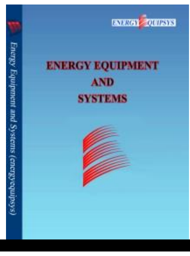
Energy Equip. Sys. / Vol. 10/No. 1/March. 2022/ 51-71

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyequipsys.com



Design of a new hybrid windcatcher and ground source heat pump system

Authors

Yousef Gorji Mahlabani [a]
Maryam Yaghoubi Moghaddam [a]
Mohammad Hakim Azari [b]
Farschad Torabi [c*]

[a] Department of Architecture, Faculty of Architecture and Urbanism, Imam Khomeini International University, Qazvin, Iran

[b] Department of Architecture, Faculty of Architecture and Urbanism, University of Art, Tehran, Iran

[c] Department of Energy Systems, Faculty of Mechanics, K. N. Toosi University of Technology, Tehran, Iran

Article history:

Received : 7 May 2021
Accepted : 17 July 2021

ABSTRACT

In order to supply the thermal load of a building, a huge amount of energy is consumed. Therefore, it is necessary to use renewable energy sources in today's architecture. As a matter of fact, this issue has begun to be the focus of many studies worldwide making the topic even more interesting. In this regard, the wind has always been known as an outstanding renewable source of energy used in Iran for thousands of years. Windcatchers, known as Badgirs in Iran, are notably used in warm-humid and hot-dry climates to make the best use of wind energy in these areas. However, Badgirs are neglected in today's life due to the limitation associated with their use in modern buildings. Accordingly, the current study aims to take into account some advantages of the windcatchers (Badgirs) in addition to highlighting their effect in both reducing energy consumption and providing thermal comfort. In previous research, humidification and similar solutions have been used to provide cooling and heating by a windcatcher, however, in none of them the Ground source heat pump system has not been used for this purpose. This study proposes a system consisting of a windcatcher and a Ground Source Heat Pump system for a building in Yazd, Iran. For this purpose, the study is conducted in three steps. First, current literature is studied. Second, the proposed system is simulated using Transys software. Finally, a mathematical calculation is performed. The simulation model consists of a room located in Yazd with width, length, and height of 4m, 6m and 3.5m, respectively. The findings show the positive effect of the proposed system in improving thermal comfort and energy by about 37.6% in summer and 7% in winter.

Keywords: Windcatcher's Efficiency, Ground Source Heat Pumps System, Energy Consumption, Thermal Comfort.

1. Introduction

Population growth and increase in energy demand have led to irreparable consequences such as increased consumption of resources, costs, and emissions, which have exacerbated the phenomenon of climate change and global warming. It is an undeniable event. Ignoring climatic conditions in the process of design that result in undesirable development of the building industry, is a destructive approach, contributing to creating unhealthy environmental conditions in an area. So, revising construction methods and redefining building components are important measures to resolve this issue. The inefficiency of current building systems in taking advantage of

* Corresponding author: Farschad Torabi
Department of Energy Systems, Faculty of Mechanics, K. N. Toosi University of Technology, Tehran, Iran
Email: ftorabi@kntu.ac.ir

potential climatic conditions along with economic conditions and the necessity for energy efficiency recall the importance of paying attention to the interaction between building and environment. This is achievable by combining climatic architectural features and modern systems.

Windcatchers are considered as one of the key elements in Iranian climate architecture. The use of them in traditional buildings in the Middle East countries dates back thousands of years [1] [2]. This passive system had been used to ventilate and cool indoor spaces in hot- dry, and hot-humid areas [3]. Despite the use of clean resources and energy (wind), the windcatcher has been forgotten over time because of some functional problems. Traditional windcatchers were usually used to ventilate and cool one floor (ground floor) or a maximum of two or three floors.

The ground, which is today regarded as a clean source of energy, is respectively cooler and warmer in the middle of summer and winter compared to the outdoor air, making it an efficient heat source. The principal components involved in a Ground are: 1) ground connection pump system, 2) heat pump subsystem, and 3) heat distribution subsystem [4,5]. In order to provide space heating and cooling, GSHP[1] systems use the ground as a heat source; they also use the ground to provide domestic hot water. Regarding the benefits of GSHP technology, one can name higher energy efficiency for air-conditioning which is due to the fact that the underground environment is associated with lower and higher temperatures respectively for cooling and heating experiences, as well as fewer temperature fluctuations compared to air temperature. [4] Therefore, GSHP can be used together with wind-based systems to use wind currents in order to supply the thermal load of the building [6].

GSHP systems can have new dimensions if windcatchers are used to supply the heating load of the building [6]. This system, in combination with the windcatcher, can help limit the temperature of inlet airflow in a certain range at different hours of the day and different seasons. It can also act as a pre-heating or pre-cooling system. In general, the windcatcher depends on many factors such as wind direction, wind velocity, inlet form, and the dimension of the windcatcher. Optimizing each of the mentioned parameters can provide better thermal behavior for the desired space. In line with the above explanations, this study seeks to provide better performance for windcatchers by combining it with the GSHP system.

The aim of the research is to improve the windcatcher's efficiency. A new design has been proposed to improve the performance of the traditional windcatcher by combining it with the GSHP system (See Fig.1). The proposed system has been used to decrease energy consumption and increase thermal comfort in both the warm and cold seasons of the year. As mentioned, the combined system has been composed of a windcatcher and a GSHP system (Fig.1). The system’s aim is not only to revive the windcatcher (a representative of the climatic architecture of Iran's hot-dry and hot-humid climate) in today's architecture but also to improve its efficiency.

The outside warm airflow is received by the windcatcher, then it passes over the pipes containing fluid (water), its temperature decreases and enters the building space. In the pipes, water circulates as a fluid in a closed cycle. To cool in the summer, water enters the pipes at a lower temperature, then exits at a higher temperature. The geothermal system has been used as a fluid cooling source. The cycle is reversed to provide preheating in the winter.

In previous research, humidification and similar solutions have been used to provide cooling and heating by a windcatcher, however, in none of them, the GSHP system has not been used for this purpose. In this research, this system combined with a windcatcher evaluated its impact on energy consumption and thermal comfort of residents.

---

[1] Ground source heat pump

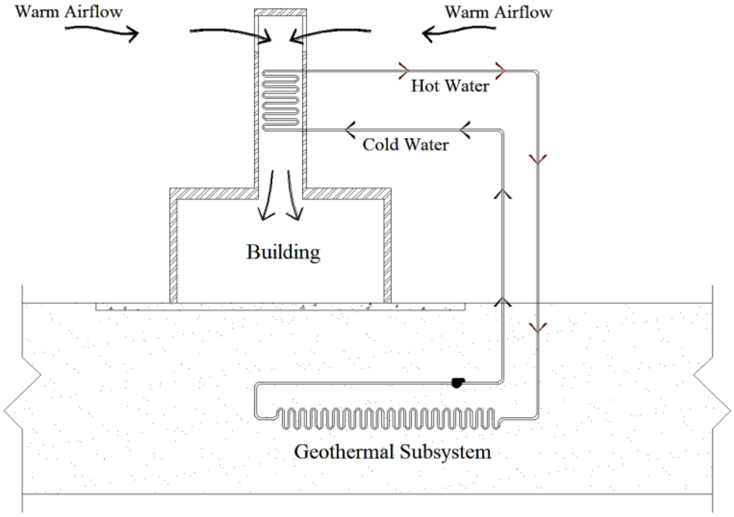


Fig. 1. The proposed system

2.Research Background

So far, a wide variety of research has been done on geothermal systems, windcatcher and vertical turbine systems. Study shows these topics have been followed more intensively in the last 10 years. Investigating these researches not only introduces various methods of using these systems and combining them with other systems but also gives valuable data and information by analyzing their strengths and weaknesses that will be effective in optimal use of the combined system and presentation of new ideas.

The use of geothermal heat pumps significantly grew by about 59 percent, mostly in the United States and Europe, between 1995 and 2000 [7]. Many studies have been done on cooling and heating systems based on the geothermal heat pumps in different types of buildings, some of which are discussed below. According to the title of the research, the priority of investigation is systems combined with windcatchers.

Nejatollahi, et al [8] have used MATLAB software and genetic algorithms to economically optimize the geothermal heat pump and cooling tower. The results show that heat gain from the ground is a suitable and economical option.

Amrollahi and Sarem [9] studied the prospects of using geothermal heat pump technologies in Iran. According to the results, the return of capital was estimated at 3 years. Their calculation had been done for a building with an area of 1000 square meters.

Bahadori [10], proposed an improved design of wind towers for natural ventilation and passive cooling. The design included water-pipes and clay ducts to improve wind tower performance. Under similar climatic conditions and design, the suggested system is able to deliver air to the building at higher flow rates. It can also reduce air temperature by evaporative cooling. Higher airflow rates and evaporative cooling of the new wind tower can be fully utilized to cool the building mass to lower temperature at night in summer. Momentum, mass, and energy analysis were carried out for the proposed design. The results were introduced in graphic forms as a guide for the application of the design in hot-dry areas in the world.

Trombe et al [11], experimentally investigated the use of underground buried pipes and used them for individual house air cooling in summer.

