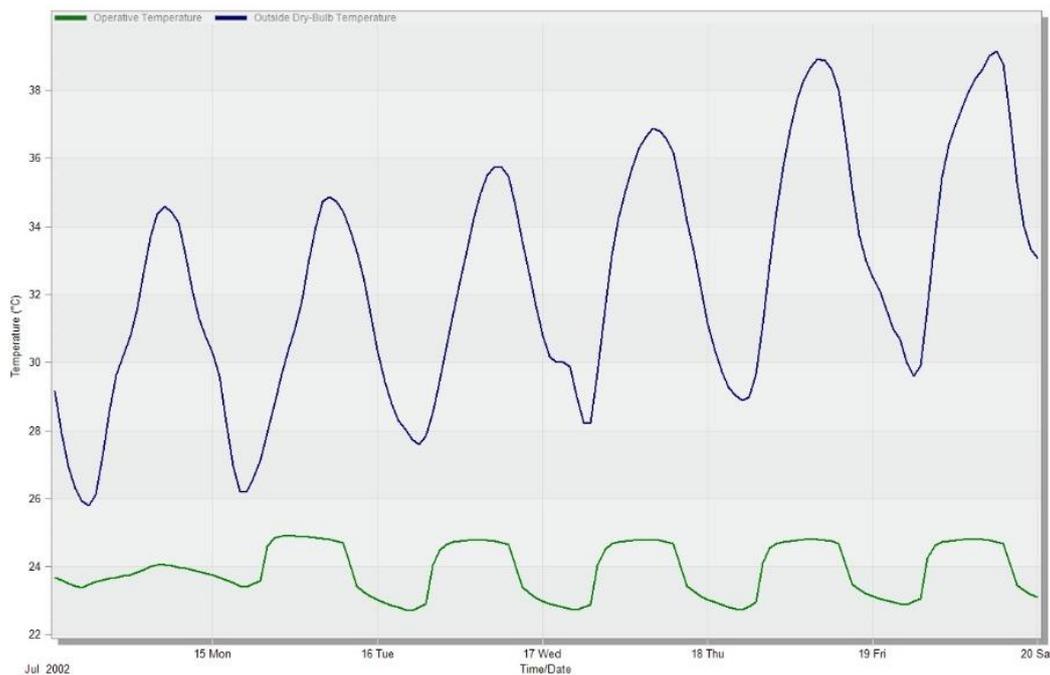**Fig. 6.** Temperature history during 6 months in the reference building

Fig. 7. Temperature history during peak load time in July

3.Conclusion

Energy consumption in buildings as a source of environmental pollution and earth temperature, can be decreased by different means. However, people satisfaction from air-condition must be considered in managing energy. Since most of energy requirements of a building is assigned for cooling systems, optimizing these systems is one of the most important ways to minimize consumption. Among the different factors affecting building temperature and cooling load with different magnitudes, the problem is finding the best mixture to gain the best cooling performance. DOE as a technique for finding the best mixture of factors in experiments has been used in previous literature of energy consumption. A method in DOE that tries to produce high results while reducing the number of experiments is Taguchi method that is used here.

In this paper, one official room in a hospital in Tehran is studied for its cooling load and energy consumption. The room is designed for 4 people with the systems operating on spring and summer. In the hospital building chilled ceiling and floor are combined with AHU. Therefore, the effects of using these systems, location of inlet and outlet diffusers, using insulation for external walls and sealant for windows are investigated. The simulated output in this research is the temperature near chair located in the office room which is selected to reach the comfort temperature of 25°C during summer. By these five inputs, the L16 Taguchi design was selected and 16 experiments have been simulated in Energy Plus (design builder).

As expected, using all the equipment can decrease the temperature by different intensities. The analysis and graphs of results show the ranking of these factors in gaining best temperature as diffuser locations, window sealant, chilled ceiling, insulation and chilled floor. For the location of diffusers, the analysis show the best result when both diffusers are positioned on the ceiling and the next near result is when both diffusers are located on the top of wall. Using other equipment had better results, as expected; but their magnitude of affect differs largely. Examining the interaction between variables shows just interaction between chilled floor and chilled ceiling. Since chilled floor had the less priority between inputs and it is suggested to be turned off, using chilled ceiling can provide a better temperature.

As the results show, just having the right place for diffusers and using window sealant can make lots of difference in the cooling performance. In fact for this coupled cooling system, using the diffusers on the ceiling and

window sealant, provides satisfaction while decrease energy consumption. The research can be expanded for all the hospital building, similar buildings and also for different inputs and equipment. Another suggestion is to use economic models to find the optimized mixture of equipment in order to gain a better temperature and optimum cost simultaneously.

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