In a study conducted by Bahadori et al [12], two modern wind towers designs were tested as being compared with a traditional type, whereby all windcatchers had the same dimensions. One of the modern wind towers had a wetted column which included wetted curtains hung in the tower column. The other, however, was characterized by wetted surfaces which included wetted evaporative cooling pads. In addition, the wind towers with evaporative cooling provisions had less air temperature, as well as much lower humidity, than the conventional design. In the modern wind towers, the airflow speed was slightly decreased. The wind tower with wet columns, as shown by the results, operates better at high wind speeds, compared to the wind tower with wet surfaces which showed better performance at low wind speeds. In their study, Bahadori et al suggested manufacturing wind towers of various sizes and combining them, in order to design new buildings. Moreover, it was shown to be an alternative for evaporative cooling systems such as water coolers, leading to a significant decrease in electrical energy consumption.

In another study, Zhao et al [13], performed an in-situ experiment for a combined system involving a solar collector with a ground-coupled heat pump (GCHP). They found the system COP to be 3.9 and 3.2 respectively for the method with serial heating mode and the conventional one. In addition, some advantages were found regarding energy and cost-saving using the optimum solution thereby leading to a 16.7% enhancement in heat pump performance, that is. 17.2% less energy consumption and 11.8% lower annual cost.

Later, Bansal et al [14] conducted a research where they examined the role of Earth–pipe–air heat exchanger (EPAHE) systems in decreasing thermal load required by buildings in winter. They applied a transit and implicit model based on computational fluid dynamics in order to predict the thermal performance and heating capacity of the system. In addition, they evaluated the effect of such parameters as air velocity and pipe material on system performance.

Another research examined how the use of EPAHE systems decreases the cooling load required by buildings in summer. This research used the same method as the previous one in order to predict the cooling capacity and thermal performance of the system. It also evaluated the effect of the parameters considered in the previous research.

Ozgener [16] conducted a study in order to examine the role of a solar-assisted geothermal heat pump [17] and a small wind turbine system in heating a residential and agricultural building.

In another study performed by Jafarian et al. [18], the effects of an old cooling system similar to windcatchers were introduced. The windcatcher is different from the system in that it has an extra channel, called Naghb Nagbh, connected to it. Naghb Nagbh is, in fact, an underground channel that uses the earth's moisture in order to cool the air. Technically, the wind in the windcatcher passes through Naghb whereby the air gets cooler by the evaporative cooling in Naghb thereby increasing the cooling effect of the windcatcher. This study provided a one-dimensional model simultaneously solving the conservation equations of energy, mass and momentum. In order to evaluate the model, a simple experiment was carried out based on the actual dimensions of Naghb. The obtained results approved the ability of Naghb in cooling the air throughout the hot and dry months of the year in hot and dry climates.

In addition, Darkwa et al [19] presented a theoretical and practical evaluation using an earth-tube ventilation system as energy-saving technology. They found that the system can supply 62% and 86% of the peak heating and cooling loads respectively.

In a study, Soutullo et al [20] attempted to optimize the energy performance of cylindrical cross-section evaporative wind towers as passive systems for thermal conditioning of urban spaces. For this purpose, they applied two theoretical models including a thermal and a fluid model for evaluation of the evaporative system and the tower design, respectively. In the process, when the fan and the nozzles are working, the tower operation is evaluated by the thermal model. In this way, the difference between the outlet temperature and inlet temperature can be shown. The above model is used in order to evaluate the thermal response of the system to fluctuations in design parameters. For this purpose, three one-parametric and one multi-parametric optimization have been conducted. In order to explain the tower operation, the fluid model was used when the fan and the nozzles were not working thereby presenting the wind behavior through the tower.

Furthermore, they examined the arrangement of the wind tower.

Another study conducted by Abdallah and Hiroshi [21] presented a numerical examination of the effect of solar chimney parameters on wind tower parameters. Their study was carried out in two phases including 1) description of all the mathematical equations and systems, and 2) description of the new integrated model. In their study, they implemented a numerical simulation using the transient systems simulation program, that is, in conjunction with multizone infiltration specialist program software. In order to achieve high performance with a new small design for summer, the parametric details of the integrated system involved in the second phase were examined. Based on the obtained results, there was shown to be at least 80% acceptable comfort range based on the Adaptive Comfort Standard of ASHRAE; moreover, the optimum ventilation rate was shown to be 414 m3/h for the hottest day.

Furthermore, a passive cooling system was proposed in a study by Benhammou et al [22] by combining wind towers and air-to-earth heat exchangers. They presented a comparison of combined system performance with wet-surface wind towers. They found that the ambient air is colder compared to the air leaving the conventional cooling tower when it passes through the wind tower connected with the EAHE system.

Using a regression model, Niu et al [23] in their study aimed to predict the cooling capacity of an EAHE. They developed a 1D steady-state control volume model in order to simulate the EAHE performance, which integrated heat and mass transfer between the air and the tube. For model calibration, they compared the experimental data from an existing renewable energy testing facility; afterward, they used the calibrated model for evaluation of the effective factors.

In the study performed by Jassim [24], a new design was presented for a passive cooling system using WEAHE. In order to moisten the air movement paths through the underground water, pipes and air, depending on the pressure, move into indoor air columns. The study aimed to examine the performance of EAHE in terms of internal environment improvement and energy consumption decrease in hot dry areas. In order to conduct field measurement, a 2.5 × 1.8 meters optimizer was used, and CFD was applied to examine the system. During summer, as shown by the results, the airflow temperature dropped to 18°C when the outside temperature was 45.3°C, also the relative humidity improved to 23%.

In their study, Calautita et al [25] presented an evaluation of the performance of a uni-directional windcatcher using CFD and wind-tunnel analysis. Using rapid prototyping, the authors provided a precise experimental model which they tested in a closed-loop subsonic wind tunnel. Afterward, they presented, in numerical modeling, a precise geometrical illustration of the wind tunnel test. In terms of indoor and external airflow, a comparison was made between the experimental results (supply rate and pressure coefficients) and the numerical results. In order to analyze the performance of airflow structure within the wind-catcher and inside the experiment room, a smoke visualization experiment was conducted. Calautita et al [25] found out that the proposed windcatcher, depending on the outdoor airspeed, can decrease the supply temperature by 12 K in the micro-climate.

In order to achieve thermal comfort, Chaudhry et al [26] performed an examination of a novel closed-loop thermal cycle containing cylindrical heat pipes within a circular wind tower. They arranged the copper heat pipes filled with water horizontally. They also used water in order to make the system carbon neutral while maintaining indoor air quality. In this study, the three-dimensional Reynolds-Averaged Navier–Stokes (RANS) equations, as well as continuity, momentum, and energy equations were solved using FLUENT code to simulate velocity and pressure. The proposed cooling system, as they found, was able to supply the fresh air intake per person of 10 L/s. In order to validate the results, the authors compared the findings with similarly analyzed wind towers structures.

Soni et al [27] investigated the applications of heating and cooling in space. In this paper, not only was the definition of hybrid ground-coupled heat exchanger (GCHE) presented but also passive approaches utilized for heating and cooling were revealed. GCHE can be classified into; Earth air heat exchange (EAHE) and

Ground Source heat pump (GSHP). These groups were compared to each other in terms of application, cost, the material of pipes, durability, Payback period, and efficiency. According to the results, GSHPs are more expensive and short-lived than EAHEs, but they have received wide currency all over the world due to their efficiency in all seasons (Fig. 2).

In this article [27], the compatibility of GSHP systems with Phase change material (PCM), solar energy, cooling tower, rainwater storage, and other factors which have been stemmed from the previous studies (background) are presented. The method, fluid type and their results are discussed too. The data of the previous papers demonstrate that the separate utilization of each of GCHEs and the passive approaches is not satisfactory, and the best solution is a combination of these techniques. The combined systems such as the solar-assisted GSHP system and the combination of GSHP with PCM have higher efficiency, approximately 5 to 15 percent of the total coefficient of overall system performance, for greenhouse heating. Moreover, GSHP causes a reduction in the initial investment due to the decrease of 47 percent in the borehole size within the combined system [27].

Calautit et al [28] analyzed and numerically simulated the multidirectional windcatcher with a combination of vertically-arranged heat transfer devices. This recommended combined system was investigated in terms of the reduction of the airflow temperature and the conservation of fresh air rate. In this article, computational fluid dynamics (CFD) and wind tunnels were used. In order to validate the CFD data, the model was created with a three-dimensional printer and then the wind tunnel with loop dependent on monotonous flow was tested. The comparison of numerical analysis and experimental method showed the marginal difference which clearly demonstrates the accuracy of data from CFD simulation. They concluded that the extracted speed of indoor air decreased by 8 to 17 percent after being combined with vertically-arranged heat transfer devices. The positive effect associated with VHTD was the reduction in the fresh air entering by 12 K.

In the article conducted by Calautit et al [29], Indoor environment quality (IEQ) of the building was analyzed by the computational fluid dynamics (CFD). This building was ventilated passively by using a windcatcher combined with vertically-arranged heat transfer devices and field analysis. The field data was utilized in order to validate the results of the simulation. The compatibility of both sets of results was revealed as well. In their paper, the simulation was performed by means of Ansys Fluent software. The recommended combined system caused the reduction in air temperature by 8 to 10 degrees Celsius. The thermal comfort was conducted by predicted mean vote (PMV), whereby sizing was variable from a little cold (-0.96) to a little hot (0.60 to 0.36).

In their experimental study, Khani et al [30] presented a wind tower design called modular wind tower with wetted surfaces. They measured the parameters including air temperature, relative humidity (RH), and airflow velocity at different points of time and also when the velocity of ambient air was zero. Based on their findings, air temperature can reduce near 10 °C on average while increasing the relative humidity of airflow in a building by approximately 36% by modular wind tower.

Calautita et al [31] used Computational Fluid Dynamics (CFD) and field test analysis to

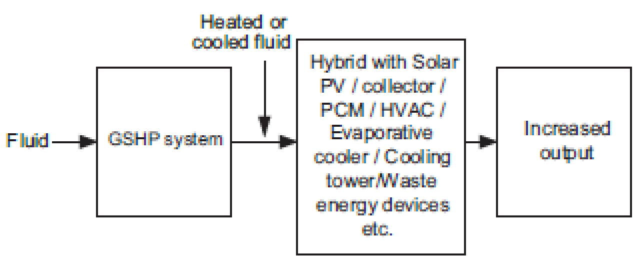


Fig. 2. Hybrid systems with Ground coupled heat exchanger system (GCHE).

investigate the performance of a cooling windcatcher located on the roof which was integrated with heat pipes. They incorporated the windcatcher into a 5m x 5m x3 m test room model. In order to perform the steady-state RANS simulation, the CFD code FLUENT 15 with the standard k-ε model was used. Based on the CO2 concentration analysis, the system was found to deliver fresh air inside the space as well as decrease the CO2 levels. The value of Predicted Mean Value (PMV) was found to range between +0.48 and +0.99 with an average of +0.85 (slightly warm). The numerical model was validated using the experimental data.

Soltani et al [32] introduced a modern wind tower design with a moistened pad including a fixed column, a rotating and movable head, an air opening with a screen, and two windows at the end of the column. It was possible to manually or automatically control the wind tower's head in order to achieve optimum wind velocity according to the preferred thermal condition. They applied CFD simulation to evaluate the ventilation performance of the system. The results showed the wind tower design to be useful for naturally improving the thermal comfort of buildings in hot and dry climates.

In another study, Noroozi et al [33] equipped a laboratory-scale windcatcher with a combined evaporative system. They provided a system including a one-sided opening with an adjustable wetted pad unit and a wetted blades section. They theoretically analyzed the system and performed some experiments to validate the results. They found that the velocity of the inside air was a bit higher under windy conditions with the pad open; however, air velocity increased inside the windcatcher with the closed pad when the wind speed was zero. It was also shown that cooling load increased by two times the amount at a wind speed of lower than 3 m/s after applying the closed-pad mode.

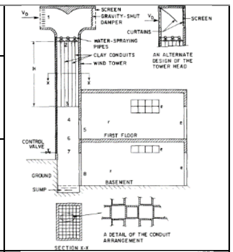
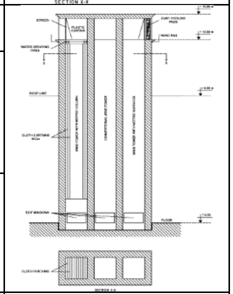
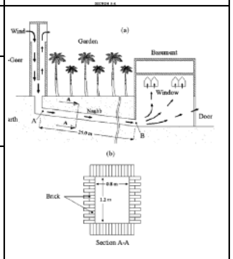
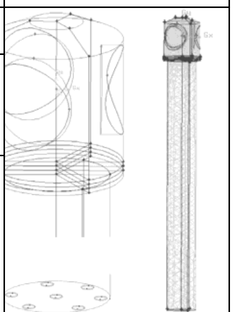
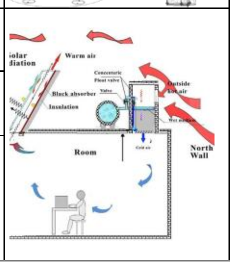
Seidabadi et al [34] performed a study on a combination of phase change materials (PCM) with a windcatcher. They conducted a comprehensive 3D Dynamic time-dependent simulation in order to decrease the temperature difference. They also applied the MATLAB software to examine the proposed system. The temperature, based on the obtained results, dropped by 25°C at about 7 working hours.

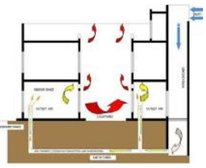
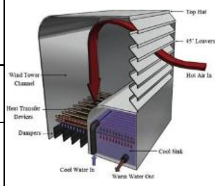
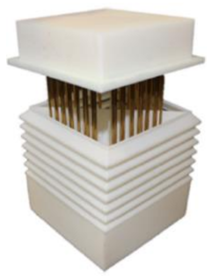
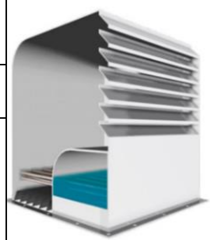
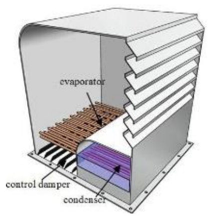
It can be concluded from the studies that hybrid systems equipped with windcatcher systems show improved performance. This system can act both as a cooling system and a preheating system; however, it has been shown to be more efficient in cooling. Table 1 illustrates the advantages and disadvantages of the novel systems mentioned in the literature review.

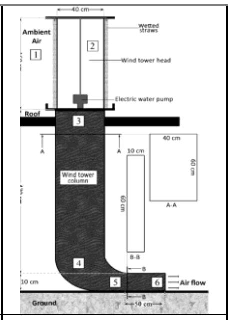
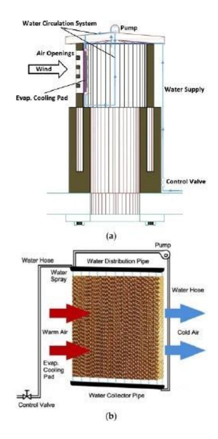
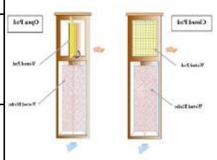
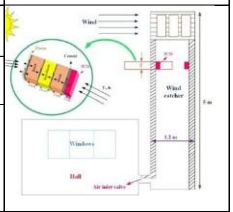
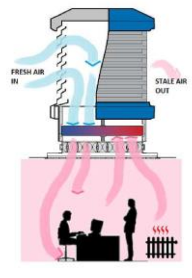
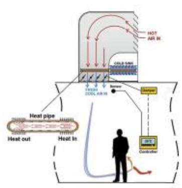
Calautit et al [35] in the present work, the thermal energy recovery in the exhaust air and its transmission to the air in order to redistribute them using natural ventilation with windcatchers is discussed. In this regard, a comprehensive study is performed to find the heat recovery systems that have the potential to be combined with windcatchers. A rotational heat recovery device is suitable for combining with multi-sided windcatchers installed on the roof. Computational fluid dynamics (CFD) and experimental methods are used to evaluate the proposed system. The research was done in two stages (phase). In the first phase, an initial prototype of the passive rotating heat-wheel apparatus was developed to evaluate the concept and performance of the design using a cross-flow channel. Two configurations of the blade rotary wheel (20 and 32 radial blade) were tested. The second phase of the study is focused on the integration of the heat recovery wheel and windcatcher system. The simulation results showed that the addition of a heat recovery wheel with Rotate 15 rpm (min) of rotational, increases the internal airflow velocity depending on the wind conditions, the outer space is reduced between 14 - 30 %. The system is able to provide the new air rate recommended at a wind speed of 1.5 m / s and above. In addition to proper ventilation, this system has a positive effect on indoor air temperature and, depending on the internal/external conditions, increases the temperature to 3.7 ° c.

Calautit et al [36] have developed their previous system. in the developed system, the extended surface component was added to the structure of the previous. its purpose is to evaluate the thermal comfort and indoor air quality in buildings ventilated with a passive cooling windcatcher integrated with heat pipes and extended surface. In this way, numerical modeling, wind tunnel and far-field testing during a summer month were used. Results of wind tunnel tests showed that added elements reduced the airflow through the windcatcher but did not impede the flow even at low outdoor wind speeds. The smoke visualization experiment also confirmed it. Analysis of pollutant concentration demonstrated that the proposed system was capable of delivering fresh air at a sufficient rate. by the thermal comfort analysis, it was detected that for this configuration, equal distribution of thermal comfort was not achieved because of a combination of high air movement, colder temperature and high humidity. This resulted in higher thermal discomfort in this area. Similar to former research, Field tests data were used to validate the numerical modeling.

Table 1. Evaluation of the new design of the windcatcher

1985	**An Improved Design of Wind Towers for Natural Ventilation and Passive Cooling [10]**		
	Advantages	The presence of pottery reduces the temperature more.	
	Disadvantages	The presence of water increases the humidity and destroys the materials. Water spraying in the system increases the cost of maintenance.	
2008	Experimental Investigation of New Designs of Wind Towers [12]		
	Advantages	Reducing the temperature received indoors compared to the traditional benefits system Ability to operate in low or high-speed environments	
	Disadvantages	The presence of water increases the humidity and damages the materials. Repairing and maintaining wet pads and curtains is difficult and expensive.	
2010	Performance Analysis of a Passive Cooling System Using Underground Channel [18]		
	Advantages	Reducing the temperature received indoors - inactive cooling	
	Disadvantages	Inefficiency for today's architecture Need a lot of space for full utilization of the designed system	
2012	Energy Performance Evaluation of an Evaporative Wind Tower [20]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	It needs water, which may enter the building structure Create noise pollution due to the presence of fans High maintenance costs due to the presence of a fan Need a lot of space for full utilization of the designed system	
2014	Parametric Investigation of Solar Chimney with New Cooling Tower Integrated in a Single Room for New Assiut City, Egypt climate [21]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	The presence of water increases the humidity and destroys the materials Application for a low number of floors	

2015	Sustainable Design of Windcatcher of an Earth-to-Air Heat Exchanger in Hot Dry Areas [24]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increase the amount of channeling and complexity of the system Application for a low number of floors	
2015	CFD and wind tunnel study of the performance of a uni-directional windcatcher with heat transfer devices [24]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increasing maintenance costs Increase construction and implementation costs	
2015	Computational Analysis of a Wind Tower Assisted Passive Cooling Technology for the Built Environment [26]		
	Advantages	Airflow short-circuiting Reduce the temperature received in the indoor environment	
	Disadvantages	Lack of water supply system Increase maintenance costs Increase construction and implementation costs	
2016	Numerical and Experimental Analysis of a Multi-Directional Wind Tower Integrated With Vertically- Arranged Heat Transfer Devices (VHTD) [27]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increase maintenance costs Increase construction and implementation costs	
2016	Indoor environmental quality (IEQ) analysis of a low energy windcatcher with horizontally-arranged heat transfer devices [28]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increase maintenance costs Increase construction and implementation costs	
2017	Thermal Comfort and Indoor Air Quality Analysis of a Low energy Cooling Windcatcher [31]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increase maintenance costs Increase construction and implementation costs	
2017	Experimental investigation of a modular wind tower in hot and dry regions [30]		
	Advantages	Reduce the temperature received in the indoor environment Increase the relative humidity of the environment	

	Disadvantages	Due to the evaporative cooling, moisture destroys the material Increase maintenance costs to replace straws Not having so interesting appearance in the indoor and outdoor environment	
2018	Investigation of Airflow Patterns in a New Design of Wind Tower with a Wetted Surface [32]		
	Advantages	Reduce the temperature received in the indoor environment Increase the relative humidity of the environment	
	Disadvantages	Due to the evaporative cooling and sprinkling of water on the straws, it destroys the materials during the life of the building. Increase maintenance costs to replace cellulose pads Create noise pollution due to the mobility of the windcatcher cap The possibility of fungal and bacterial growth inside the pads	
2018	Thermal Assessment of a Novel Combine Evaporative Cooling Windcatcher [33]		
	Advantages	Reduce the temperature received in the indoor environment Increase the relative humidity of the environment	
	Disadvantages	Due to the evaporative cooling, moisture destroys the material Increase maintenance costs to replace the straw	
2019	A Novel Integration of PCM with Windcatcher Skin Material in Order to Increase Heat Transfer Rate [34]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Significant increase in implementation and construction costs Executive and construction problems Increase the cost of maintenance	
2020	Thermal comfort and indoor air quality analysis of a low energy cooling windcatcher [35]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	Increase maintenance costs High maintenance costs due to the presence of a fan Increase construction and implementation costs	
2020	Numerical and experimental investigation of the indoor air quality and thermal comfort performance of a low energy cooling windcatcher with heat pipes and extended surfaces [36]		
	Advantages	Reduce the temperature received in the indoor environment	
	Disadvantages	**Increase maintenance costs** **Increase construction and implementation costs**	

The results of the research showed that the presented new systems have advantages and disadvantages. When studying the results from this research, one of the main problems is the presence of moisture in materials due to the use of water or its droplets. On the other hand, most of them have little economical and practical justification. So, they have remained only in the stage of ideas and innovations. But it should not be ignored that all of them have improved the performance of traditional windcatchers and indoor conditions in terms of thermal comfort. Another considerable disadvantage of the novel systems is that their usage is limited to low-rise buildings.

3.Climatic Studies

Iran's geographical location has created different climatic conditions. The city of Yazd, located in the central part of Iran, has a hot-dry climate and a special position in Iran and the world in terms of history and climatic architecture. It is known as the city of windcatchers and is a key element of Yazd's climatic architecture [37,38].

At available stations in Yazd, climatological data is recorded at three-hourly intervals (also known as synoptic), but hourly weather data is required to analyze climatological data, find climatic design strategies, and simulate the energy consumption of the model. So, the required hourly weather data were achieved through the site [39] and Meteonorm software using the interpolation method. Then, they were compared. Finally, according to the weather station's data. The desired file has been modified and validated. The weather data file received in EPW format has been used in all analyzes. In order to validate, the information obtained from the EPW file was compared with the city's weather information. The difference between them was minor. In this regard, the average temperature of the region was compared with the average temperature of the weather information obtained from the weather bureau [40], and the coefficient of determination obtained was about 0.96. This value shows that the weather data is valid (Fig. 2).

Based on studies and statistical information, depending on the level of work, the division model is considered as the following groups:

(0.8 to 1). Good quality model;

(0.5 to 0.8). Acceptable quality model but without validity;

(0 to 0.5). Low-quality model.

The average maximum air temperature indicates the air condition in the hottest times and the average minimum air temperature indicates the temperature condition in the coldest times of the year. Fig 3 shows the minimum, maximum, and average monthly and annual air temperatures. According to the values of the chart, it can be seen that Yazd has hot summers and cold winters. The average annual temperature in Yazd is about 21°C, the average monthly

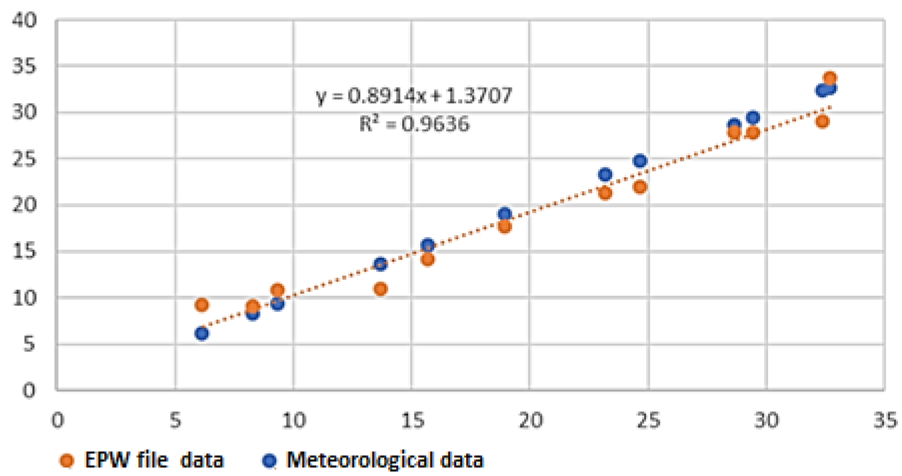


Fig.2. Determination coefficient of Yazd's weather data.

temperature in the coldest month of the year in January is about 7°C and the average monthly temperature in the warmest month of the year in July is about 34°C. On average, in 5 months of the year, the average monthly temperature is lower and in 5 months of the year the average monthly temperature is more than the range of thermal comfort conditions and the building needs proper heating and cooling. Finally, in the two months of April and October, relative comfort conditions have been provided.

Figure 4 is a graph of wind speed in the city of Yazd. The average annual wind speed is about 2.5 m / s, and the minimum and maximum annual wind speeds are 0 and 13.5 m / s, respectively. The average wind speed in the hot months is higher than in the cold months of the year, which allows the use of natural ventilation or the use of wind systems in this climate.

According to the psychometric chart (Fig. 5), in this city, there is a need for both heating and cooling, the relative humidity is low, especially in summer and the need for cooling is more than heating.

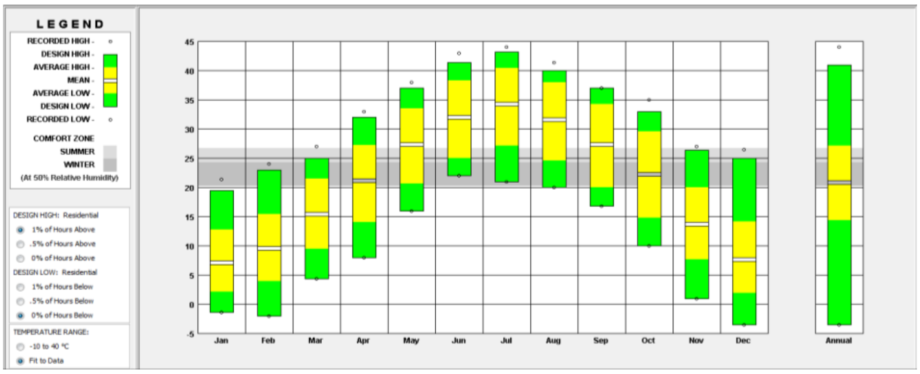


Fig. 3. Yazd's Monthly Dry Temperature chart (Climate Consultant Software)

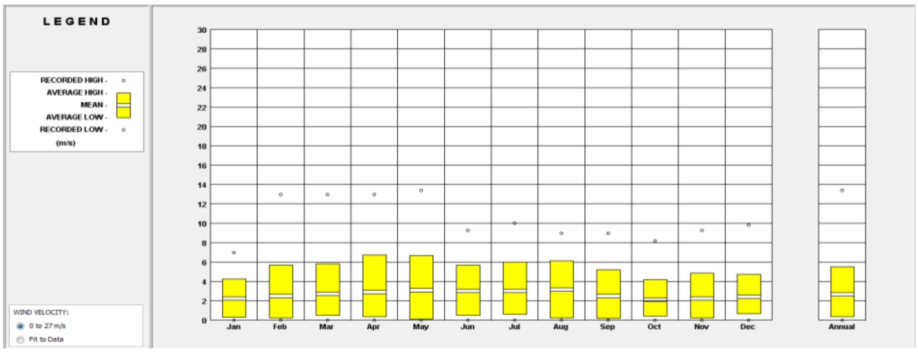


Fig. 4. Yazd's Wind Speed chart (Climate Consultant Software)

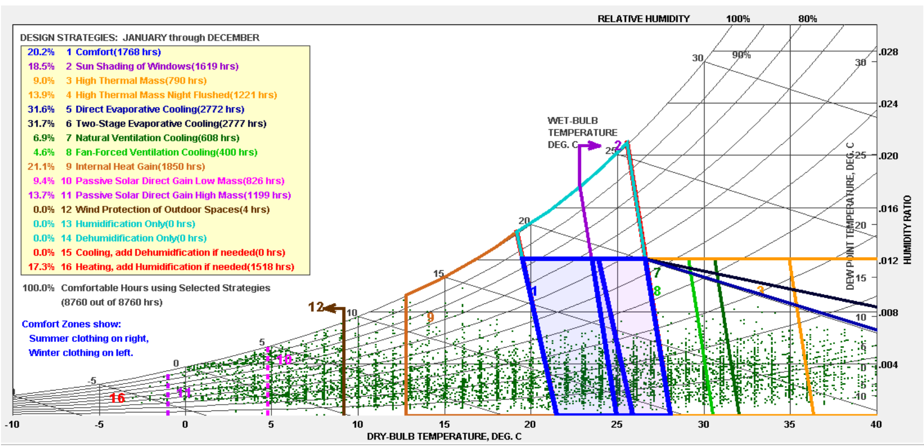


Fig. 5. Yazd's Psychrometric chart (Climate Consultant Software)

In Table 2, different passive strategies have been stated and the number of hours and the percentage of each of them was estimated to provide thermal comfort in Yazd's climate. Based on the table resulting from the psychometric chart analysis, the temperature is in the thermal comfort range for 20% of the year and does not need heating and cooling.

4. Simulation

TRNSYS software, a graphically based software, is used to simulate the behavior of transient systems. TRNSYS is made of two parts. First, an engine (called the kernel) that reads an input file, processes it, solves the system, determines convergence, and then plots system variables [41], Among other things, it also provides utilities: determines thermophysical properties, inverts matrices, performs linear regressions, and interpolates external data files. Second, a number of components model the performance of one part of the system. Many professionals across the world such as consultants, engineers and building experts use TRNSYS. This system, used by many, can be applied in many applications due to its flexibility, such as optimization, building simulation, energy system research, hydrogen fuel cell systems, data and simulation calibration, and so on [41], Given the possible relationship between the windcatcher and geothermal system in TRNSYS software, the current study, therefore, used TRNSYS to simulate, model and evaluate the proposed system (Fig. 6).

Table 2. Usable passive strategies to provide thermal comfort in Yazd (Climate Consultant Software)

Nm	Design strategies: January through December	Hours	Percentage
1	Comfort	1768	20.2
2	Sun Shading of Windows	1619	18.5
3	High Thermal Mass Zone	790	9
4	High Thermal Mass with Night Flushing Zone	1221	13.9
5	Direct Evaporative Cooling Zone	2772	31.6
6	Two-Stage Evaporative Cooling Zone	2777	31.7
7	Natural Ventilation Cooling Zone	608	6.3
8	Fan Forced Ventilation Cooling Zone	400	4.6
9	Internal Heat Gain Zone	1850	21.1
10	Passive Solar Direct Gain Low Mass Zone	826	9.4
11	Passive Solar Direct Gain High Mass Zone	1199	13.7
12	Wind Protection of Outdoor Spaces	4	0
13	Heating Zone (add Humidification if Necessary)	1518	17.3

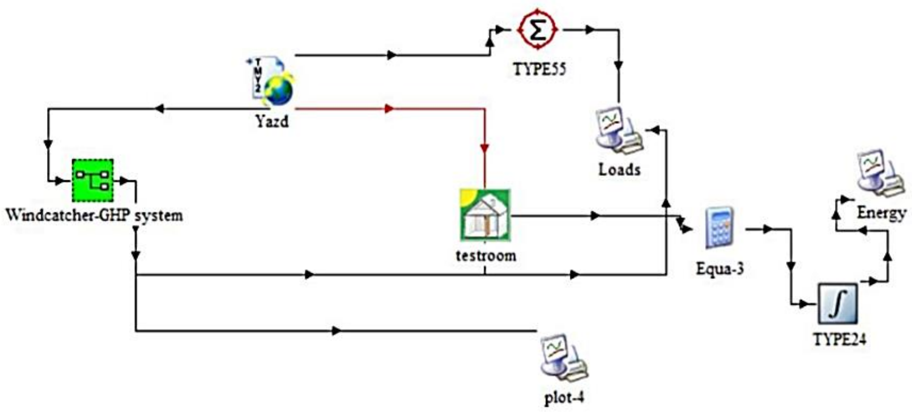


Fig. 6. The modeled system in TRNSYS Software

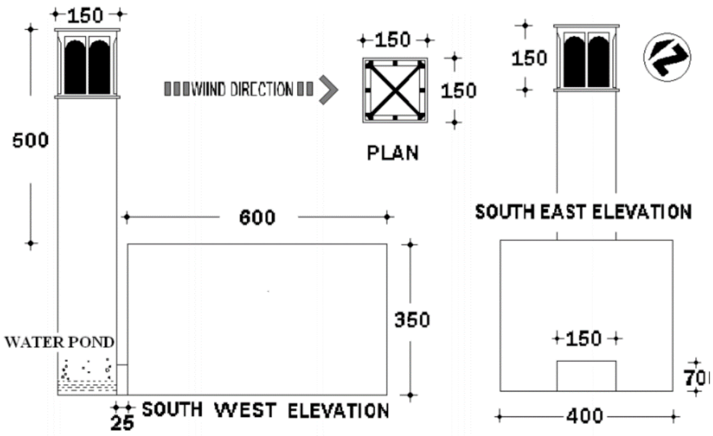


Fig. 7. The dimension of the test room and windcatcher [40].

The presented model includes a test room with an area of 24 square meters and a ceiling height of 3.5 meters. The specifications of the building's walls and windows are as follows:
It is assumed that the test room has a window in the south wall with a dimension of 1.5 × 1.5 meters. Dimensions of the test room and windcatcher have been chosen based on the studied model in the article of Hossein Ghadiri et al. in 2011 (Fig. 7) [42].
The important parameters considered in the model are respectively stated; comfort temperature is an important parameter in the climate of the Yazd, so it is the first parameter in the process of modeling. The adjusted temperature had been chosen 23 and 25°C in the winter and summer seasons, respectively. The chosen temperatures were based on the optimal energy consumption and better performance of the system. The considered temperature range had been based on ASHRAE-standard 55 and the system condition. Another important factor in the simulation process is the characteristic of external walls. The thickness and heat transfer coefficient of the external wall was considered 16 cm and 1,952 W/m^{2}K respectively. It is also assumed that in the room, there is a person with sitting activity based on the ISO 7730 standard and a 230 W computer. And the energy consumption of lighting is 10 W/m^2 lighting. In the simulation, these were considered as heat generators in space. On the other hand, to evaluate the thermal comfort in the space, it has been assumed that the airflow velocity is a coefficient of the wind velocity passing through the windcatcher, which is proportional to the city's wind velocity [43]. Thus, the occupant thermal comfort was investigated under its effect. Also, the temperature in the research was constant and was determined based on the adjusted temperature for heating and cooling [44]. This parameter can be considered as a variable in future research. So, the analysis of thermal comfort was investigated with the constant temperature in two situations: the test room with the combined system including windcatcher and geothermal and the room without it. To model the system, a water-to-air converter was used Instead of a wind catcher and it was assumed that the flow rate passing through it is equal to the wind velocity in the area and the airflow velocity in the inlet of the windcatcher at the desired height.

5 .Results

In this research, the results were illustrated as graphs for the different scenarios, including the with and without the combined system in summer and winter. Then, each of them was analyzed. It should be noted that to provide the thermal load for the room in the situation without the proposed system, a heat pump system with an efficiency coefficient of 3, and a boiler with 80% efficiency have been used.

5.1. In summer

One of the important parameters in each system is energy consumption. As mentioned, the research has investigated this parameter in two situations; with the combined system and without it. The energy consumption of the test room without the system, solid line, is 1010 kWh and it is 630 kWh for the room with the proposed system, dashed line, in the summer solstice (Fig. 8).

One of the important variables of the designed model is the temperatures related to the windcatcher and the soil temperature of the region (Fig. 9 and 10). The presented graph in Fig. 8 includes 2 curved lines; the curved dot line shows the windcatcher's inlet air temperature. The curved solid line demonstrates the windcatcher's outlet air temperature. In Fig.9, there are 2 curved lines. The curved dot line shows the soil temperature and the curved solid line indicates the geothermal system's outlet fluid temperature.

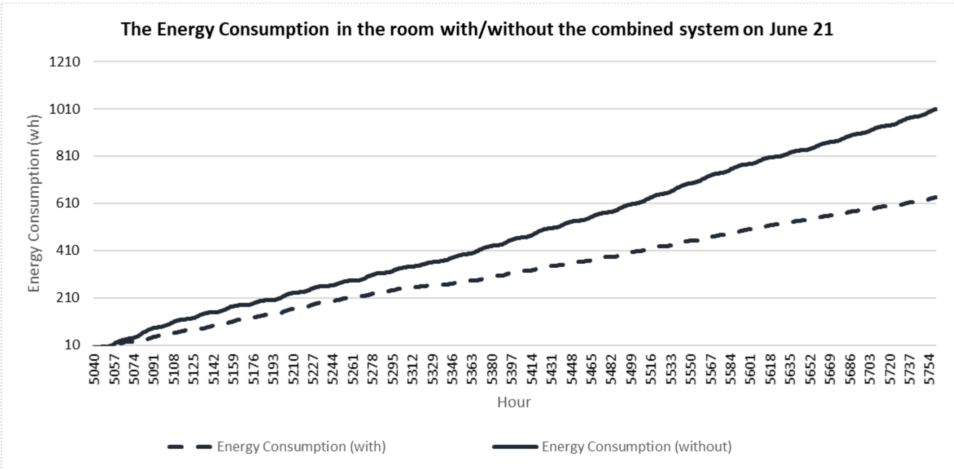


Fig. 8. The energy consumption of the room with/without the system on June 21

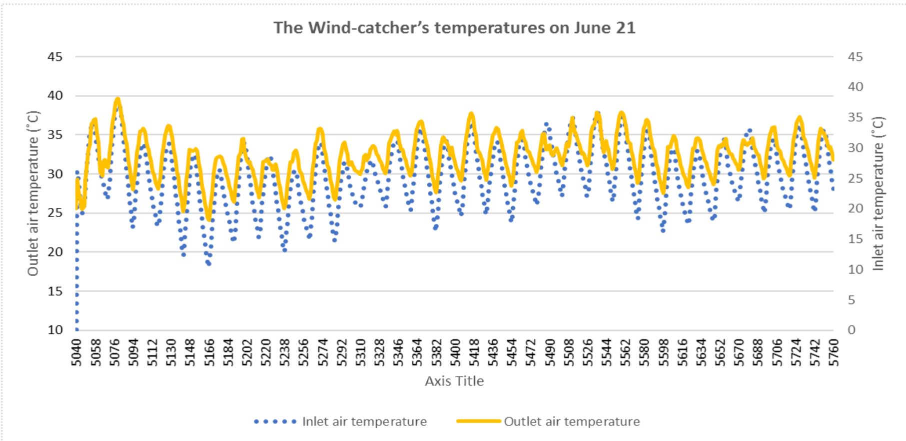


Fig. 9. The Windcatcher's temperatures on June 21

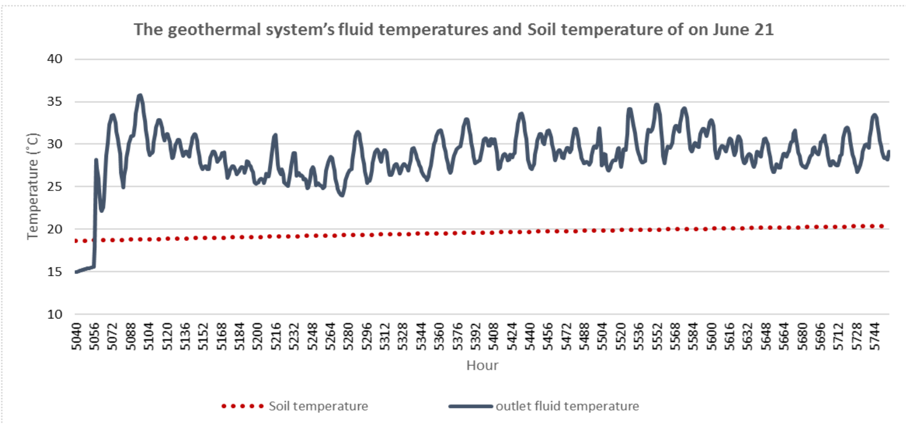


Fig. 10. The geothermal system's fluid temperatures and Soil temperature of on June 21

On the other hand, another aim of the research has been to investigate thermal comfort. Thermal comfort is assessed by studying Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD indices)[2]. These values predict the thermal sensation and the thermal dissatisfaction experienced by occupants in the indoor environment [45,46]. By using them, the percentage of thermal dissatisfaction of individuals was predicted. In the study, as mentioned, the temperature is considered a constant parameter.

By comparing the two graphs presented in Figs.11 and 12, it can be found that the airflow can improve thermal comfort in summer. This has been achieved by the combined system.

5.2 . In Winter

According to Fig.13, the energy consumption of the room without the system, solid line, is 1712 kWh. It is 1585 kWh for the room with the proposed system, dashed line, in the winter solstice (22 December).

The windcatcher's temperatures, soil temperature, and the geothermal system's temperatures have been illustrated in Figs. 14 and 15. The interpretation of the graph's curved lines is similar to the ones explained in the part of summer.

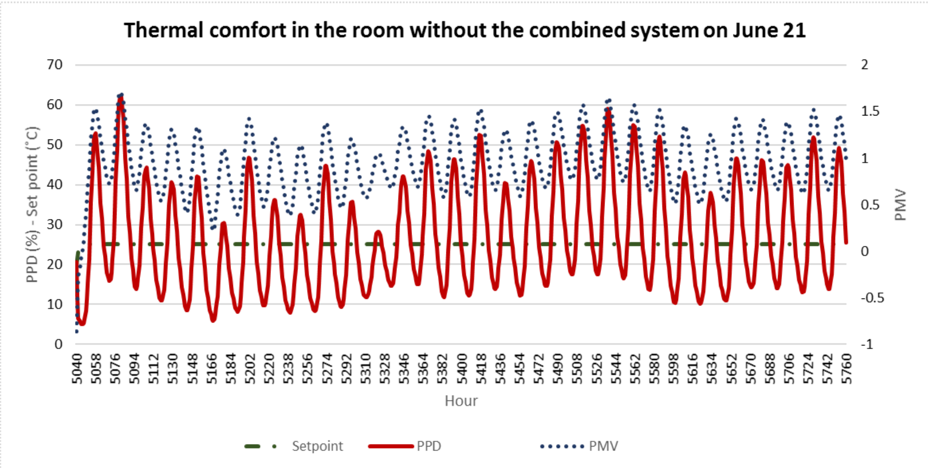


Fig.11. Thermal comfort in the room without the combined system on June 21

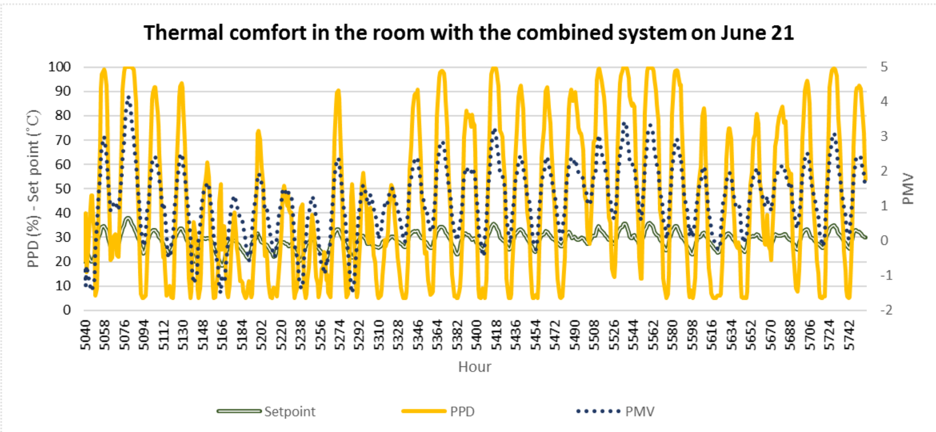


Fig.12. Thermal comfort in the room with the combined system on June 21

---

[2] The PMV is an index which predicts the average climate assessment value of a large group of people. The PPD Index provides a quantitative prediction of the number of people that will be dissatisfied with a certain ambient atmosphere [45].

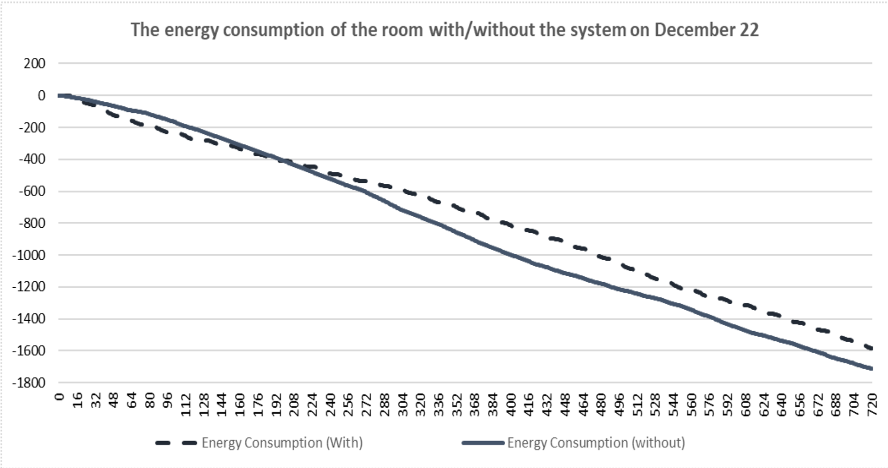


Fig. 13. The energy consumption of the room with/without the system on December 22.

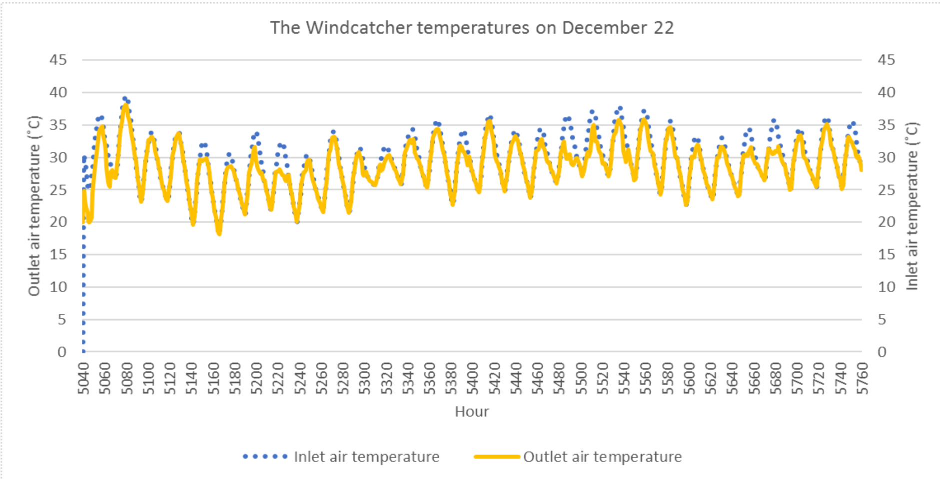


Fig. 14. The Windcatcher temperatures on December 22

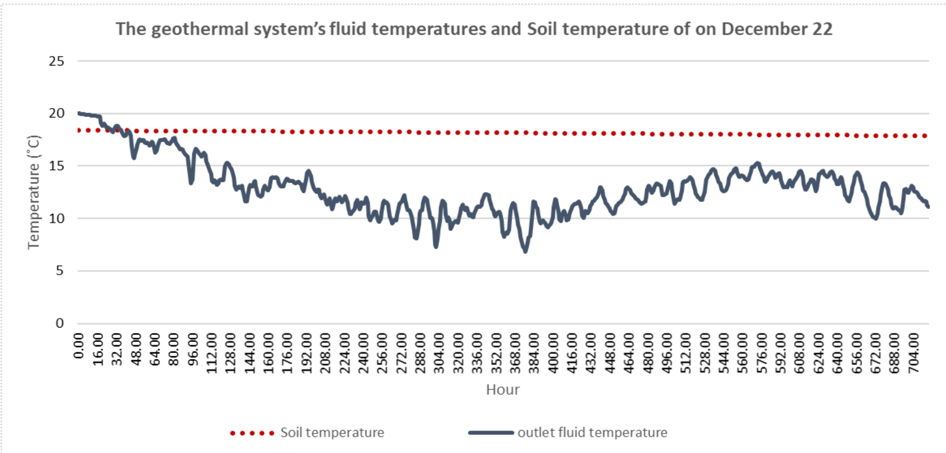


Fig. 15. The geothermal system's fluid temperatures and Soil temperatures on December 22

As mentioned, one of the objectives of the present study is to improve thermal comfort. The results indicate that the system has improved (see Fig. 16 and 17). By examining the simultaneous effect of the wind and temperature, more acceptable results can be obtained like summer.

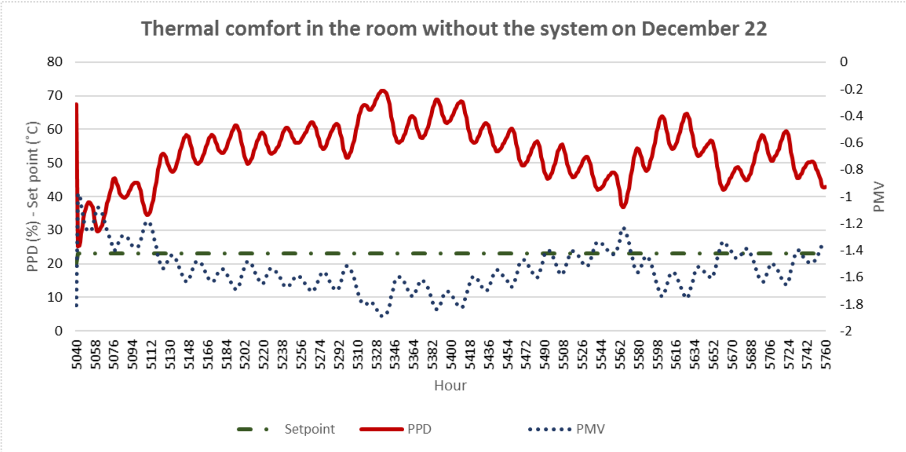


Fig. 16. Thermal comfort in the room without the system on December 22

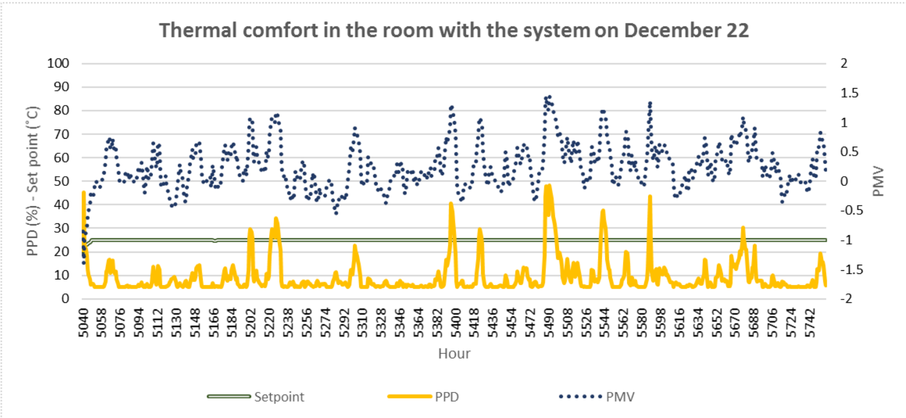


Fig. 17. Thermal comfort in the room with the system on December 22

6 .Conclusion

Changes in construction methods and the use of components of traditional architecture in the new formats can improve the energy consumption of buildings. This is very important in today's world and should not be ignored. Therefore, a building's components must be an effective combination of climatic architectural features and new systems. This study has tried to improve the performance of the traditional system of windcatcher by combining it with the geothermal system. For this, background research was carried out, and then the simulation of the proposed model was done by TRNSYS software. The results indicate that the energy consumption of the test room has improved by 37.6% in summer and 7% in winter. According to the presented graphs, the system has also improved thermal comfort. This can be more accurately investigated in future research by considering variable temperature and different parameters of thermal comfort. In addition to the items mentioned in the system, a 1 kWh pump has been used, which has been supplied by a vertical turbine. This means the system supplies adequate pre-heating and pre-cooling for the room without using any fossil fuels.

Acknowledgments

This article is the result of a research project titled "Improvement of Windcatcher's Efficiency by Using GSHP System and Savonius Wind Turbine (To Supply Thermal Comfort)" which was funded by Imam Khomeini International University in collaboration with the Faculty of Mechanics of the K. N. Toosi University of Technology. The authors would like to thank them.

References

[1] Bahadori, N.M. (1994). Viability of Wind Towers in Achieving Summer Comfort in the Hot Arid Regions of the Middle East, Renewable Energy, Volume 5, Issues 5–8, Pages 879-892. https://doi.org/10.1016/0960-1481(94)90108-2.

[2] Roaf, S., Manuel, F., Stephanie, T., (2007). Ecohouse, a Design Guide, Third Edition.

[3] Badran, A. (2003). Performance of Cool Towers Under Various Climates in Jordan, Energy and Buildings, Vol 35, 10, pp 1031-1035, https://doi.org/10.1016/S0378-7788(03)00067-7

[4] Sarbu, I., Sebarchievici, C. (2014). General Review of Ground-Source Heat Pump Systems for Heating and Cooling of Buildings, Energy and Buildings 70,441–454. https://doi.org/10.1016/j.enbuild.2013.11.068.

[5] Soltani M, Kashkooli FM, Dehghani-Sanij AR, Kazemi AR, Bordbar N, Farshchi MJ, Elmi M, Gharali K, Dusseault MB, (2018), A comprehensive study of geothermal heating and cooling systems, Sustainable Cities and Society, https://doi.org/10.1016/j.scs.2018.09.036.

[6] Reda. Francesco, Arcuri. Natale, Loiacono. Pasquale, Mazzeo. Domenico (2015), Energy assessment of solar technologies coupled with a ground source heat pump system for residential energy supply in Southern European climates, Energy, Volume 91, Pages 294-305. https://doi.org/10.1016/j.energy.2015.08.040.

[7] Karimi Dastjerd, A. (2013). Evaluate Exergoeconomic and Economic Analysis of GSHP, M.Sc. Thesis, Islamic Azad University, Science, and Research Branch. Tehran (in Persian).

[8] Nejatolahi, M., Sayadi, H., Molaei Kermani, E. (2009). Economic Comparison of Heat Dissipation of Cooling Systems to Air and Ground, 7th National Energy Conference. Tehran - National Energy Committee of the Islamic Republic of Iran (in Persian).

[9] Amrollahi, M.H., Najafi Sarem, Y. (2010). Perspectives of the Use of Geothermal Energy Technology (Geothermal Thermal Pump) in Iran, First Iranian Conference on Renewable Energy and Distributed Production. Birjand University. Birjand, Iran (in Persian).

[10]Bahadori, N.M. (1985). An Improved Design of Wind Towers for Natural Ventilation and Passive Cooling, Solar Energy 35(2):119-129. https://doi.org/10.1016/0038-092X(85)90002-7.

[11] Trombe, A., Pettit, M., Bourret, B. (1991). Air Cooling by Earth Tube Heat Exchanger: Experimental Approach, Renewable Energy, vol. 1, No 5/6, pp. 699-707. https://doi.org/10.1016/0960-1481(91)90016-I.

[12] Bahadori, M.N., Mazidi, M., Dehghani, A.R. (2008). Experimental Investigation of New Designs of Wind Towers, Renewable Energy 33.2273–2281. https://doi.org/10.1016/j.renene.2007.12.018.

[13] Zhao, J., Chen, Y., Lu, S., Cui, J. (2009). Optimization of Serial Combined System of Ground-Coupled Heat Pump and Solar Collector, Journal of Transaction of Tianjin University, vol.15, pp. 37-42. DOI: 10.1007/s12209-009-0008-3.

[14] Bansal, V., Misra, R., Agrawal, G.D., Mathur, J. (2009). Performance Analysis of Earth-Pipe-Air Heat Exchanger for Winter Heating, Energy and Buildings, vol. 41, pp. 1151-1154. https://doi.org/10.1016/j.enbuild.2009.05.010.

[15] Bansal, V., Misra .R, Agrawal, G.D., Mathur, J. (2010). Performance Analysis of Earth–Pipe–Air Heat Exchanger for Summer Cooling, Energy and Buildings 42(5):645-648. DOI: 10.1016/j.enbuild.2009.11.001.

[16] Ozgener, O., (2010). Use of Solar Assisted Geothermal Heat Pump and Small Wind Turbine Systems for Heating Agriculture and Residential Buildings, Energy, Vol. 33, No. 1, pp. 262-68.

https://doi.org/10.1016/j.energy.2009.09.018.

[17] Abu-Rayash. A, Dincer. I (2020), Development of an integrated energy system for smart communities, Energy, https://doi.org/10.1016/j.energy.2020.117683.

[18] Jafarian, S.M., Jaafarian, S.M., Haseli, P., Taheri, M. (2010). Performance Analysis of a Passive Cooling System Using Underground Channel (Naghb), Energy and Buildings 42. 559–562. https://doi.org/10.1016/j.enbuild.2009.10.025.

[19] Darkwa, J., Kokogiannakis, G., Magadzire. C.L., Yuan. K. (2011). Theoretical and Practical Evaluation of an Earth-Tube (E-Tube) Ventilation System, Energy and Buildings, vol. 43, pp. 728–736. https://doi.org/10.1016/j.enbuild.2010.11.018.

[20] Soutullo, S., Sanjuan, C., Heras, M.R. (2012). Energy Performance Evaluation of an Evaporative Wind Tower, Solar Energy 86, 1396–1410. https://doi.org/10.1016/j.solener.2012.02.001.

[21] Abdallah, A.S.H., Hiroshi, Y. (2014). Parametric Investigation of Solar Chimney with New Cooling Tower Integrated in a Single Room for New Assiut City, Egypt climate, Int J Energy Environ Eng 5:92. DOI 10.1007/s40095-014-0092-6.

[22] Benhammou, M., Draoui, B., Zerrouki, M., Marif, Y. (2015). Performance Analysis of an Earth-to-Air Heat Exchanger Assisted by a Wind Tower for Passive Cooling of Buildings in Arid and Hot Climate, Energy Conversion and Management, vol. 21, pp. 1-11. https://doi.org/10.1016/j.enconman.2014.11.042.

[23] Niu, F., Yu, Y., Yu, D., Li, H. (2015). Heat and Mass Transfer Performance Analysis and Cooling Capacity Prediction of Earth to Air Heat Exchanger, Applied Energy, Vol. 137, pp.211-221. https://doi.org/10.1016/j.apenergy.2014.10.008.

[24] Jamal Abed Al Wahid Jassim (2015). Sustainable Design of Windcatcher of an Earth-to-Air Heat Exchanger in Hot Dry Areas, International Journal of Scientific & Engineering Research, Volume 6, Issue 4, April-2015.

[25] Calautita, J.K., Hughes, B.R., Shahzad, S.S, (2015). CFD and Wind Tunnel Study of the Performance of a Uni-Directional Windcatcher with Heat Transfer Devices, Renewable Energy 83. 85-99. https://doi.org/10.1016/j.renene.2015.04.005.

[26] Chaudhry, H.N., Calautit, J.K., Hughes, B.R. (2015). Computational Analysis of a Wind Tower Assisted Passive Cooling Technology for the Built Environment, Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2015.03.004.

[27] Soni. Suresh. Kumar, Pandey. Mukesh, Bartaria. Vishvendra Nath (2016), Hybrid ground coupled heat exchanger systems for space heating/cooling applications: A review, Renewable and Sustainable Energy Reviews, Volume 60, Pages 724-738. https://doi.org/10.1016/j.rser.2016.01.125.

[28] Calautit. John Kaiser, Hughes. Ben Richard, O'Connor. Dominic, Shahzad. Sally Salome (2016), Numerical and experimental analysis of a multi-directional wind tower integrated with vertically-arranged heat transfer devices (VHTD), Applied Energy, Volume 185, Part 2, Pages 1120-1135. https://doi.org/10.1016/j.apenergy.2016.02.025.

[29] Calautit.J, Aquuino. A, O'Conno. D, Cabaneros. Sh, Shahzad. S, Wazed. S, Garwood. T, Calautit. K, Hughes. B, (2017), Indoor environmental quality (IEQ) analysis of a low energy windcatcher with horizontally-arranged heat transfer devices, Energy Procedia, Volume 142, Pages 2095-2101. https://doi.org/10.1016/j.egypro.2017.12.582.

[30] Khani, S.M.R., Bahadori, M.N., Dehghani-Sanij, A.R. (2017). Experimental Investigation of a Modular Wind Tower in Hot and Dry Regions, Energy for Sustainable Development 39.21–28. DOI: 10.1016/j.esd.2017.03.003.

[31] Calautita, J.K., Aquinoa, A.I., Shahzad, S., Diana, S.N.M., Hughesa. B.R., (2017). Thermal Comfort and Indoor Air Quality

Analysis of a Low-energy Cooling Windcatcher, Energy Procedia 105.2865 – 2870. https://doi.org/10.1016/j.egypro.2017.03.634.

[32] Soltani, M., Dehghani-Sanij, A., Sayadnia, A., Kashkooli, F., Gharali, K., Mahbaz, S.B., Dusseault, M.B. (2018), Investigation of Airflow Patterns in a New Design of Wind Tower with a Wetted Surface, Energies. https://doi.org/10.3390/en11051100.

[33] Noroozi, A., Veneris, Y.S. (2018)," Thermal Assessment of a Novel Combine Evaporative Cooling Windcatcher", Energies 2, 11, 442. DOI: 10.3390/en11020442.

[34] Seidabadi. L., Ghadamian, H., Aminy, M. (2019). A Novel Integration of PCM with Windcatcher Skin Material in Order to Increase Heat Transfer Rate, Int. Journal of Renewable Energy Development 8 (1): 1-6. https://doi.org/10.14710/ijred.8.1.1-6.

[35] Calautit, J. K., O'Connor, D., Tien, P. W., Wei, S., Pantua, C. A. J., & Hughes, B. (2020). Development of a natural ventilation windcatcher with passive heat recovery wheel for mild-cold climates: CFD and experimental analysis. Renewable Energy, 160, 465-482, https://doi.org/10.1016/j.renene.2020.05.177.

[36] Calautit, J. K., Tien, P. W., Wei, S., Calautit, K., & Hughes, B. (2020). Numerical and experimental investigation of the indoor air quality and thermal comfort performance of a low energy cooling windcatcher with heat pipes and extended surfaces. Renewable Energy, 145, 744-756, https://doi.org/10.1016/j.renene.2019.06.040.

[37] Internal Journal of the General Meteorological Department of Yazd Province, Abr Specialized Yearbook, Tenth Year, No. 50, December 2009.

[38] Pranesh, V., Velraj, R., Christopher, S., & Kumaresan, V. (2019). A 50-year review of basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications. Solar Energy, 187, 293-340, https://doi.org/10.1016/j.solener.2019.04.056.

[39] http://climate.onebuilding.org/. Retrieved (2020).

[40] Khajehzadeh. Iman, Vale. Brenda, Yavari. Fatemeh, (2016). A comparison of the traditional use of courthouses in two cities, International Journal of Sustainable Built Environment 5, 470–483, https://doi.org/10.1016/j.ijsbe.2016.05.010.

[41] TRNSYS (2020). Transient System Simulation Tool, www.trnsys.com, retrieved on 3 March 2020.

[42] M. Hossein Ghadiri, N. Lukman N. Ibrahim, R. Aayani (2011). The Effect of Windcatcher Geometry on the Indoor Thermal Behavior. Conference Paper publication at: https://www.researchgate.net/publication/281774033 • January 2011.

[43] Agrawal. Kamal Kumar, Agrawal. Ghanshyam Das, Misra. Rohit, Bhardwaj. Mayank, Jamuwa. Doraj Kamal. (2018). A Review on Effect of Geometrical, Flow and Soil Properties on the Performance of Earth Air Tunnel Heat Exchanger, Energy & Buildings, https://doi.org/10.1016/j.enbuild.2018.07.035.

[44] Chiesa G, (2018), EAHX – Earth-to-air heat exchanger: Simplified method and KPI for early building design phases, Building and Environment. https://doi.org/10.1016/j.buildenv.2018.08.014.

[45] ISO 7730 (2005). Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, European Committee for Standardization This European Standard was approved by CEN on 21 October. https://www.testo.com/en-us/comfort-level. Retrieved (2020).